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Identifying multiple stressors that influence eutrophication in a Finnish agricultural river

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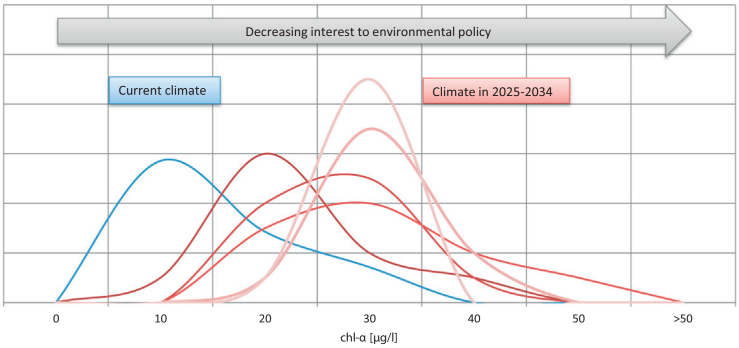
HIGHLIGHTS

- Chl-*a* depended on TP with synergistic interaction with water temperature.
- Climate change influences mainly indirectly via intensifying agriculture.
- Riparian re-forestration for shading the river to decrease water temperature is needed.

GRAPHICAL ABSTRACT



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ABSTRACT

In Finland, a recent ecological classification of surface waters showed that the rivers and coastal waters need attention to improve their ecological state. We combined eco-hydrological and empirical models to study chlorophyll-*a* concentration as an indicator of eutrophication in a small agricultural river. We used a modified story-and-simulation method to build three storylines for possible changes in future land use due to climate change and political change. The main objective in the first storyline is to stimulate economic activity but also to promote the sustainable and efficient use of resources. The second storyline is based on the high awareness but poor regulation of environmental protection, and the third is to survive as individual countries instead of being part of a unified Europe. We assumed trade of agricultural products to increase to countries outside Europe. We found that chlorophyll-*a* concentration in the river depended on total phosphorus concentration. In addition, there was a positive synergistic interaction between total phosphorus and water temperature. In future storylines, chlorophyll-*a* concentration increased due to land use and climate change. Climate change mainly had an indirect influence via increasing nutrient losses from intensified agriculture. We found that well-designed agri-environmental measures had the potential to decrease nutrient loading from fields, as long as the predicted increase in temperature remained under 2 °C. However, we were not able to achieve the nutrient reduction stated in current water protection targets. In addition, the ecological status of the river deteriorated. The influence of temperature on chlorophyll-*a* growth indicates that novel measures for shading rivers to decrease water temperature may be needed in the future.

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1. Introduction

The main goal of the Water Framework Directive (WFD 2000) is to achieve good ecological and chemical status for all inland and coastal surface waters. In Finland, the WFD covers the whole of the country. A recent ecological classification of surface waters showed that the rivers and coastal waters need attention to improve their ecological status, but larger lakes were mainly in excellent or good state SYKE (2015, 2018). Rivers flowing directly into the Baltic Sea in particular need improvement because of their own ecological state but also because they carry nutrients to the coastal areas. On a European level, WFD has faced problems in achieving its targets for the non-deterioration of waters (Voulvoulis et al., 2017).

The ecological status of European inland waters and seas has also attracted interest in terms of reducing nutrient losses from anthropogenic sources at other administrative levels. The Helsinki Commission (HELCOM) negotiated the Baltic Sea Action Plan that aimed to cut phosphorus (P) and nitrogen (N) inputs to the Baltic Sea by 42% and 18%, respectively, from the average loads of 1997–2003 by the year 2016. On a national level, the Finnish Council of State issued a Decision-in-Principle on water protection targets for 2005 (Ministry of the Environment, 1998). Due to the failure to meet these, new targets for 2015 were set in 2006 (Ministry of Environment, 2007).

Nowadays, water protection policy concentrates on agriculture as it comprises the largest source of nutrients fed into water bodies in Finland. Agricultural land use covers only 7% of the total land area but it is concentrated in the southern and western parts of the country. Earlier investments in municipal and industrial waste water purification effectively improved the quality of inland waters (Räike et al., 2003). The key objective is that nutrient loads entering water bodies from agriculture should be reduced by a third compared to their levels over the period 2001–2005, and halved over a longer timescale (Ministry of the Environment, 2005). That means a reduction of P loading to the Baltic Sea by 330 tn per year. The last water protection target to cut nutrient loading from agriculture by 2015 was only partly achieved (Rankinen et al., 2016).

The reduction of P inputs has decreased eutrophication in many lakes, but was not successful in others. Whole-lake experiments indicate that biomass growth is often stimulated more by stoichiometrical relationships of P, N and carbon (C) enrichment rather than by N or P alone (Elser et al., 2007; Paerl et al., 2016; Stutter et al., 2018). Hence, controlling both N and P inputs will help control eutrophication in some lakes and also reduce N export to downstream N-sensitive ecosystems, such as the Gulf of Finland in the Baltic Sea (Tamminen and Andersen, 2007).

Environmental decision-making in the EU requires an understanding of policy effects at the ecosystem level. Thus a solid methodological framework for mapping and assessing ecosystem services is needed. The Millennium Ecosystem Assessment (MA Millenium Ecosystem Assessment, 2005) defines ecosystem services as the benefits people obtain from ecosystems. Different typologies of ecosystem services cover a broad range of services, such as providing food, fibre, shelter and available habitats, regulating carbon, water and pollination, and creating opportunities for recreation, religion and aesthetics. MA (2005) deals with the full range of ecosystems, from those that are relatively undisturbed such as natural forests to ecosystems that are intensively managed and modified by humans, such as agricultural land and urban areas.

A framework for integrating ecosystem services into decision-making incorporates a variety of methods, including impact assessment, valuations, scenarios and policies (de Groot et al., 2002; de Groot et al., 2010). Ecosystem functioning or a resource can only be called an ecosystem service when people recognise its value. The mapping of ecosystem services also serves the purpose of making them more visible to the public, policy makers and other stakeholders.

Multiple pressures and their changes can result in the alteration of both the status and the services of aquatic ecosystems. The excess use of nutrients has increased productivity of water bodies, and the combustion of fossil fuels has increased CO_2 content in the atmosphere, leading to climate change. In Finland, annual precipitation is expected to increase by 13–26% and temperature by 2–6 °C by the end of the century, with the increases expected to be greater in winter than in summer (Jylhä et al. 2009). Further, climate change is projected to favour Finnish agriculture over the coming decades due to the prolongation of the growing season ($T > 5$ °C) (Peltonen-Sainio et al., 2009; Peltonen-Sainio et al., 2010). Thus, climate change may have a significant effect on land use. In addition, climate and diffuse pollution from different land uses may interact and have combined effects on water resources.

The principle of scenario analysis is to explore alternative future developments and strategies to respond to such developments (Alcamo, 2008). For example, the International Panel for Climate Change (IPCC) describes scenarios as alternative futures that are neither projections nor forecasts. A scenario typically describes an initial situation and the key driving forces and changes that lead to a particular future state. Thus, different scenario analysis techniques may serve as links between science and policy (Guivarch et al., 2017).

Modelling approaches have become widely used in the planning and evaluating of ecosystem management, as they are able to take into account the combined effect of different pressures. Catchment-scale models, e.g. eco-hydrological models INCA and SWAT (Arnold et al., 1998; Whitehead et al., 1998) are valuable in assessing both water quality and quantity, and their impact on ecology. Process-based models are common in hydrology. They are considered to be more accurate than empirical models for simulating conditions outside the current observations and for making predictions (e.g. Leavesley, 1994).

Empirical equations and models have a long history in ecology, but newer techniques that use artificial intelligence, machine learning or more advanced linear models have only recently been adopted. Commonly used methods to make predictions are different versions of linear regression models. For example, generalised linear models (GLM) are widely used because they can handle non-normal distributions and nonlinear relationships (McGullagh and Nelder, 1989). Also machine learning (ML) methods, like artificial neural networks and decision tree learning, are used to predict alternative options. Machine learning is a method used in computer science that uses statistical techniques to give computers the ability to progressively improve performance on a specific task with data (learning from data). A combined method is boosted regression trees (BRT), which does not produce a single best regression model, but uses the technique of boosting to combine a large number of relatively simple tree models adaptively (Elith et al., 2008; Feld et al., 2016).

A key research question concerning the water quality of river basins in southern Finland is the impact of human activities, mainly agriculture, on eutrophication. We combined ecosystem service assessment and scenario techniques to estimate the effect of land use and climate change on eutrophication, nutrient losses and ecological status. In terms of scenarios, we created three different possible futures of societal and political development. In the first scenario, the EU's environmental policy continues. In the second scenario we no longer have EU policy, but we try to solve environmental policies by technology. In the third scenario we do not have an environmental policy and we prefer economic growth to environmental protection. As regards the modelling approach, we combined physical and empirical models. Dissolved and total nutrient loading from the small agricultural catchment of Lepsämänjoki, characterised by clay soils, were simulated using the INCA model according to different climate change scenarios and storylines. The effect of climate, runoff and nutrient concentrations on summer time phytoplankton (Chl-*a*) growth in river were estimated using empirical models (GLM and BRT).

2. Material and methods

2.1. Area description

The Lepsämänjoki catchment (214 km^2) is a sub-basin of the Vantaanjoki basin in southern Finland. The Vantaanjoki discharges into the Gulf of Finland outside the capital, Helsinki (Fig. 1) and the area is very important for outdoor recreation. The Vantaanjoki is the secondary drinking water source for Helsinki, though it suffers from water quality problems; occasionally even toxic cyanobacteria blooms.

The mean discharge in the Lepsämänjoki was 2.2 m^3 s^{-1} in the 2000s (Korhonen and Haavanlammi, 2012). The mean annual precipitation in the area was 650 mm, and the mean annual temperature was +4 °C (data from the Finnish Meteorological Institute). The mean summer temperature (June–August) was +16.5 °C and the winter mean (December–February) −3.8 °C. There is also a small groundwater aquifer discharging into the river (base flow index 0.5).

The Lepsämänjoki catchment is a crop production area. In 2005 animal density was only 0.08 animal units (AU) per hectare of field (Mattila et al., 2007). The main soil types in the Lepsämänjoki catchment are clay

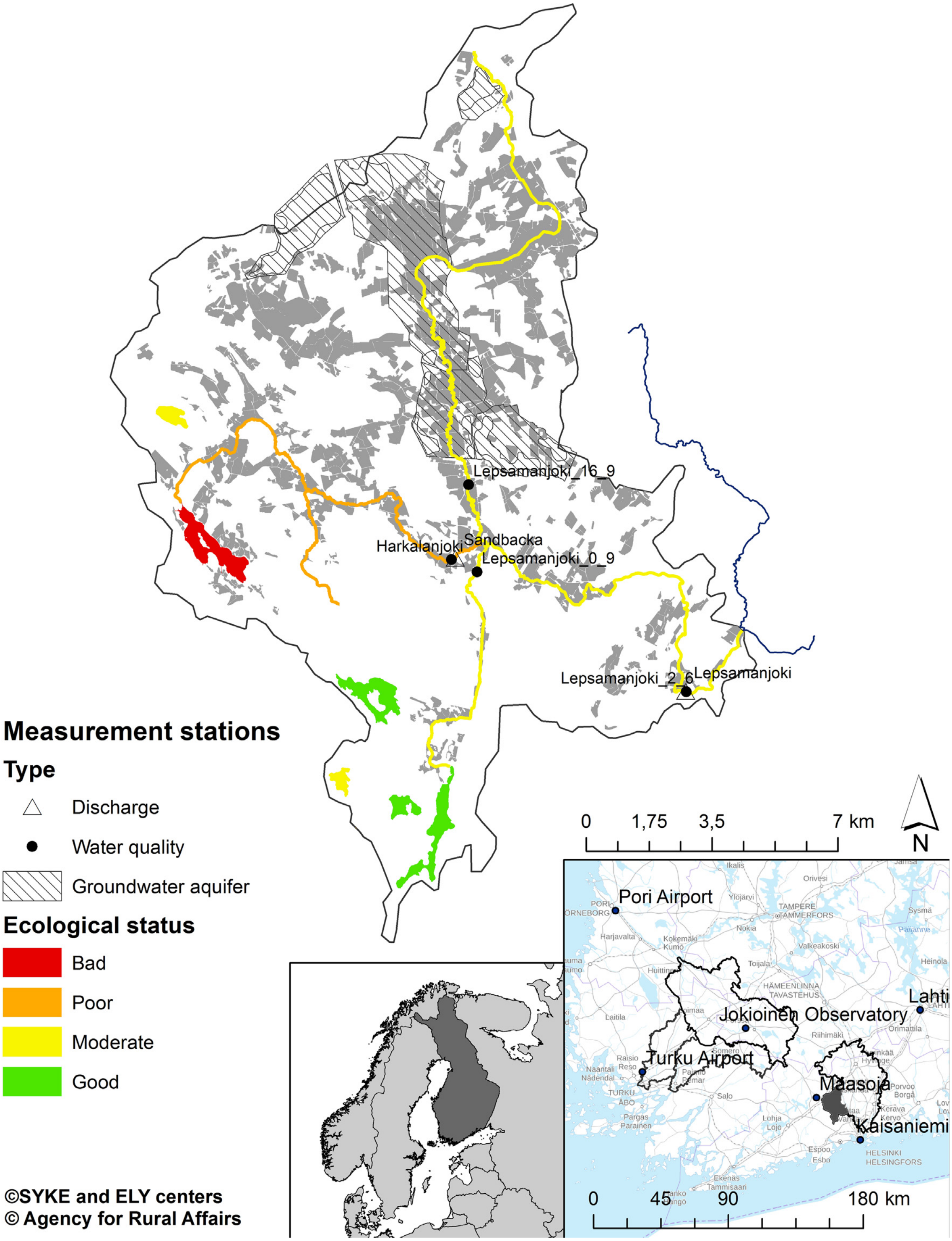

Fig. 1. Location of the Lepsämänjoki catchment (field areas are marked in grey), the river basins with Chl-*a* observations, and the location of the weather stations.

(*Vertic Cambisol*) and rocky soils (*Dystric Leptosol*) (Lilja et al., 2006). Arable fields are located on clay soils and they cover 23% of the area, the rest being mainly forest. The main crops are spring cereals: barley (*Hordeum vulgare* L.), spring wheat (*Triticum aestivum* L.) and oats (*Avena sativa* L.), but in the upper reaches of the catchment there is also some cabbage (*Brassica oleracea* var. *capitata*) cultivation (about 3% of the total area).

The ecological status of the Lepsämänjoki is moderate, and that of the tributary Härkälänjoki is poor. In the river basin plan, it is estimated that the Lepsämänjoki will achieve good ecological status by 2021 (Joensuu et al., 2010). Most of the farmers are committed to fulfilling environmentally sound cultivation practices included in the Finnish agri-environmental support scheme (Aakkula et al., 2012), the main tool for the Water Framework Directive (WFD).

One of the most important objectives of agri-environmental measures (Ministry of Agriculture and Forestry, 2013) is to control field-scale erosion. Measures include vegetative filter strips and buffer zones that are not ploughed or fertilised but from where crops are reaped to prevent dissolved phosphorus loads. Wintertime vegetation cover is seen as important to prevent erosion outside the growing season. For fertilisation, the agri-environmental programme sets lower limits than the Nitrates Directive (EEC, 1991). In addition, it is seen as important to increase the capacity of water bodies to retain nutrients by introducing artificial wetlands, for example.

2.2. Data availability

The Lepsämänjoki catchment has two discharge gauging stations and several water quality sampling sites. For empirical modelling the data set was extended by including data from surrounding river basins that have a similar climate, soil types and land cover to the Lepsämänjoki catchment (Fig. 1, Table 1). The data set contained a total of 175 observations (summer means) from years 1985–2014.

Discharge and water quality data were taken from the databases of the Finnish Environment Institute. The data from before 1985 was excluded due to major changes in chemical analysis methods.

Daily discharge values were based on daily water level recordings with calibrated flow rating curves. Mean runoff and minimum and maximum 1-day and 7-day runoff were calculated from discharge data.

Suspended sediment samples were filtered through a 0.4 μm polycarbonate filter (Ekholm and Krogerus, 2003). Total phosphorus (TP) analysis was performed using the molybdenum blue method with ascorbic acid as a reductant and a digestion with potassium peroxodisulphate. Total nitrogen (TN) determination was initiated by digestion with peroxodisulphate, followed by reduction of nitrate (NO_3) with a cadmium amalgam and determination of nitrite using the azo colour method. Total organic carbon (TOC) was analysed by infrared spectrometry. Water temperature was measured by thermometer when taking water samples. Chl-*a* was analysed by colourimetry after digestion by acetone or in some cases by ethanol.

Data on land use was available as CORINE 2000, 2006 and 2012 databases in 25 × 25 m grids. Soil types were available in a soil profile database in 25 × 25 m grids (Lilja et al., 2006). The Digital Elevation Model has the same resolution. Field parcel data from Natural Resources Finland was used to include the crop types in the land use data. In physical and empirical modelling, the data from the nearest Finnish Meteorological Institute weather station was used (Fig. 1).

2.3. Empirical models and their set-ups

We chose two statistical models (GLM and BRT) to link explanatory variables to summer mean Chl-*a* concentration. Both methods are able to address the influence of multiple stressors according to a protocol suggested by Feld et al. (2016). These models represent different approaches, as the generalised linear model (GLM) is a flexible generalisation of ordinary linear regression, and Boosted Regression Trees Analysis (BRT) is a method based on machine learning to fit and combine many models for prediction.

GLM allows for non-normal error distributions (McGullagh and Nelder, 1989) but it is not able to handle correlation between explanatory variables (collinearity). We used mixed models, because the data set contained random effects: year and site. Most of the water quality variables were biased, so they were log-transformed to better follow normal distribution. We used the package 'lmer' (Bates et al., 2015) in R (2018).

BRT can accommodate collinear data, handle non-linear variables with missing values, and identify interactions between explanatory variables (Elith et al., 2008). However, The BRT method requires a large number of observations to deliver stable and reliable results (Feld et al., 2016). We did BRT analysis by using the R packages 'gbm' (Ridgeway, 2006) and 'dismo' (Hijmans et al., 2017). The package 'gbm' is the main tool for running BRT, but 'dismo' provides a number of functions that assist in applying BRT to ecological data and to enhance interpretation.

We used the field percentage of the catchment above the sampling point, water quality observations (TP, TN, NO_3-N, TOC, colour, turbidity, suspended sediments, water temperature), discharge estimates (mean Q, mean R, 1-day minimum R, 1-day maximum R, 7-day minimum R, 7-day maximum R) and meteorological observations (air temperature, precipitation and solar radiation) to explain summertime Chl-*a* concentration. In addition, we divided TP by turbidity to be used as a proxy for non-particulate P (Bechmann and Stålnacke, 2005; Bechmann et al., 2008). As this relationship may change over time and place, we used the residuals from a locally estimated regression LOESS. The LOESS method is non-parametric, thus avoiding advance specification of the functional relationship between the variables (Jacoby, 2000). The regression was calculated with the 'loess' function of the 'stats' package

Table 1
Characteristics of the catchments in 1985–2014 and origin of the data.

Catchment	Water quality site	Fields (%)	Discharge gauging station	Q ($m^3 s^{-1}$)	Weather station
Lepsämänjoki	Lepsämänjoki 2.8	25.1	Lepsämänjoki	1.2	Lohja Porla/Maasoja
Lepsämänjoki	Lepsämänjoki 16.9	35	–	–	Lohja Porla/Maasoja
Lepsämänjoki	Härkälänjoki	19.8	Sundsbacka	0.7	Lohja Porla/Maasoja
Loimijoki	Lojo 68	36.3	Maurialankoski	23.0	Jokioinen Observatory
Loimijoki	Lojo 64	35.9	Maurialankoski	23.0	Jokioinen Observatory
Loimijoki	Lojo 40	25.6	Sallilankoski	19.6	Jokioinen Observatory
Loimijoki	Loimijoki 92	21.1	Sallilankoski	19.6	Jokioinen Observatory
Loimijoki	Loimijoki 113	12	Kuhalankoski	5.8	Jokioinen Observatory
Loimijoki	Lojo 58	35.1	Kuhalankoski	5.8	Jokioinen Observatory
Aurajoki	Aurajoki 54	37.2	Aurajoki	2.1	Turku Airport
Paimionjoki	Pajo 44	42.9	Halistenkoski	7.0	Turku Airport
Vantaanjoki	Vantaanjoki 4.2	23.4	Oulunkylä	16.0	Helsinki Kaisaniemi

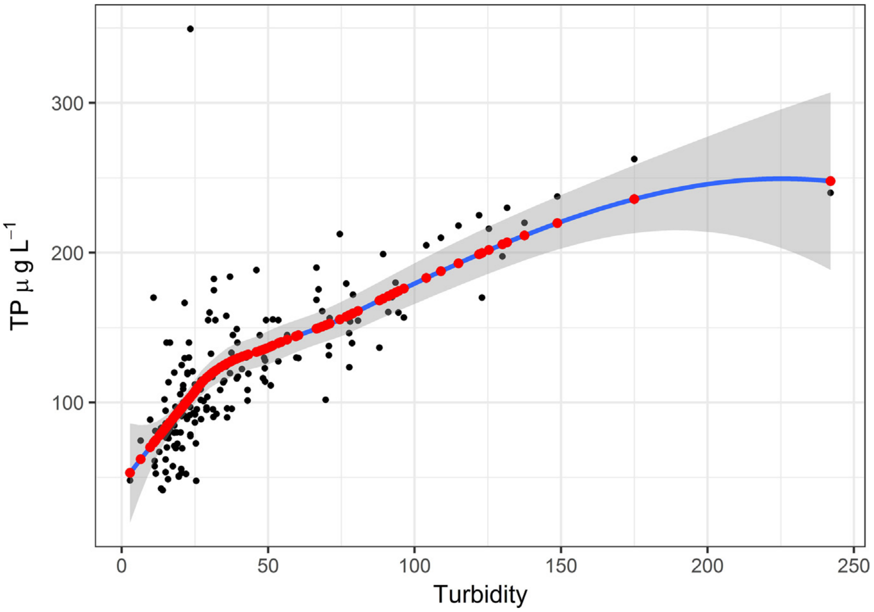

Fig. 2. Locally estimated regression (red dots on blue line) of TP on turbidity. Scatter in background represent observed TP and turbidity values. Grey area represents the confidence interval of the same estimate.

in R (2018), using locally quadratic polynomials and a bandwidth 0.75 to control the smoothing (Fig. 2).

As a detection limit we used both goodness-of-fit values (R^2-values) and Akaike's Information Criteria (AIC; (Akaike, 1973). Marginal R^2 (R^2m) is concerned with the variance explained by the fixed factors, and conditional R^2 (R^2c) is concerned with the variance explained by both the fixed and the random factors.

In the GLM model, the Chl-*a* concentration was best explained by a simple model including only TP concentration and interaction between TP and water temperature:

$$\text{log.Chl}-a \sim \text{log.TP} + \text{log.TP} : T_{\text{-}W} + (1|\text{site}) + (1|\text{year}) \qquad (1)$$

where log.Chl-*a* is a logarithm of the Chl-*a* concentration (μg l^{-1}), log.TP is a logarithm of TP concentration (μg l^{-1}), and T_w is water temperature (°C).

Goodness-of-fit values of the model are shown in Table 2, and partial responses in Fig. 3.

The simplified BRT model contained five parameters: TP, NO_3-N, proxy for non-particulate P (LOESS TP/Turb), water temperature (T_w) and 7-day minimum runoff (r_7day_min). It explained 61% of the variance. Partial responses are presented in Fig. 4. In this model there was also a clear additive interaction between TP concentration and water temperature, as well as between TP and NO_3-N concentration.

Table 2
Goodness-of-fit values of the GLMM model.

	Single influence	Interaction	Estimate	Significance	R^2m	R^2c
Model					0.21	0.41
	Intercept		0.758	*		
	log.TP		−0.68	**		
		log.TP:T_w	0.047	***		

*** 0.001 level of significance.
** 0.01 level of significance.
* 0.05 level of significance.

For the non-linear models, BRT R^2-value explaining <30% of their deviance were considered as not satisfactory in their accuracy, 30–50% as satisfactory, 50–60% as good and ≥60% as very good. For the linear model GLMM, <20% of their deviance were considered as not satisfactory in their accuracy, 20–40% as satisfactory, 40–50% as good and ≥50% as very good (Moriasi et al., 2015).

2.4. Eco-hydrological models and their set-up

We combined eco-hydrological INCA family models to simulate explanatory factors of Chl-*a* concentration according to different storylines. Simulated explanatory factors were then used to predict Chl-*a* concentration using empirical models.

PERSiST is a flexible rainfall-runoff modelling toolkit for use with the INCA family of models (Futter et al., 2014). PERSiST (the Precipitation, Evapotranspiration and Runoff Simulator for Solute Transport) is designed to simulate present-day hydrology; projecting possible future effects of climate or land use change on runoff and catchment water storage. PERSiST has limited data requirements and is calibrated using observed time series of precipitation, air temperature and runoff at one or more points in a river network.

INCA is a dynamic mass-balance model used to calculate the temporal variations in the hydrological flowpaths and nutrient transformations and stores in both the land and the river system. As output, INCA provides daily and annual land-use–specific nutrient loads for transformation processes and stores within the land phase, and daily time series of land-use–specific flows and concentrations. The N model solves traditional N cycle in different land use classes. The P reactions are based on equilibrium equations, and transported as soluble substances or attached on soil particles. The erosion sub-model describes the erosion and suspended sediment transportation processes from land use classes to river water. The model equations are described by Whitehead et al. (1998), Wade et al. (2002), Wade (2004), Lazar et al. (2010) and Jackson-Blake et al. (2016).

The PERSiST model and the INCA models were calibrated and validated against measured data in the Lepsämänjoki catchment (Granlund et al., 2015). There were several water quality measurement stations and two discharge gauging stations, so the multi-branch structure of the model was used. The main stream was divided into three

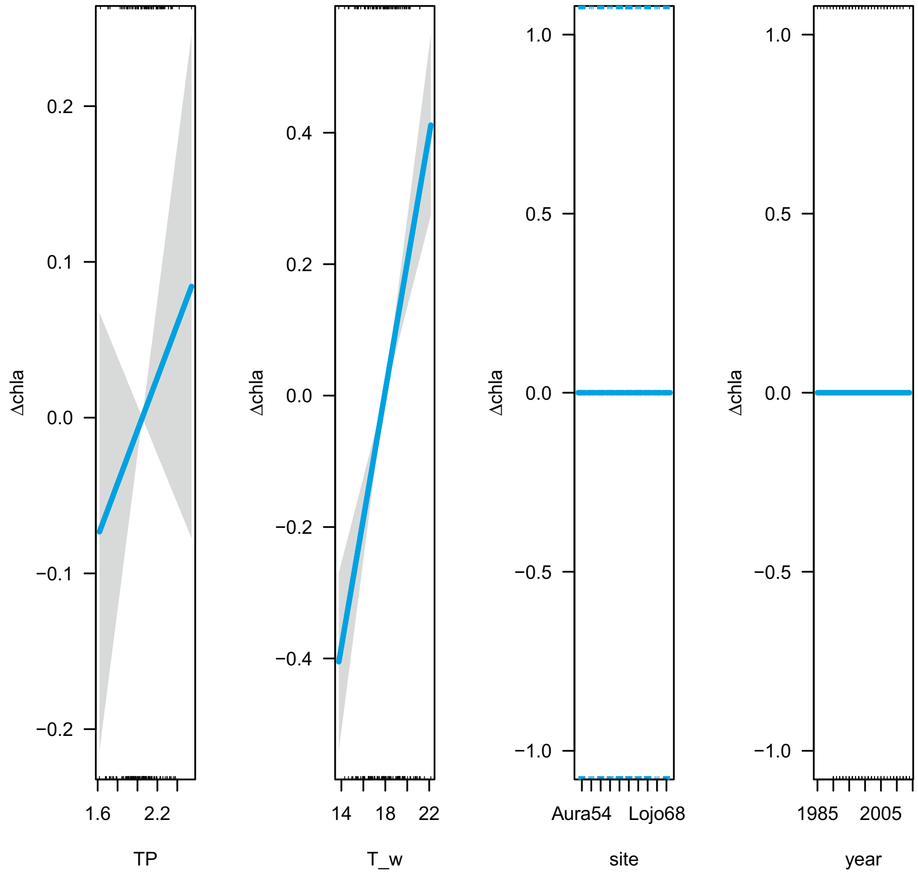

Fig. 3. Partial responses of the parameters in GLM model.

sub-catchments with tree tributaries. The main calibration points were those close to the discharge gauging stations. The other water quality stations had less data and were mainly used to check the correct level of simulations. The calibration period was 2004–2006 and the validation period was 2007–2009.

We used four goodness-of-fit values based on Moriasi et al. (2007) and Silgram and Schoumans (2004). R-squared (R^2) is a statistical measure of the proportion of variance in measured data explained by the model. R^2 can take a value between 0 and 1, where values closer to 0 represent a poor fit while values closer to 1 represent a perfect fit. Root Mean Squared Error (RMSE) is a measure of accuracy as the difference between measured and simulated values. A lower RMSE is better than a higher one, as a value of 0 would indicate a perfect fit to the data. However, optimal RMSE may give small error variance at the expense of significant model bias. Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. The optimal value for PBIAS is 0. The Nash-Shutcliffe coefficient of determination (N-S) shows how well the model reproduces all of the variation about the mean of the series (Nash and Sutcliffe, 1970; Aitken, 1973). We calculated this coefficient only for discharge, as it was originally developed for rainfall-runoff simulations and is most reliable when used with a large amount of observation data.

Equations of goodness-of-fit values in Table 3 are:

$$R^2 = \frac{\sum_{i=1}^{n}\left(P_i - \overline{O}\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \tag{2}$$

$$RMSE = \frac{100}{\overline{O}}\sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \tag{3}$$

$$PBIAS = \frac{\sum_{i=1}^{n}(O_i - P_i) * 100}{\sum_{i=1}^{n}(O_i)} \tag{4}$$

$$N\text{–}S = \frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 - \sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}\left(\left(O_i - \overline{O}\right)\right)^2} \tag{5}$$

In the equations above, O_i is the observed data point, P_i is the simulated data point, $\overline{O}$ is the mean of the observed data series and n is the number of data points.

Calibration and validation of discharge is satisfactory according to the guidelines given by Moriasi et al. (2015). For phosphorus validation, measures with $R^2 \leq 0.40$ were considered as not satisfactory, whereas for nitrogen $0.30 < R^2 \leq 0.60$ were satisfactory and $0.60 < R^2 \leq 0.70$ were good. Regarding PBIAS, we used absolute values and validation measures with PBIAS ≥ |30| were considered not satisfactory, |20| ≤ PBIAS < |30| satisfactory, |15| ≤ PBIAS < |20| good and PBIAS < |15| very good in their accuracy.

2.5. Analysis of ecosystem services

To structure the analysis of ecosystem services and select appropriate indicators, we used the conceptual framework proposed by Grizzetti et al. (2016), based on the cascade model. The framework includes the capacity of the ecosystem to deliver the service, the actual flow of the service and the benefits. Capacity refers to the potential of the ecosystem to provide ecosystem services, while flow is the actual use of the ecosystem services.

For water purification we considered the rate of nutrient removal ($kg\ km^{-2}\ year^{-1}$), which is an indicator of the actual flow of the service.

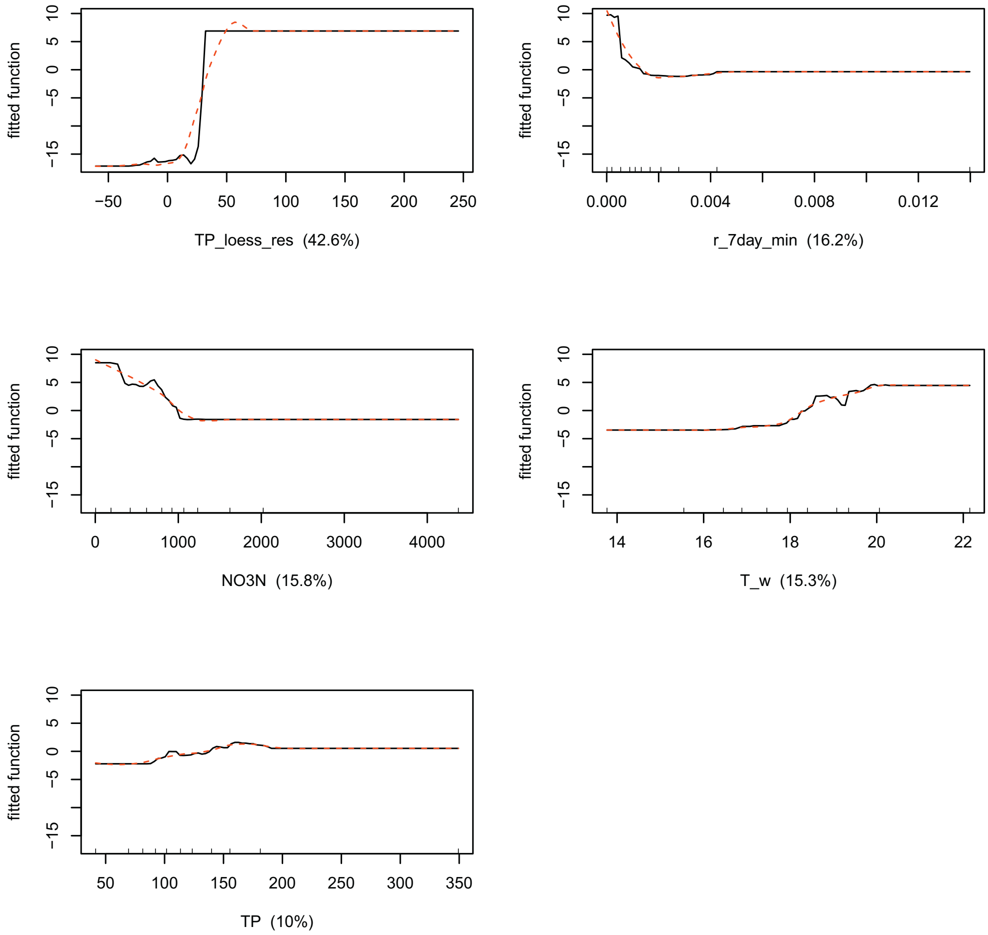

Fig. 4. Partial responses in BRT model. Percentage represents the explanatory power of the explanatory factor to fitted value of Chl-*a*.

To assess the capacity of the ecosystem to provide clean water for drinking, agricultural and recreational purposes we referred to the Finnish standards for ecological status.

2.6. Development of storylines

We used a modified story-and-simulation method (Alcamo, 2008; Guivarch et al., 2017) to build storylines for possible changes in future land use. Our storylines are based on IPCC (International Panel for Climate Change) climate scenarios.

We used outputs of the global general circulation models GFDL-ESM2M (the Geophysical Fluid Dynamics Laboratory, USA) and IPSL-CM5A-LR (the Institute Pierre Simon Laplace climate modelling centre, France) as they give results close to the Inter-Sectoral Impact Model Inter-comparison Project median for the northern region (Faneca Sanchez et al., 2015). These two models differ in terms of atmospheric prognostic state variables (wind, pressure, temperature, humidity, cloud water and ice, and cloud fraction for GFDL and wind, pressure, temperature and cloud water for IPSL). Further conceptual differences between the GFDL and IPSL are given in Warszawski et al. (2014). Outputs from each of the two global climate models were used to generate air temperature and precipitation data for the period 2006–2099.

The design of the following two qualitative storylines were based on expected changes in climate, and their quantitative implementation in cooperation with stakeholders. Behind the storylines is the assumption that the climate in the future will favour agricultural production by increasing temperature and prolonging the growing period (Peltonen-Sainio et al., 2009). It is assumed that precipitation will also increase, and possible seasonal drought problems can be solved by technical solutions, e.g. by irrigation. The implementation of the storylines is listed

Table 3
Goodness-of-fit values for calibration and validation periods.

Parameter	Site	Calibration					Validation				
		R^2	*N-S*	*RMSE*	*PBIAS*	*n*	R^2	*N-S*	*RMSE*	*PBIAS*	*n*
Q	Sundsbacka	0.615	0.608	69.250	14.5	1039	0.542	0.516	60.802	18.3	731
	Lepsämänjoki	0.640	0.540	92.361	11.0	261	0.612	0.528	57.346	2.18	672
NO_3-N	Härkälänjoki	0.654	–	348.102	-	7	–	–	–	–	–
	Lepsämänjoki 2.6	0.412	–	96.032	0.1	64	0.126	–	78.376	0.1	61
Susp. sed.	Härkälänjoki	–	–	–	–	–	0.020	–	103,053	52.2	9
	Lepsämänjoki 2.6	0.195	–	97.315	7.29	63	0.008	–	104.079	12.9	60
Tot-P	Härkälänjoki	–	–	–	–	–	0.396	–	51.106	1.8	9
	Lepsämänjoki 2.6	0.285	–	70.325	26.3	64	0.173	–	61.097	11.8	71

Table 4
Implementation of the storylines.

Storyline	Sector	Type of measure	Specific measure
Consensus	Agriculture	Increase in agricultural land; up to 50%	Forest turned into fields
		Less intensive agriculture	30% increase in yields
		CAP greening crop rotation	40% spring cereals-30% winter cereals, 15% grass, 15% fallow
		Fertilisation	No change
		Increase in erosion control	80% on stubble in spring cereals fields
	Urban	No change	No change in population
Techno	Agriculture	Increase in agricultural land	Forest turned into fields
		More intensive agriculture	20% increase in yields
		Moderate crop rotation	50% spring cereals-50% winter cereals, no change in grass and fallow
		Increase in fertilisation	20% increase in N- and P fertilizer application
		No change in erosion control	50% in stubble on spring cereal fields
	Urban	Increase in urban areas	1.5% of forest areas turned into urban
		Improvement in waste water treatment	New central sewage system (outside the area), decrease in sewage by 50%
Fragmented	Agriculture	High increase in agricultural land	up to 90% of forest areas (soil type limited) turned into fields
		More intensive agriculture	25% increase in yields
		Monoculture	Mainly barley
		Increased fertilisation	30% increase in N and P fertilizer application
		No erosion control	No erosion control
	Urban	Increase in urban areas	5% of forest areas turned into urban
		Increase in population and waste water	Effluents from scattered dwellings and sewage treatment plants are increased by 10%

in Table 4. The qualitative storylines were included in the model application by making a quantitative change in the relevant model parameter value (Table 4).

The following storylines were simulated:

Storyline 1 – Consensus world

In this storyline, the main objective of the government and citizens is to stimulate economic activity but also to promote the sustainable and efficient use of resources. The current guidelines and policies are continued. As it is assumed that the climate of the future will favour agricultural production by increasing yields in Finland (Peltonen-Sainio et al., 2010; Peltonen-Sainio et al., 2009), it is also assumed that field percentage will increase, limited only by soil types and field slopes (>10%) which are not suitable for cultivation.

Storyline 2 – Techno world

This storyline is based on high awareness but poor regulation of environmental protection. Most actions are the result of individual or shared interest in protecting the environment, and are based on technical solutions. Cultural services like recreation opportunities are locally important. In the Lepsämänjoki basin, this storyline is based on the improvement of sewage treatment. A moderate increase in urban land cover (human settlements) is assumed, according to Haakana et al. (2015).

Storyline 3 – Fragmented world

The focus of this storyline is to survive as individual countries instead of being part of a unified Europe. National institutions focus on economic development and no attention is paid to the preservation of ecosystems. A large economic gap within Europe is emerging, caused by the absence of international trade. The current environmental policies are discontinued around 2025 and the focus is set on economic development. Agri-environmental policy resembles that of the pre-EU time, when it was focused on voluntary measures with minor monetary incentives (Valpasvuo-Jaatinen et al., 1997). The main markets for Finnish agricultural products are in the neighbouring countries. Exports to Russia are expected to increase when EU relationships do not restrict it. Traditionally, the share of exports to Russia has been large, at times even over 25% of the total export (Niemi and Väre, 2017). In this storyline, the agricultural field area is assumed to increase up to 90% of the sub-catchment area, as the climate of the future favours agricultural production. As current environmental guidelines are not valid, the main production type is monoculture of cereals with increased fertilisation level. As the catchment is located relatively close to the capital, an increase in human settlements is also assumed.

3. Results and discussion based on the storylines

3.1. Discharge and temperature

Future climate scenarios highlighted an increase in both annual mean temperature and mean precipitation. At the Lohja Porla meteorological station, the temperature increase was predicted to be <1.5 °C in the near future (2025–2034), but close to 2.5 °C later (2055–2064) when precipitation was also predicted to increase over 10% (Fig. 5). Because precipitation was predicted to increase in spring and late autumn in particular, current peak runoff due to snow melting in April occurs earlier in spring, simulated also by Veijalainen et al. (2010). Some scenarios also suggested an increase in runoff in late autumn.

On the other hand, summer runoff decreased according to all of the climate scenarios. Summer is already now the low flow period, the mean discharge being 1.6 $m^3\ s^{-1}$ in 2003–2014. Simulated mean discharge was 1.1 $m^3\ s^{-1}$ in 2025–2034 and 1.0 $m^3\ s^{-1}$in 2055–2064. Seven-day minimum runoff decreased from 0.003 $m\ s^{-1}$ (discharge 0.65 $m^3\ s^{-1}$) to 0.0023 $m\ s^{-1}$ (0.5 $m^3\ s^{-1}$) and 0.0022 $m\ s^{-1}$ (0.47 $m^3\ s^{-1}$), respectively. There were no major changes in hydrological extremes. The duration of high pulses decreased, and that of low pulses increased by a couple of days.

In the summer months, water temperature in rivers is associated with air temperature, according to Arora et al. (2016), who assumed that a decreasing flow led to a summer temperature increase. In our simulations, river water temperature also showed an increasing trend. In the period 2004–2013 water temperature was 16.5 °C. In the period 2025–2034 the mean summer temperature was 17.3 °C, and in 2055–2064 19.3 °C. On the other hand, groundwater flow is known to have a cooling effect (Wawrzyniak et al., 2017). Thus, rivers with a smaller groundwater input than Lepsämänjoki may warm more rapidly.

3.2. Ecosystem services

The annual nutrient removal/production rate on the field scale correlated with that on the catchment scale (Fig. 5), indicating that agriculture was the main source of nutrients. On a catchment scale there were also other nutrient sources than agriculture, and the nutrient removal

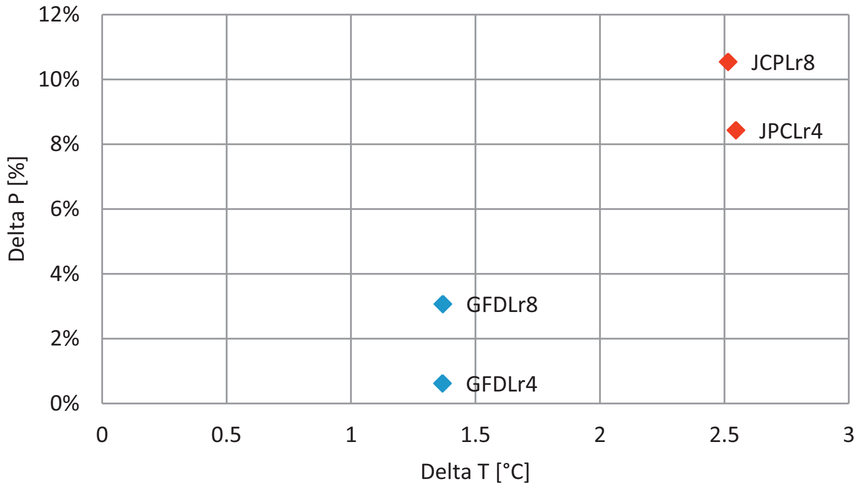

Fig. 5. Increase in temperature and precipitation according to different climate scenarios.

rate was negative (increasing nutrient losses) according to all storylines. The 'Fragmented world' storyline produced the highest increase and 'Consensus world' the lowest increase in nutrient losses.

According to storyline 'Consensus world', agri-environmental regulation led to increased nutrient removal (decrease in losses) on the field scale in the near future, when the increase in temperature and precipitation remained low. In the 'Consensus world' scenario, agri-environmental measures were fully implemented. In addition, the longer and warmer growing period increased yields and thus nutrient uptake of crops. That observation is in line with earlier studies where well-designed agri-environmental measures decreased nutrient loading and enhanced nutrient retention in a terrestrial environment (Turtola, 1999; Valkama et al., 2007; Valkama et al., 2015; Valkama et al., 2017).

Most of the increase in nutrient concentration seemed to be due to an increase in field area and urban settlements rather than climate change. Urban settlements are observed to have the same level of specific nutrient loads as that of agricultural areas (Sillanpää, 2013). An increase in field area was highest in the middle reaches of the river, and the increase in nutrient concentrations was also highest there. Nutrient concentrations increased according to all storylines in the river, even though the naturally meandering Lepsämänjoki had a relatively high capacity to retain nutrients – up to 16% (Rankinen et al., 2013).

Already in the near future (2025–2034) mean annual NO_3-N concentrations increased by 16–63%, suspended sediment concentration by 45–146% and TP concentration by 38–100%. In the 'Fragmented world' storyline, TP concentration almost doubled in the middle reaches of the Lepsämänjoki, both by 2025–2034 and by 2055–2064. Climate change alone (no land-use change included) had more effect on NO_3-N (increase of 15%) than on TP (increase of 7%) concentrations, suggesting that higher temperatures accelerate the decay of N-rich organic matter (Bokhorst et al., 2007; Follett et al., 2012). Clay soils in the Lepsämänjoki catchment are highly erosion-prone marine deposits. Tracer analysis has shown that cultivated fields contributed 66–100% of suspended sediment load from a small study catchment located on these soil types (Pietiläinen and Ekholm, 1992). In addition, the Lepsämänjoki catchment is a very erosion-sensitive area due to its steep fields. In the storylines, the increase in field area compensated for the positive development in nutrient loading. Here there are still relatively large areas of soil types that are suitable for cultivation under forests. On the other hand, there is not a lot of potential to increase erosion control methods, as they have been one of the most popular methods in the area (Mattila et al., 2007; Rankinen et al., 2015).

There were two exceptions from the linear relationship between field-scale and catchment-scale nutrient retention/losses (Fig. 6). For N, these exceptions were the 'Techno world' storylines, where catchment-scale losses were smaller than what could be expected based on field-scale losses. In 'Techno world', the increase in field area was smaller than in other storylines. In addition, we assumed more effective waste water purification, including effective N reduction.

For P, the exception was the 'Fragmented world 2055–2064' storyline, where catchment scale loading was higher than in other storylines. Field-scale loading did not differ from that of the other storylines. The source of catchment-scale loading may be something other than agriculture, such as river banks and other land use classes.

In the ecological classification of WFD, the TP concentration is the only water quality-related classification criterion for rivers in clay soil areas. According to that criterion, the status of the Lepsämänjoki deteriorated, such that the status of the main channel changed to bad, and that of the Härkälänjoki tributary to poor (Table 5). Current water protection targets were not achieved at a field scale, and at a catchment scale we did not find any reduction in nutrient losses.

3.3. Chlorophyll-a concentrations

We found considerable increases in Chl-*a* concentrations so that they doubled or tripled in the near future, depending on the storyline. The shifts in peak concentration are shown in Figs. 7 and 8. The

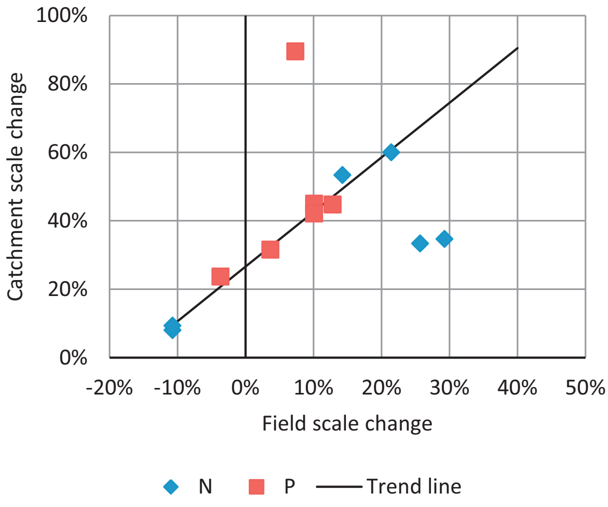

Fig. 6. Nutrient production/removal rates in field and catchment scale.

Table 5
Capacity of the ecosystem.

Storyline	Period	Sub-catchment	NO_3-N [mg/l]	Susp. sed. [mg/l]	TP [mg/l]	Ecological status
Base	2004–2013	Lepsämänjoki mid	1.25	30.90	0.10	Poor
Base	2004–2013	Härkälänjoki	1.27	18.50	0.09	Moderate
Consensus	2025–2034	Lepsämänjoki mid	1.44	44.59	0.14	Bad
Consensus	2025–2034	Härkälänjoki	1.52	27.62	0.11	Poor
Techno	2025–2034	Lepsämänjoki mid	1.79	56.82	0.15	Bad
Techno	2025–2034	Härkälänjoki	1.71	30.26	0.11	Poor
Fragmented	2025–2034	Lepsämänjoki mid	2.04	76.00	0.19	Bad
Fragmented	2025–2034	Härkälänjoki	1.99	49.72	0.16	Bad
Consensus	2055–2064	Lepsämänjoki mid	1.40	53.06	0.15	Bad
Consensus	2055–2064	Härkälänjoki	1.47	30.34	0.11	Poor
Techno	2055–2064	Lepsämänjoki mid	1.73	60.17	0.16	Bad
Techno	2055–2064	Härkälänjoki	1.66	32.68	0.11	Poor
Fragmented	2055–2064	Lepsämänjoki mid	1.80	65.09	0.18	Bad
Fragmented	2055–2064	Härkälänjoki	1.71	42.79	0.14	Bad

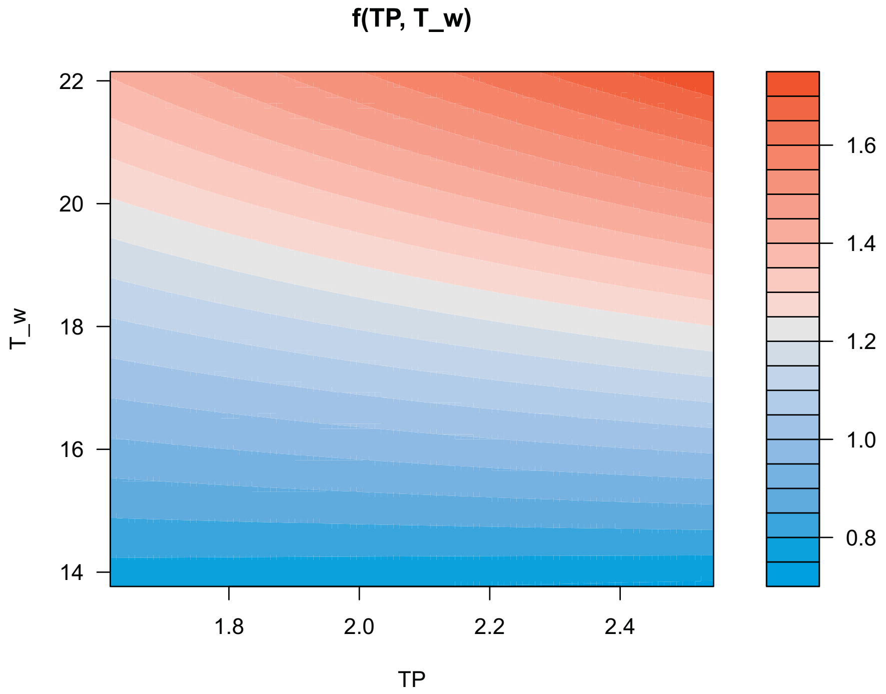

Fig. 7. Interaction between logarithmic value of total P concentration (TP) and water temperature (T_w) on logarithmic value of Chl-*a* concentration in GLM model.

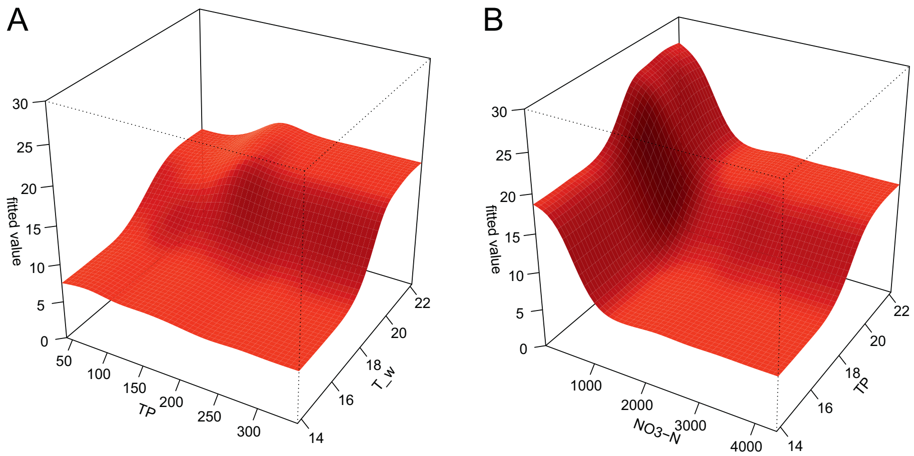

Fig. 8. Interactions between total P concentration (TP) and (a) water temperature (T_w) and (b) nitrate concentration on fitted value of Chl-*a* concentration in BRT model.

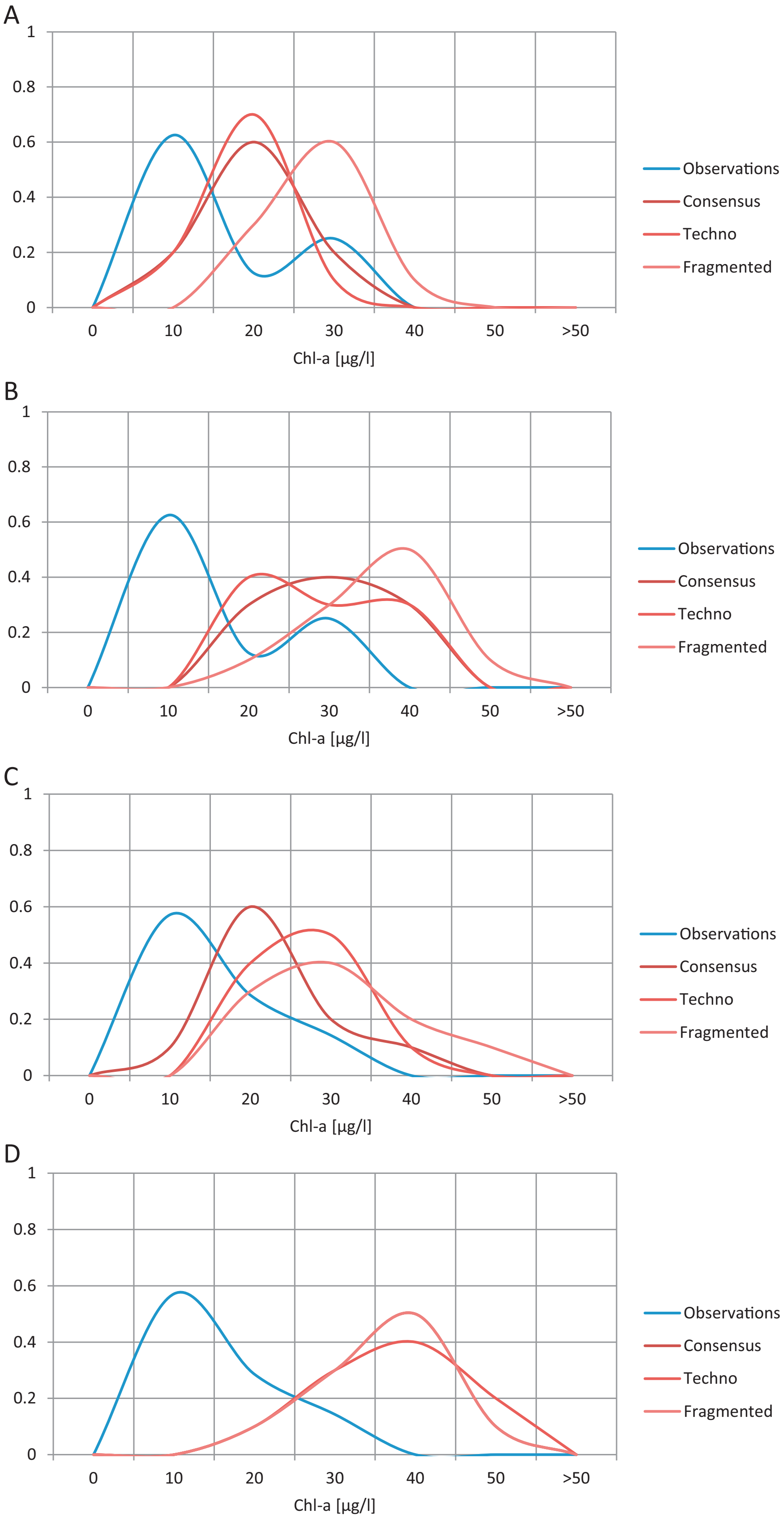

Fig. 9. Deviation of Chl-*a* concentrations according to different story lines simulated by GLMM (a) Härkälänjoki tributary in 2025-2034 (b) Härkälänjoki tributary in 2055-2064 (c) middle reaches of the river Lepsämänjoki in 2025-2034 (d) middle reaches of the river Lepsämänjoki in 2055-2064.

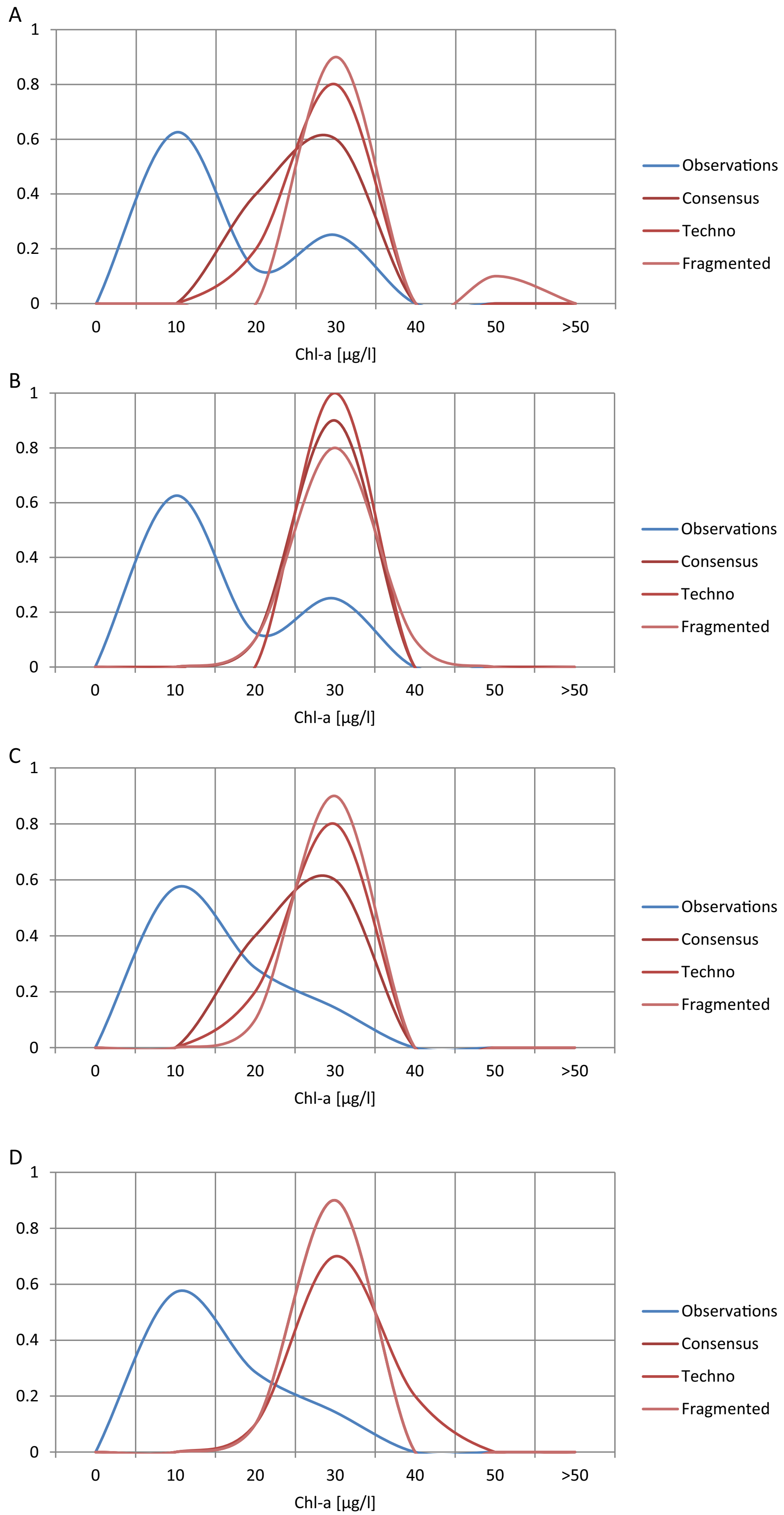

Fig. 10. Deviation of Chl-*a* concentrations according to different storylines simulated by BRT (a) Härkälänjoki tributary in 2025-2034 (b) Härkälänjoki tributary in 2055-2064 (c) middle reaches of the river Lepsämänjoki in 2025-2034 (d) middle reaches of the river Lepsämänjoki in 2055-2064.

development was relatively similar in the main channel and in the Härkälänjoki tributary, though 'Techno world' led to a slightly more optimistic development there than in the main channel. In general, the simulated increase in Chl-*a* concentration was slightly smaller by the GLMM than by BRT, probably because BRT had more explanatory factors than GLMM. Similar results gained by two different methods support each other.

Climate change is directly or indirectly going to enhance the main explanatory factors (TP and water T) of Chl-*a* growth. In most freshwater courses, P is the limiting factor for algal growth (Ruttner, 1963; Elser et al., 2007), like we observed in the Lepsämänjoki. In addition, temperature is known to regulate growth (Ruttner, 1963), and it explained 20% of the fitted value of Chl-*a* concentration in the BRT model. A simulated increase in summer mean water temperature was in the influential range, simulated by both GLM and BRT models. Both GLM and BRT models found a synergistic interaction between TP and water T (Figs. 9 and 10), so that their effect together was stronger than their individual or additive effect (Feld et al., 2016).

Light conditions are also known to regulate biota growth (Ruttner, 1963), though the response varies between species (Turunen et al., 2019). Zhang et al. (2018), for example, found that of the climate variables, wind speed and underwater available light were better predictors for phytoplankton biomass growth than temperature in Lake Taihu (Lat 31 °N). Binding et al. (2018) found light limitation, TP loading and summer surface temperature to explain phytoplankton biomass in Lake Winnipeg (Lat 50–54 °N). In our study, solar radiation did not explain Chl-*a* concentration. One reason may be that at high latitudes (Lat 60 °N) light is not a limiting factor during summer months. The other possibility is that there is not enough variation in light climate, as flowing river water is not stratified and high turbidity keeps light conditions similar in the whole water column.

Dissolved nutrients and runoff only had an influence on Chl-*a* concentration in the BRT model. Dissolved P is also known to be highly algal available (Ruttner, 1963; Ekholm, 1994). The decreasing shape of fitting function and interaction of NO_3-N in the BRT model in Fig. 10 may also indicate rapid uptake of dissolved nutrient by biota. The influence of NO_3 was not seen in the GLMM model, which had a lower explanatory power than the BRT model. Low runoff means lower flow velocity in the river, giving longer living time for biota (Ruttner, 1963). The predicted seven-day minimum runoff in the main channel was only slightly higher than the range where the BRT model shows the main influence. In these river basins dominated by clay soils, TOC concentration did not have an effect on Chl-*a* concentration, though it is known to be a substrate for biota (Ruttner, 1963).

In the current agri-environmental programme, crops should be removed from buffer zones to reduce dissolved P loading. If the focus is also in the ecological state of the river, riparian vegetation and other measures around the river itself should be considered. Riparian vegetation can reduce water temperature by providing shade. Depending on location and vegetation type, the cooling effect may vary between 0.3 °C and 3.0 °C (Garner et al., 2017; Loicq et al., 2018; Turunen et al., 2019). Stream temperature varies depending on different riparian vegetation types, coniferous plantations being the most effective at reducing summer temperature (Dugdale et al., 2018), though Garner et al. (2017) concluded that relatively sparse but strategically located vegetation could also produce substantial reductions.

Climate change influences the ecological status of rivers in southwestern Finland not only by increasing nutrient loading but also by increasing temperature. As a result, it influences the whole functioning of the ecosystem. In addition, there is synergistic interaction between TP concentration and water temperature. Even though Chl-*a* concentration can only be explained by TP concentration, this study indicates that soluble nutrients (both P and N) are more important regulators. The Chl-*a* concentration indicates ecosystem functioning and well-being, though it is not an official indicator of ecological status in Finnish rivers.

4. Conclusions

In our calculations, Chl-*a* concentrations in the Lepsämänjoki in summer depended on TP concentration and water temperature. In addition, there was a positive synergistic interaction between these two explanatory variables. These results are indicative for other river basins in clay dominated soils in southern Finland.

In the future storylines, Chl-*a* concentrations increased in the Lepsämänjoki due to land use and climate change. Climate change increased TP concentrations mainly indirectly via an intensification of agricultural production. Well-designed agri-environmental measures had the potential to decrease nutrient loading from fields, as long as the predicted increase in temperature and precipitation remains low. However, current water protection targets are not expected to be achieved.

At the catchment level, nutrients were transported from other sources (forest, settlements) as well, and the influence of agri-environmental measures on river water quality was lower. As a result, water protection measures should also be planned in other sectors than agriculture. The influence of temperature on Chl-*a* growth indicates that measures for shading the river to decrease water temperature may also be needed.

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