Marine Environmental Research 197 (2024) 106446

Contents lists available at ScienceDirect

Marine Environmental Research

journal homepage: www.elsevier.com/locate/marenvrev

Large reductions in nutrient losses needed to avoid future coastal eutrophication across Europe

Aslıhan Ural-Janssen [a,b,*], Carolien Kroeze [a], Erik Meers [b], Maryna Strokal [a]

[a] Earth Systems and Global Change Group, Wageningen University & Research, PO Box 47, 6700AA, Wageningen, the Netherlands
[b] Laboratory of Bioresource Recovery (RE-SOURCE LAB), Ghent University, Coupure Links 653, 9000, Ghent, Belgium

ARTICLE INFO

Keywords:
Coastal eutrophication
Future scenario analysis
MARINA-Nutrients model for Europe
River export of nutrients
Source contribution

ABSTRACT

Rapid technological development in agriculture and fast urbanization have increased nutrient losses in Europe. High nutrient export to seas causes coastal eutrophication and harmful algal blooms. This study aims to assess the river exports of nitrogen (N) and phosphorus (P), and identify required reductions to avoid coastal eutrophication in Europe under global change. We modelled nutrient export by 594 rivers in 2050 for a baseline scenario using the new MARINA-Nutrients model for Europe. Nutrient export to European seas is expected to increase by 13–28% under global change. Manure and fertilizers together contribute to river export of N by 35% in 2050. Sewage systems are responsible for 70% of future P export by rivers. By 2050, the top ten polluted rivers for N and P host 42% of the European population. Avoiding future coastal eutrophication requires over 47% less N and up to 77% less P exports by these polluted rivers.

1. Introduction

Coastal eutrophication is a serious problem in Europe (Boesch, 2019). Eutrophication occurs by nutrient enrichment in aquatic environments from land-based diffuse (e.g., agricultural runoff) and point sources (e.g., sewage systems), and atmospheric deposition (Andersen et al., 2019). Eutrophication directly affects the aquatic environment by e.g., the increased frequency of algal blooms (Glibert et al., 2018a), increased sedimentation, depletion of light, changes in aquatic vegetation (Njock et al., 2023) and indirectly by oxygen depletion (Glibert et al., 2018b) and fish kills (Kudela et al., 2018). Despite the environmental policies, rivers transport large amount of nutrients to coastal waters (Nikolaidis et al., 2022; Vigiak et al., 2023) and thus, eutrophication is still an issue in European seas (Jansson et al., 2019).

Human activities are main drivers of nutrient losses in surface waters (Grizzetti et al., 2021; Poikane et al., 2020), and thus coastal eutrophication. Intensive agriculture (e.g., use of synthetic fertilizers, animal manure) and domestic sewage systems have been major diffuse and point sources of nutrients in Europe, respectively (European Environment et al., 2018; Ural-Janssen et al., 2023). Other pressures (e.g., morphological, hydrological) also play a role in the coastal eutrophication (Garnier et al., 2021). It is important to estimate the nutrient losses to rivers and seas to reduce or prevent the risk of coastal eutrophication in future.

Water quality models can help to estimate nutrient losses to surface waters (Shan et al., 2023). Several models have been developed for Europe at different spatial scales. For example, GREEN is a statistical model estimating the annual loads of nitrogen (N) and phosphorus (P) to seas at a catchment scale around 200 km^2 (Grizzetti et al., 2012). Riverstrahler is a biogeochemical drainage network model calculating the nutrient export at the river outlet considering processes through the drainage network (e.g., retention, transfer and transformations) and in the riparian zone (e.g., denitrification) (Billen and Garnier, 2022; Billen et al., 2018). The MARINA-Nutrients model for Europe is a process based model quantifying the inputs of N and P to rivers, and their river export to seas at the river basin scale (Ural-Janssen et al., 2023), and developed based on the MARINA (Model to Assess River Inputs of pollutaNts to seAs) model approach. MARINA model has been implemented to predict future nutrient pollution in surface waters based on scenario analyses globally (Strokal et al., 2021) and for China (Wang et al., 2020). These provide useful insights on the future trends of water pollution. However, such future analyses using the MARINA-Nutrients model are limited for European river basins.

Scenario analyses can help to analyse future trends in coastal eutrophication. Shared Socio-economic Pathways (SSPs) are environmental narratives that are widely used in modelling studies (Beusen

---

* Corresponding author. Earth Systems and Global Change Group, Wageningen University & Research, PO Box 47, 6700AA, Wageningen, the Netherlands.
E-mail address: aslihan.ural@wur.nl (A. Ural-Janssen).

https://doi.org/10.1016/j.marenvres.2024.106446
Received 16 November 2023; Received in revised form 19 January 2024; Accepted 10 March 2024

et al., 2022; van Vuuren et al., 2021). The SSPs consist of five future trajectories based on various drivers (e.g., socio-economic, tecnological) (Riahi et al., 2017). Changes in land use and climate are significant pressures driven by population growth, socio-economic development and diatery choices (van Vuuren et al., 2017). Changes in agricultural practices associated with land use alter nutrient runoff. SSPs are used alongside Representative Concentration Pathways (RCPs) to analyse the impacts of global change (Beusen et al., 2022; A. A. Li et al., 2022). RCPs identify several alternatives for radiative forcing reaching 2.6–8.5 W m^{-2} by 2100 for future climate change (van Vuuren et al., 2011). These scenarios have been well applied to predict future N and P delivery to surface waters (Beusen et al., 2022; Wang et al., 2020).

Most future studies on nutrients apply forecasting techniques to explore the future consequences of expected trends (de Vries et al., 2023; Hader et al., 2022; van Puijenbroek et al., 2019). Studies applying backcasting, by exploring ways to reach a desirable future, are scarce (Li et al., 2019). To our knowledge, no studies have been published on backcasting the future export of N and P by European rivers. Such backcasting exercises could be based on maximum allowable nutrient losses to seas, and support the formulation of effective nutrient management strategies that help to avoid the risk of coastal eutrophication in future.

Models quantifying nutrient delivery to surface waters can provide important inputs to assess the risk of coastal eutrophication (Billen and Garnier, 2022; Garnier et al., 2021). Indicator for Coastal Eutrophication Potential (ICEP) is an approach to estimate the risk based on the Redfield ratio (Billen and Garnier, 2007). The Redfield ratio represents the C:N:P:Si ratio (106:16:1:20) for the growth of diatoms (Redfield et al., 1963). When there is excess N and/or P over silica (Si) in coastal waters, the non-siliceous algae might grow instead of diatoms (Billen and Garnier, 2007; Garnier et al., 2010). ICEP uses this imbalance to indicate the potential for coastal eutrophication, and the risk for harmful algal blooms (Billen and Garnier, 2007). Based on the limiting nutrient, N-ICEP or P-ICEP is calculated by an empirical formula based on the fluxes of N, P and dissolved silica (DSi) in coastal waters (Billen and Garnier, 2007). The ICEP value indicates coastal eutrophication potential (i.e. high or low) (Billen and Garnier, 2007), and hence can support the future scenario analyses to estimate the risk of coastal eutrophication in European seas.

This study aims to assess the future river exports of N and P, and identify required reductions to avoid coastal eutrophication in Europe under global change. We used the MARINA-Nutrients model for Europe (Ural-Janssen et al., 2023) to estimate the nutrient exports by 594 European rivers and ICEP by 2050 with a baseline scenario combining SSP5 and RCP8.5 (SSP5-RCP8.5) with the largest socio-economic and climate change to observe the effect on the nutrient losses to waters. The year 2050 was chosen arbitrary as a medium-term between short-term (2030) and long-term (2100) future. In addition, many versions of the MARINA model have been applied to 2050 and already provided data for our model application (Li et al., 2019; Strokal et al., 2021; Strokal et al., 2017; Strokal et al., 2023; Wang et al., 2020). We combine forecasting and backcasting. First, we quantified the nutrient inputs to rivers and their export by rivers to the coastal waters of Europe for 2050 under the SSP5-RCP8.5 scenario. Second, we calculated the maximum allowable river export of nutrients to avoid coastal eutrophication based on the ICEP approach (Billen and Garnier, 2007; Garnier et al., 2010). Finally, we identified required reductions to avoid the risks of coastal eutrophication for the top ten polluted rivers of Europe regarding N and P.

2. Materials and methods

2.1. MARINA-nutrients model for Europe

The MARINA-Nutrients model for Europe is developed to quantify N emissions to the atmosphere from agriculture, inputs of the N and P to rivers and river exports of N and P to seas from diffuse (i.e. agricultural and non-agricultural areas) and point (i.e. sewage systems) sources at the basin scale (Ural-Janssen et al., 2023). Diffuse sources include various land-based sources of nutrients per basin (and sub-basins of the Danube River, see Supplementary Text 1) while accounting for nutrient retention on land, and parameterized export processes of nutrients as a function of runoff (Ural-Janssen et al., 2023). The model has been validated for the river exports of N and P based on long term observations, and applied for current pollution in Europe in our pervious study (e.g., Pearson's coefficient of determination (R^2) = 0.72–0.95 depending on nutrient form, R^2 = 0.85 and Nash-Sutcliffe efficiency (NSE) = 0.85 for all nutrient forms of nutrient exports by 58 European rivers, indicating good performance (Ural-Janssen et al., 2023)). In addition, uncertainty assessments (e.g., sensitivity analyses) associated to the simulated river exports of nutrients by the MARINA models were applied for various model inputs as well as parameters in other studies (Chen et al., 2019; Strokal et al., 2016; Wang et al., 2020). Based on those results, the outputs of the MARINA models are sensitive mostly to changes in the following model inputs: water discharges, manure production and synthetic fertilizer application (Strokal et al., 2016; Wang et al., 2020). We believe that this also holds for the MARINA-Nutrients model for Europe because we build on the modeling approach of the existing MARINA models. Here, we applied the model for future analyses of nutrient pollution in rivers and coastal waters of Europe.

The MARINA-Nutrients model for Europe calculates the river exports of N and P in dissolved inorganic (i.e. DIN, DIP) and organic (i.e. DON, DOP) forms as a function of nutrient inputs to agricultural and non-agricultural areas, nutrient inputs to rivers from sewage systems, and export fractions of those inputs reaching the coastal waters (Ural-Janssen et al., 2023). Sources of nutrient inputs to agricultural areas are the application of synthetic fertilizers, application of animal manure and manure deposited on land during grazing, biological N_2 fixation by crops, atmospheric deposition and human waste from population not connected to sewage treatment systems. Sources of nutrient inputs to non-agricultural areas are biological N_2 fixation by natural vegetation and atmospheric deposition. Parameterized export processes are organic matter leaching from agricultural and non-agricultural soils, and P weathering from agricultural and non-agricultural soils following (Strokal et al., 2016). Point sources of nutrient inputs to rivers include urban and rural wastewater treatment systems, except industrial wastewaters.

The model accounts for hydrology (e.g., natural and actual water discharges), basin characteristics (e.g., land use), retention and losses of nutrients on land and rivers, and the distance between the source and river mouth (i.e. coastal waters) (Ural-Janssen et al., 2023). The model quantifies the river exports of N and P for all mentioned forms by the equations in Box 1 and Box S1 (Ural-Janssen et al., 2023).

Box 1 Main equations for quantifying the river exports of N and P to seas by the MARINA-Nutrients model for Europe (further equations in Box S1 and descriptions in Box S2).

In Box 1: $M_{F.y.j}$ is the total river export of nutrient form F (generic for DIN, DON, DIP, DOP) by source y and basin j (kg yr^{-1}). River export of nutrients is quantified as a function of nutrient inputs to rivers that are corrected for removal (e.g., water consumption) and retention (e.g., sedimentation, damming) in rivers, and the travelling distance of nutrients to the river mouth (Eq. 1). $RSdif_{F.y.j}$ is the total input of nutrient form F (DIN, DON, DIP, DOP) to rivers by diffuse source y and basin j (kg yr^{-1}). Nutrient inputs to rivers from diffuse sources are calculated as a function of nutrient inputs to agricultural and non-agricultural land that are corrected for removal (via crop harvesting and animal grazing) and retention (e.g., accumulation) in soils and runoff from land to streams (Eq. 2). $RSpnt_{F.y.j}$ is the total input of nutrient form F (DIN, DON, DIP, DOP) to rivers by point source y and basin j (kg yr^{-1}). Nutrient inputs to rivers from point source are quantified as a function of population that is connected to sewage systems, human N and P excretion rates, removal

$M_{F.y.j}$: River export of nutrients by source y and basin j

$$M_{F.y.j} = \left(RSdif_{F.y.j} + RSpnt_{F.y.j}\right) \times FE_{riv.F.outlet.j} \times FE_{riv.F.mouth.j} \quad (1)$$

$$RSdif_{F.y.j} = WSdif_{E.y.j} \times G_{F.j} \times FE_{ws.F.j} \quad (2)$$

$$RSpnt_{F.y.j} = RSpnt_{E.hum.con.j} \times FEpnt_{F.hum.con.j} \quad (3)$$

$$G_{F.j} = 1 - \left(WSdif_{E.ex.j} / WSdif_{F.gross.j}\right) \quad (4)$$

$$FE_{ws.F.j} = CR_F \times Rnat_j \quad (5)$$

$$RSpnt_{E.hum.con.j} = RSpnt_{E.hum.con.urb.j} + RSpnt_{E.hum.con.rur.j} \quad (6)$$

$$RSpnt_{E.hum.con.urb.j} = Eexc_{hum.con.urb.j} \times \left(1 - hw_{frem.E.j}\right) \quad (7)$$

$$RSpnt_{E.hum.con.rur.j} = Eexc_{hum.con.rur.j} \times \left(1 - hw_{frem.E.j}\right) \quad (8)$$

$$FEpnt_{DIN.hum.con.j} = 0.485 + 0.225 \times \left(hw_{frem.N.j} \,/\, 0.86\right), \text{ constant parameters for DON, DIP and DOP} \quad (9)$$

$$FE_{riv.F.outlet.j} = \left(1 - D_{F.j}\right) \times \left(1 - L_{F.j}\right) \times \left(1 - FQrem_j\right) \text{ for DIN and DIP} \quad (10)$$

$$FE_{riv.F.outlet.j} = \left(1 - FQrem_j\right) \text{ for DON and DOP} \quad (11)$$

$$FE_{riv.F.mouth.juT} = {}^{juT}FE_{riv.F.outlet.jmC} \times {}^{juT}FE_{riv.F.outlet.jdC} \quad (12)$$

$$FE_{riv.F.mouth.jmT} = {}^{jmT}FE_{riv.F.outlet.jdC} \quad (13)$$

$$FE_{riv.F.mouth.jmC} = {}^{jmC}FE_{riv.F.outlet.jdC} \quad (14)$$

$$FE_{riv.F.mouth.jdC} = 1 \text{ as the outlets of down-stream sub-basins discharge directly to seas}$$

efficiencies of nutrients during wastewater treatment and the fraction of nutrients entering rivers by the effluent from sewage treatment systems (Eq. 3). $FE_{riv.F.outlet.j}$ is the fraction of nutrient form F (DIN, DON, DIP, DOP) exported to the outlet of basin j (0–1). This export fraction accounts for aquatic retention (e.g., sedimentation) and losses in water systems (e.g., denitrification and water removals) (Strokal et al., 2016). $FE_{riv.F.mouth.j}$ is the fraction of nutrient form F (DIN, DON, DIP, DOP) exported from the basin j outlet to the river mouth (0–1). $WSdif_{E.y.j}$ is the total input of nutrient element E (generic for N, P) to agricultural or non-agricultural land in basin j from source y (kg yr^{-1}). $G_{F.j}$ is the fraction of nutrient form F (DIN, DON, DIP, DOP) that is remained in soils of basin j after nutrient export from agricultural land by animal grazing and crop harvesting (0–1). The fraction is calculated as the ratio of nutrient inputs remained on agricultural land after animal grazing and crop harvesting ($WSdif_{F.gross.j} - WSdif_{E.ex.j}$) to the total inputs of nutrients to agricultural land ($WSdif_{F.gross.j}$). $FE_{ws.F.j}$ is the export fraction of nutrient form F (DIN, DON, DIP, DOP) entering rivers of basin j (0–1). The export fraction is calculated as a function of annual runoff from land to streams ($Rnat_j$) and implicitly accounts for nutrient retention in soils (e.g., denitrification, temporary accumulation in soils/aquifers) into account prior to nutrient transport to rivers (Strokal et al., 2016). $WSdif_{E.ex.j}$ is the export (ex) of nutrient element E (N, P) from agricultural land via crop harvesting and animal grazing in basins j (kg yr^{-1}). $WSdif_{F.gross.j}$ is the sum of all the inputs of nutrient form F (DIN, DON, DIP, DOP) to agricultural land in basin j (kg yr^{-1}). CR_F is the uncalibrated export coefficient of nutrient form F (DIN, DON, DIP, DOP) for runoff exporting nutrients from land to rivers (unitless). $Rnat_j$ is the annual surface runoff from land to streams in basin j (m yr^{-1}). $RSpnt_{E.hum.con.j}$ is the input of nutrient element E (N, P) to rivers from population connected to sewage systems in basin j (kg yr^{-1}). $FEpnt_{F.hum.con.j}$ is the fraction of nutrient form F (DIN, DON, DIP, DOP) entering rivers from population connected to sewage systems in basin j (0–1) (Table S2 for details). $Eexc_{hum.con.urb.j}$ is the nutrient element E (N, P) in human excretion from urban population connected to sewage systems in basin j (kg yr^{-1}). $Eexc_{hum.con.rur.j}$ is the nutrient element E (N, P) in human excretion from rural population connected to sewage systems in basin j (kg yr^{-1}). $hw_{frem.E.j}$ is the removal fraction of nutrient element E (N, P) during wastewater treatment in basin j (same for urban and rural treatment systems) (0–1). $D_{F.j}$ is the fraction of nutrient form F (DIN, DIP) retained in reservoirs and lakes in basin j (0–1). $L_{F.j}$ is the fraction of nutrient form F (DIN, DIP) retained in and/or lost from water systems (e.g., denitrification, sedimentation) in basin j (0–1). $FQrem_j$ is the fraction of nutrient form F (DIN, DON, DIP, DOP) removed from water systems in basin j by water consumption (0–1). Eqs. 12–14 are only used for the sub-basins of the Danube River (see Supplementary Text 1). $FE_{riv.F.mouth.juT}$ is the fraction of nutrient form F (DIN, DON, DIP, DOP) exported from the outlet of upstream tributary (juT) to the river mouth (0–1). ${}^{juT}FE_{riv.F.outlet.jmC}$ and $juTFE_{riv.F.outlet.jdC}$ are the fractions of nutrient form F (DIN, DON, DIP, DOP) exported from the outlet of upstream tributary (upper case: juT) to the outlets of the main channel in middlestream (lower case: jmC) and in downstream (lower case: jdC) sub-basins (0–1). $FE_{riv.F.mouth.jmT}$ is the fraction of nutrient form F (DIN, DON, DIP, DOP) exported from the outlet of middlestream tributary (jmT) to the river mouth (0–1). ${}^{jmT}FE_{riv.F.outlet.jdC}$ is the fraction of nutrient form F (DIN, DON, DIP, DOP) exported from the outlet of middlestream tributary (upper case: jmT) to the outlet of the main channel in downstream (lower case: jdC) sub-basins (0–1). $FE_{riv.F.mouth.jmC}$ is the fraction of nutrient form F (DIN, DON, DIP, DOP) exported from the outlet of middlestream main channel (jmC) to the river mouth (0–1). ${}^{jmC}FE_{riv.F.outlet.jdC}$ is the fraction of nutrient form F (DIN, DON, DIP, DOP) exported from the outlet of the main channel in middlestream (upper case: jmC) to the outlet of the main channel in downstream (lower case: jdC) sub-basin (the outlet of this downstream subbasin is the river mouth) (0–1).

2.2. Description of baseline scenario for 2050 and model inputs

We selected the SSP5-RCP8.5 as a baseline scenario for the year 2050 to identify required reductions in the river export of nutrients. SSP5 includes relatively rapid economic development, high fossil fuel dependency, high-tech increased agricultural production and local environmental management strategies (O'Neill et al., 2017). Our SSP5 scenario assumes a high economic development with high urbanization and low population growth (Strokal et al., 2021). We coupled the SSP5 with the RCP8.5 scenario considering high-end climate change (van Vuuren et al., 2011). Scenario considerations are indicated in Table S1 (Table S2 for model inputs). We estimated the inputs of N and P to rivers, and their export by rivers to seas for 2050 based on the SSP5-RCP8.5 scenario in a pessimistic future by using the MARINA-Nutrients model for Europe.

Model inputs for agricultural activities (e.g., nutrient inputs to land from fertilizers) were derived from the MITERRA-Europe model at regional scale and processed to a basin scale (see Ural-Janssen et al. (2023) for further details). MITERRA-Europe is an integrated model to assess the implementation of agricultural measures on emissions to air and waters in Europe (Velthof et al., 2009). The model estimates N emissions to air (e.g., N_2O, NH_3) from cropland, grassland, and animal housing and storage systems, and N and P balances in agriculture at NUTS2 scale based on emission factors and mass balance approach (Velthof et al., 2009). We used nutrient inputs to agricultural land by e.g., synthetic fertilizers and manure application from the MITERRA-Europe model (see Ural-Janssen et al. (2023) for further details). Current model inputs for agriculture for the year 2017 (Duan et al., 2021) were projected for 2050 as a function of the percent changes between 2015 and 2050 in the IMAGE model based on the SSP5-RCP8.5 scenario (Beusen et al., 2022). We chose the year 2015 to represent our current model results (2017–2020) and 2050 for future. Main assumptions in the SSP5-RCP8.5 scenario of Beusen et al. (2022) for 2050 are (1) calculation of overall N use efficiency (NUE = N yield/total N input) based on the NUE in 2015 and the change between 1980 and 2015, which is corrected for the future N yield change relative to the historical yield change; (2) for a given NUE, calculation of fertilizer use on croplands by the difference between total N inputs and manure, atmospheric deposition and biological N_2 fixation; (3) substitution of synthetic fertilizers by recycled N and P from human urine obtained from new sewage systems installed after 2015 and (4) excluding the pastoral grasslands from the calculation of fertilizer input considering the use of synthetic fertilizer in pastoral areas is negligible. We did not consider the human urine as a source of fertilizer in agriculture in our scenario application. Model inputs for non-agricultural sources (i.e. atmospheric deposition over non-agricultural areas and biological N_2 fixation by natural vegetation) were derived from the IMAGE model at 0.5° resolution and processed to basin scale for current (2015) and 2050 based on the SSP5-RCP8.5 scenario (Beusen et al., 2022).

Model inputs for sewage systems were derived from Ural-Janssen et al. (2023) for current (2020) and from Strokal et al. (2021) for 2050 at basin scale based on the SSP5 scenario. Model inputs for hydrology were derived from the Variable Infiltration Capacity (VIC) model (i.e. natural water discharges) (van Vliet et al., 2016) and calculated as a function of sectoral water consumptions from Khan et al. (2022) (i.e. actual water discharges) at 0.5° resolution and processed to basin scale for current (the most recent data on natural water discharges was for 2010) and future (2050) based on the RCP8.5 scenario.

2.3. *Required reductions in river export of nutrients to avoid coastal eutrophication*

2.3.1. *Indicator for coastal eutrophication potential*

We used the Indicator for Coastal Eutrophication Potential (ICEP) approach of Billen and Garnier (2007) to estimate the risk of eutrophication in the coastal waters of Europe by 2050 (Fig. 1). ICEP is calculated by fluxes of N, P and Silica (Si) based on the Redfield ratio (C:N:P:Si = 106:16:1:20 (Redfield et al., 1963; Billen and Garnier, 2007). The Redfield ratio is the requirement for the growth of diatoms. When there is excess N and P fluxes over Si, the harmful non-siliceous algae (e.g., cyanobacteria) might develop instead of diatoms (Billen and Garnier, 2007). The ICEP value is quantified based on the following Eqs. (15) and (16) (Billen and Garnier, 2007):

$$ICEP_N = \left[\frac{TDN_{flux}}{(14 \text{ x } 16)} - \frac{DSi_{flux}}{(28 \text{ x } 20)}\right] \text{x } 106 \text{ x } 12 \text{ when N : P ratio} < 16 \text{ (N limiting)} \tag{15}$$

$$ICEP_P = \left[\frac{TDP_{flux}}{31} - \frac{DSi_{flux}}{(28 \text{ x } 20)}\right] \text{x } 106 \text{ x } 12 \text{ when N : P ratio} > 16 \text{ (P limiting)} \tag{16}$$

where $ICEP_N$ is the Indicator for Coastal Eutrophication Potential for N (kg C-eq. km^{-2} day^{-1}), TDN_{flux} is the total dissolved N flux (the sum of DIN and DON) to seas by rivers (kg km^{-2} day^{-1}) and DSi_{flux} is the total dissolved Si flux to seas by rivers (kg km^{-2} day^{-1}). $ICEP_P$ is the Indicator for Coastal Eutrophication Potential for P (kg C-eq. km^{-2} day^{-1}) and

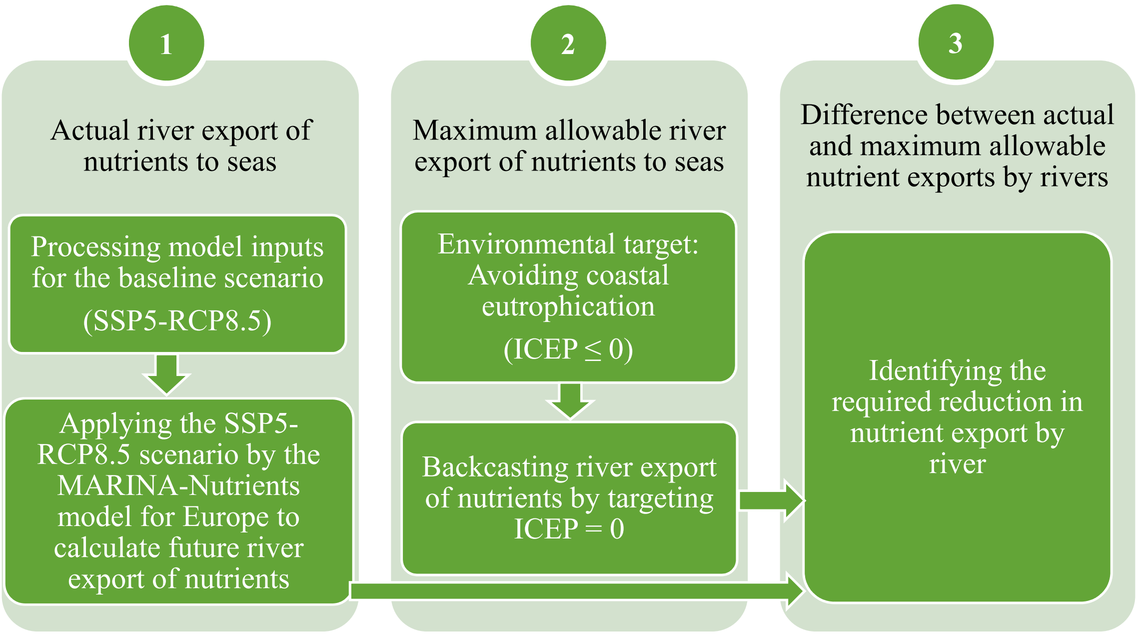

Fig. 1. Stepwise methodology as applied in this study. SSP5 is short for Shared Socio-economic Pathway 5 (fossil fueled development) and RCP8.5 is short for Representative Concentration Pathways (high-end climate change) (Section 2.1 for a description of the MARINA-Nutrients model for Europe).

TDP_{flux} is the total dissolved P flux (the sum of DIP and DOP) to seas by rivers (kg km^{-2} day^{-1}). The potential risk of coastal eutrophication is low when the ICEP value is below zero and vice versa (Billen and Garnier, 2007).

2.3.2. Backcasting calculations

We applied backcasting in a stepwise approach (Fig. 1). First, we quantified the maximum allowable river exports of N and P to seas by targeting the ICEP as "0" to ensure low risks of coastal eutrophication following the approach of Li et al. (2019). We used an uncertainty range of "-1" and "+1" (kg C-eq. km^{-2} day^{-1}) as in Li et al. (2019). For backcasting the maximum allowable river export of total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP), Eqs. (17) and (18) are as follows (Li et al., 2019):

$$TDN_{max} = \left[\frac{ICEP_N}{(106 \text{ x } 12)} + \frac{DSi_{flux}}{(28 \text{ x } 20)}\right] \text{x } 14 \text{ x } 16 \quad (17)$$

$$TDP_{max} = \left[\frac{ICEP_P}{(106 \text{ x } 12)} + \frac{DSi_{flux}}{(28 \text{ x } 20)}\right] \text{x } 31 \quad (18)$$

where $ICEP_N = 0$ (-1 and $+1$), $ICEP_P = 0$ (-1 and $+1$), TDN_{max} and TDP_{max} are the maximum allowable river export of TDN and TDP (kg km^{-2} day^{-1}), and DSi_{flux} is total dissolved Si flux to seas by rivers (kg km^{-2} day^{-1}) for 2050 (Table S2 for model inputs).

Second, we calculated the required reductions in nutrient exports based on the SSP5-RCP8.5 scenario for 2050 relative to the maximum allowable nutrient exports by rivers. We did backcasting calculations for the top ten polluted rivers per nutrient. Top ten rivers were chosen based on their pollution levels for N (i.e. Danube, Rhine, Elbe, Wisla, Weser, Douro, Seine, Odra, Ebro, Tejo) and P (i.e. Danube, Wisla, Rhine, Seine, Odra, Tejo, Nemanus, Dnestr, Daugava).

3. Results and discussion

3.1. Current and future river export of nutrients: totals by form

In this section, we describe the model results for future river exports of N and P to the coastal waters of Europe based on the SSP5-RCP8.5 scenario. We estimated nutrient inputs in European seas by sources and basins for the year 2050. We compared the future (2050) river export of nutrients with the current (2017–2020) nutrient export from Ural-Janssen et al. (2023).

River exports of total dissolved N (TDN) and total dissolved P (TDP) to European seas are projected to increase by 13% and 28%, respectively, between today and 2050 under global change (Fig. 2). Today (2017–2020), rivers export 2690 Gg of TDN and 128 Gg of TDP to the coastal waters. By 2050, these amounts are projected to be 3044 Gg for TDN and 163 Gg for TDP (Fig. 2). Less than half of TDN in the coastal waters (39%) is from synthetic fertilizers and animal manure (applied on agricultural land from housing systems and deposited on land during grazing) today (Fig. 2). Sewage systems are responsible for over half of TDP in the coastal waters (60%) (Fig. 2). In the future, synthetic fertilizers and manure (applied on agricultural land from housing systems and deposited on land during grazing) will contribute to river export of TDN by 35% (with an increase of 15% from manure) (Fig. 2). This is due to the fact that our assumptions do not include the implementation of the EU policies (e.g., Green Deal Farm to Fork Strategy) (Section 2.2 for scenario description). Sewage systems are expected to be responsible for 70% of future TDP export by rivers with an increase of 49% relative to today (Fig. 2).

We found that socio-economic change (related to the SSP5) has a large impact on nutrient losses to rivers, and hence on the river exports of TDN and TDP. Climate change (related to the RCP8.5) will alter runoff and river discharges,. Lower natural water discharges are projected for most of the basins (70%) for 2050 compared to the current level (2017–2020). This can affect the nutrient retention on land and in rivers, and nutrient losses to rivers and to seas. Global change will lead to the increased river export of TDN and TDP by 2050 is mainly by sewage systems, followed by animal manure (applied on agricultural land from housing systems and deposited on land during grazing) among the considered sources in this study. This is due to the increased urbanization (moving towards cities and increasing population connected to sewage systems) but moderate improvement of the urban wastewater treatment plants (Strokal et al., 2021), and the increased livestock production and thus, manure production and application (Beusen et al., 2022).

Future river exports of nutrients show large variability among the basins relative to 2017–2020 (Fig. 3). Nearly two-thirds of the European

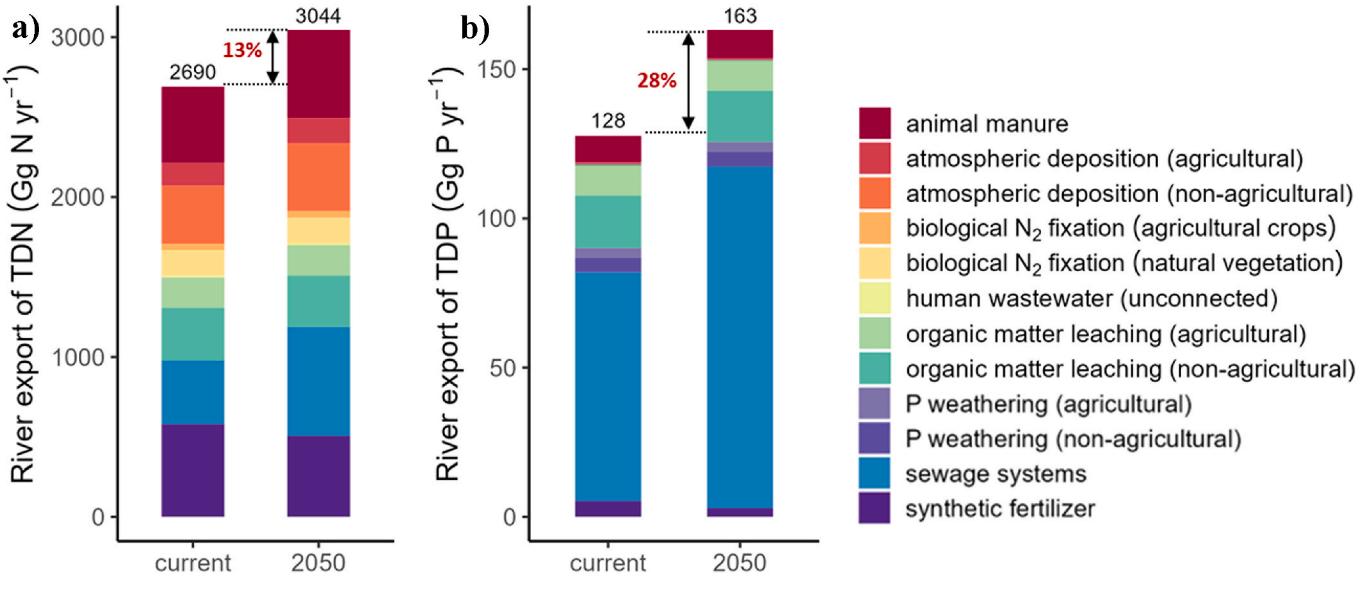

Fig. 2. Current (2017–2020) and future (2050) river export of nutrients by source to the coastal waters of Europe based on the SSP5-RCP8.5 scenario. (a) River export of total dissolved nitrogen (TDN, Gg N yr^{-1}). (b) River export of total dissolved phosphorus (TDP, Gg P yr^{-1}). SSP5 is short for Shared Socio-economic Pathway 5 (fossil fueled development) and RCP8.5 is short for Representative Concentration Pathways (high-end climate change). Source: MARINA-Nutrients model for Europe (Section 2.1).

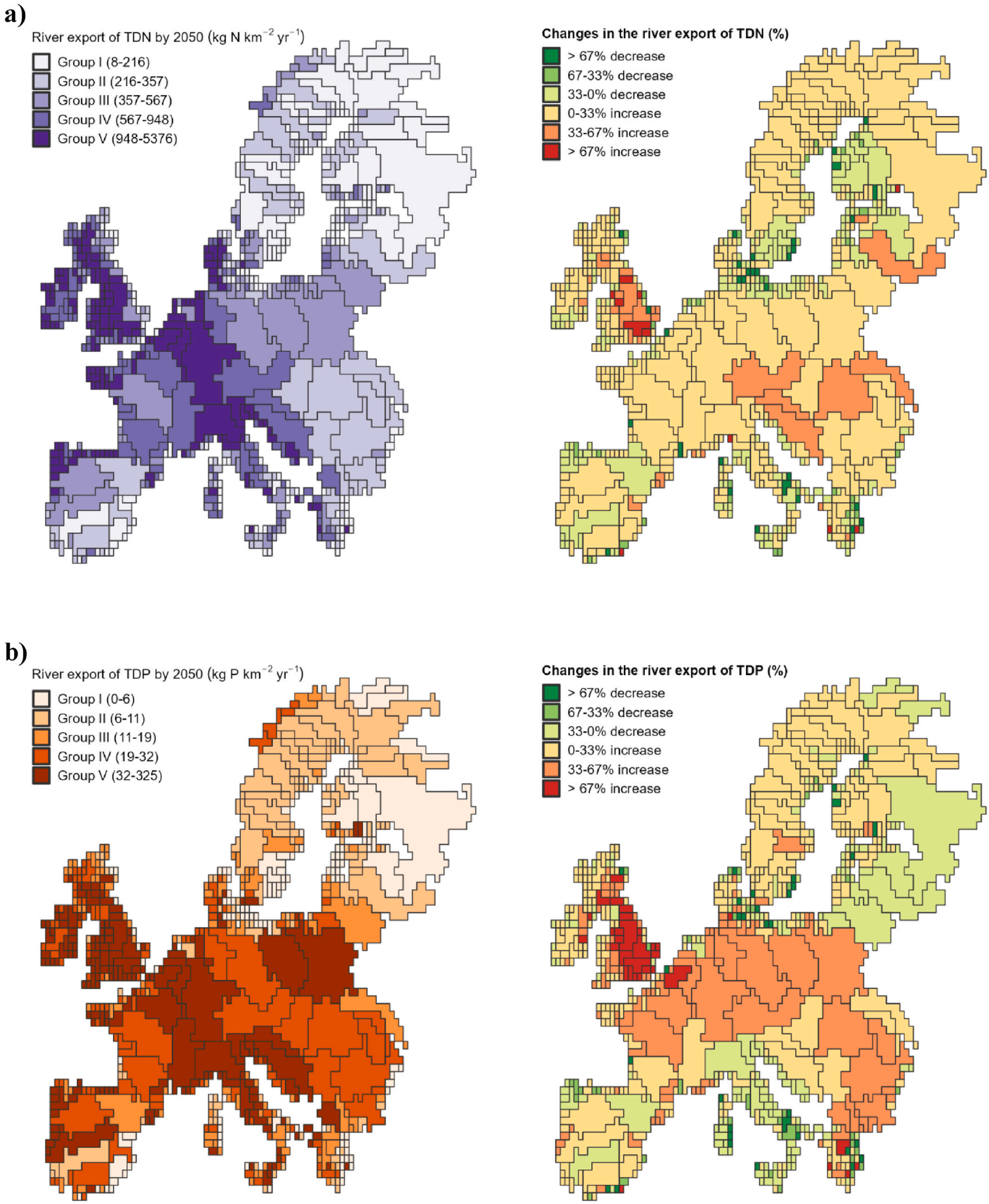

Fig. 3. Future (2050) river export of nutrients to the coastal waters of Europe based on the SSP5-RCP8.5 scenario. (a) River export of total dissolved nitrogen (TDN, kg N km^{-2} yr^{-1}) and percent changes relative to 2017–2020 (%). (b) River export of total dissolved phosphorus (TDP, kg P km^{-2} yr^{-1}) and percent changes relative to 2017–2020 (%). Groups I–V are defined based on the current river export of TDN and TDP to seas (each group has 20% of basins, from highest to lowest river exports). SSP5 is short for Shared Socio-economic Pathway 5 (fossil fueled development) and RCP8.5 is short for Representative Concentration Pathways (high-end climate change). Source: MARINA-Nutrients model for Europe (Section 2.1).

rivers are projected to export more nutrients in 2050 than today (59% for TDN and 67% for TDP). For TDN export (kg N km^{-2} yr^{-1} per basin) a few rivers (~2%) are projected to have large increases by more than 67%, 6% of the rivers will have moderate increases and half of the rivers will have small increases by up to 33% (Fig. 3). The pollution is projected to be worse for the river export of TDP (kg P km^{-2} yr^{-1} per basin) (Fig. 3). 5% of the rivers will have large increases by more than 67%, 18% of the rivers will have moderate increases and 43% of the rivers will have increases by up to 33% compared to the current (2017–2020) TDP export by rivers (Fig. 3). About one-third of the rivers are projected to export less TDP and TDN in 2050 than today (Fig. 3). These reductions are generally calculated for relatively small rivers, covering a relatively small part of the total study area.

The relative changes between current and future river export of nutrients vary among the basins and nutrient forms (i.e. DIN, DON, DIP, DOP) (Figs. 4 and 5). We calculated increases in the total river export of nutrient forms to seas for 2050 with the SSP5-RCP8.5 scenario compared to the current situation, except for DOP. The largest exports of all nutrient forms are often by the rivers located in western, central and southern Europe (Figs. 4 and 5). The dominant source of nutrient pollution in rivers varies based on the nutrient form. Below, we describe the changes in future river export of each nutrient form compared to today, and their largest contributor among the sources considered in this study.

In Europe, river export of DIN and DON is projected to increase by 13% and 12% by 2050 relative to today, respectively (Fig. 4). The future DIN export by rivers to seas is projected to be by up to 4949 kg N km^{-2} yr^{-1} while the maximum current DIN export is 2510 kg N km^{-2} yr^{-1} (Fig. 4). Spatial variability for the magnitude of the DIN export by rivers is similar for both current (2017–2020) and future (2050) years (Fig. 4), while source attribution differs among the basins and seas (Fig. 6). Animal manure (application on agricultural land from housing systems and deposited on land during grazing) is expected to be an important source and contribute to the river export of DIN by 23% (e.g., up to 71% per basin) in 2050, followed by synthetic fertilizer application (22%) and sewage systems (20%) (Fig. 6). The future DON export by rivers to seas is projected to vary between 4 and 744 kg N km^{-2} yr^{-1} (Fig. 4). More basins are expected to shift to the largest river export range (Group V) (Fig. 4). Organic matter leaching over non-agricultural areas is projected to dominate the river export of DON by 41% (e.g., up to 77% per basin) in 2050 (Fig. 6).

River export of DIP is projected to increase by 37%, while the DOP export by European rivers will slightly decrease (1%) in 2050 (Fig. 5). The changes in the magnitude of the DIP export by rivers to seas vary among both temporal and spatial scales (Fig. 5). The future DIP export by rivers to seas is projected to be up to 316 kg P km^{-2} yr^{-1}, more than duplicate of the maximum current DIP export (146 kg P km^{-2} yr^{-1}) (Fig. 5). Sewage systems are expected to remain as a significant contributor to the DIP export by 86% (e.g., up to 97% per basin) in 2050 (Fig. S1). The ranges for future DOP export by rivers to seas are expected not to change relative to today (Fig. 5). Similar to DON, organic matter leaching over non-agricultural areas is projected to dominate the river export of DOP by 53% in 2050 (Fig. S1).

3.2. River export of nutrients by 2050: source attribution

In this section, we describe the river export of nutrients to seas/oceans for 2050 by nutrient form and source. The Atlantic Ocean is projected to receive the largest river export of nutrients for all forms in 2050 (e.g., 28% of DIN, 27% of DIP) (Fig. 6 and S1). The Mediterranean and North Seas are expected to receive similar river export of nutrients (e.g., 23% of DIN, 24-23% of DIP respectively) (Fig. 6 and S1). The Baltic and Black Seas are projected to receive similar river export of DIN and DIP, but different DON (21% and 14% of the total, respectively) and DOP (24% and 14% of the total, respectively) exports (Fig. 6 and S1). The least nutrients for all forms will be exported by rivers to the Arctic Ocean due to less human activities in those river basins (Fig. 6 and S1).

The relative share of sources of nutrient exports differs among the seas. For example, animal manure (applied on agricultural land from housing systems and deposited on land during grazing) is expected to be a major source for the river export of DIN to seas by 2050 (e.g., Atlantic Ocean, Mediterranean and North Seas), followed by the application of synthetic fertilizers and sewage systems except for the Arctic Ocean (Fig. 6). Sewage systems are expected to remain as the main source of the DIP export by rivers in 2050 except for the Arctic Ocean (Fig. S1). Most of the DIN and DIP exports to the Arctic Ocean will be from non-agricultural sources (e.g., atmospheric deposition over non-agricultural areas, P weathering over non-agricultural soils) (Fig. 6 and S1). River export of DON and DOP will be mainly from non-agricultural sources (e.g., 41% of DON and 53% of DOP exports by the organic matter leaching over non-agricultural areas) (Fig. 6 and S1).

3.3. Required reductions to avoid coastal eutrophication

In this section, we present the maximum allowable nutrient exports by rivers and required reductions to avoid the risks of coastal eutrophication in Europe. First, we describe the maximum allowable river export of nutrients that is calculated by the ICEP approach for the top ten most polluted rivers (Section 2.3.2 for the approach). Second, we present the required reductions to meet the allowable nutrient exports to seas and reduce coastal eutrophication risk in European seas by 2050.

3.3.1. Maximum allowable river export of nutrients to seas

We used Eqs. (17) and (18) to calculate maximum allowable river exports of nutrients. More than half of the rivers (53%) are expected to exceed the maximum allowable levels for TDN export, while 18% exceed the allowable levels for TDP export by 2050 based on the SSP5-RCP8.5 scenario. We selected the top ten most polluted rivers from the analyses of Figs. 2–6 (Fig. 7). The number of people living in these river basins and affected by coastal eutrophication from 2050 onwards is projected to be 42% of the European population in the study area.

The maximum allowable levels reflect the river export of TDN and TDP to ensure ICEP = 0 (with an uncertainty range of −1 to +1), indicating low risk for harmful algal blooms. The calculated maximum allowable river exports of TDN are 112 (60–163) Gg yr^{-1} for Danube, 14 (3–25) Gg yr^{-1} for Rhine, 34 (21–46) Gg yr^{-1} for Wisla, 43 (33–52) Gg yr^{-1} for Elbe, 21 (13–28) Gg yr^{-1} for Odra, 18 (13–23) Gg yr^{-1} for Seine, 6 (1–12) Gg yr^{-1} for Tejo, 10 (4–16) Gg yr^{-1} for Nemanus, 5 (-2-11) Gg yr^{-1} for Daugava and 3 (-3-8) Gg yr^{-1} for Ebro (Fig. 7). The maximum allowable river exports of TDP are 15 (8–22) Gg yr^{-1} for Danube, 2 (0.4–3) Gg yr^{-1} for Rhine, 5 (3–6) Gg yr^{-1} for Wisla, 2 (2–3) Gg yr^{-1} for Seine, 3 (2–4) Gg yr^{-1} for Odra, 1 (0.1–2) Gg yr^{-1} for Tejo, 0.3 (−0.3-1) Gg yr^{-1} for Dnestr, 0.4 (−0.4-1) Gg yr^{-1} for Ebro, 0.6 (−0.3-1) Gg yr^{-1} for Daugava and 0.4 (0.2–0.6) Gg yr^{-1} for Pregolya (Fig. 7). These levels are considerably lower than the actual nutrient exports projected for 2050 by the MARINA-Nutrients model based on the SSP5-RCP8.5 scenario (Fig. 7 and Section 3.3.2).

3.3.2. Required reductions to meet the allowable nutrient exports to seas

To meet the maximum allowable nutrient export levels by 2050, river export of nutrients needs to be reduced considerably. Avoiding future coastal eutrophication requires over 47% less N and up to 77% less P export by the top ten polluted rivers to seas relative to the SSP5-RCP8.5 scenario levels (Fig. 7). River exports of TDN and TDP need to be reduced by 69-26%, 91-74% and 64-29% for Danube, Rhine and Wisla, respectively (Fig. 7). More than 47% of TDN and more than 12% of TDP exports need to be reduced for the rest of the top ten rivers to limit ICEP to 0 (Fig. 7).

3.4. Comparisons of model outputs with literature

Our study focuses on future analyses of river exports of nutrients to

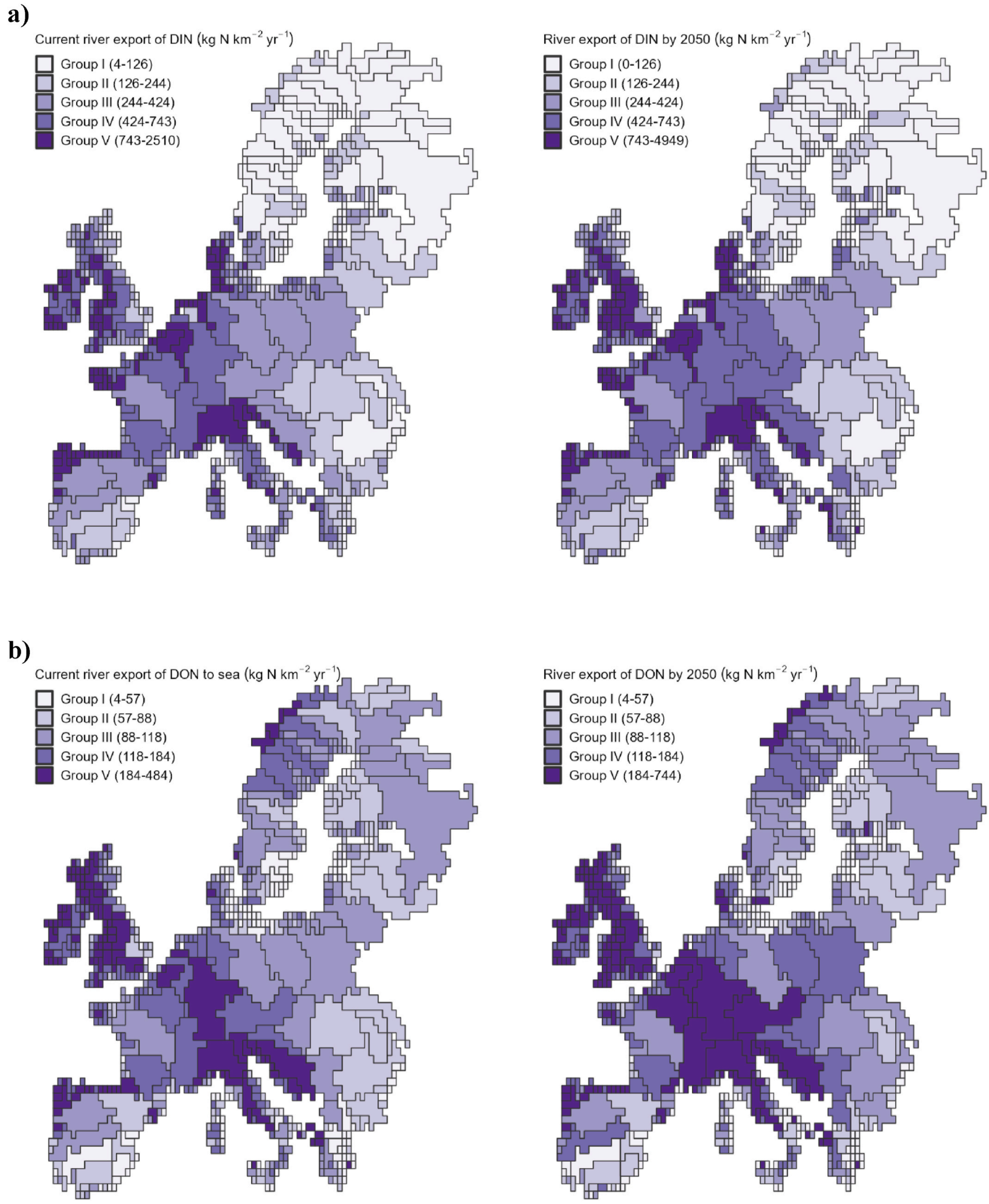

Fig. 4. Current (2017–2020) and future (2050) river export of nitrogen to the coastal waters of Europe based on the SSP5-RCP8.5 scenario. (a) River export of dissolved inorganic nitrogen (DIN, kg N km^{-2} yr^{-1}). (b) River export of dissolved organic nitrogen (DON, kg N km^{-2} yr^{-1}). Groups I–V are defined based on the current river export of DIN and DON to seas (each group has 20% of basins, from highest to lowest river exports). SSP5 is short for Shared Socio-economic Pathway 5 (fossil fueled development) and RCP8.5 is short for Representative Concentration Pathways (high-end climate change). Source: MARINA-Nutrients model for Europe (Section 2.1).

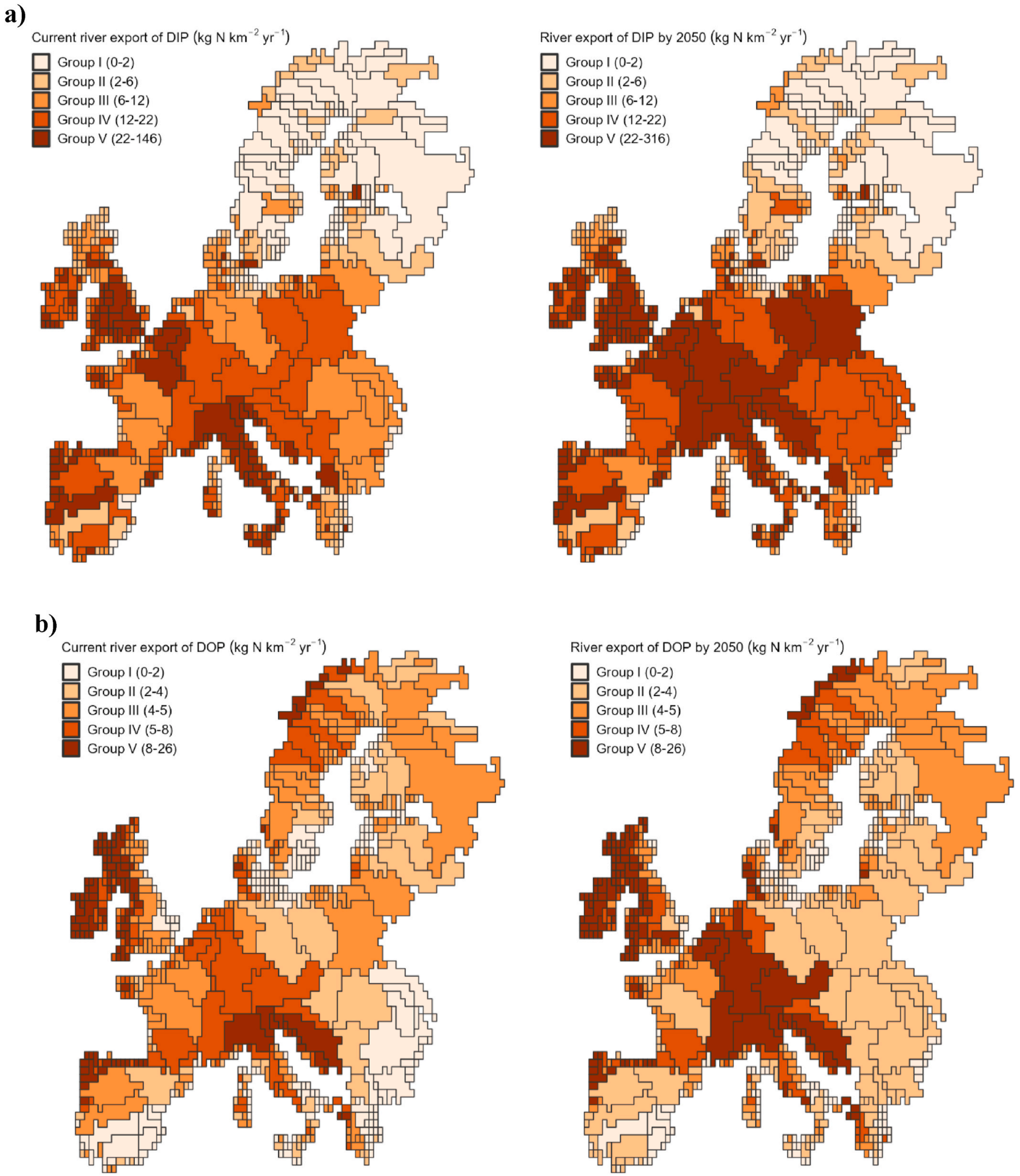

Fig. 5. Current (2017–2020) and future (2050) river export of phosphorus to the coastal waters of Europe based on the SSP5-RCP8.5 scenario. (a) River export of dissolved inorganic phosphorus (DIP, kg P km^{-2} yr^{-1}). (b) River export of dissolved organic phosphorus (DOP, kg P km^{-2} yr^{-1}). Groups I–V are defined based on the current river export of DIP and DOP to seas (each group has 20% of basins, from highest to lowest river exports). SSP5 is short for Shared Socio-economic Pathway 5 (fossil fueled development) and RCP8.5 is short for Representative Concentration Pathways (high-end climate change). Source: MARINA-Nutrients model for Europe (Section 2.1).

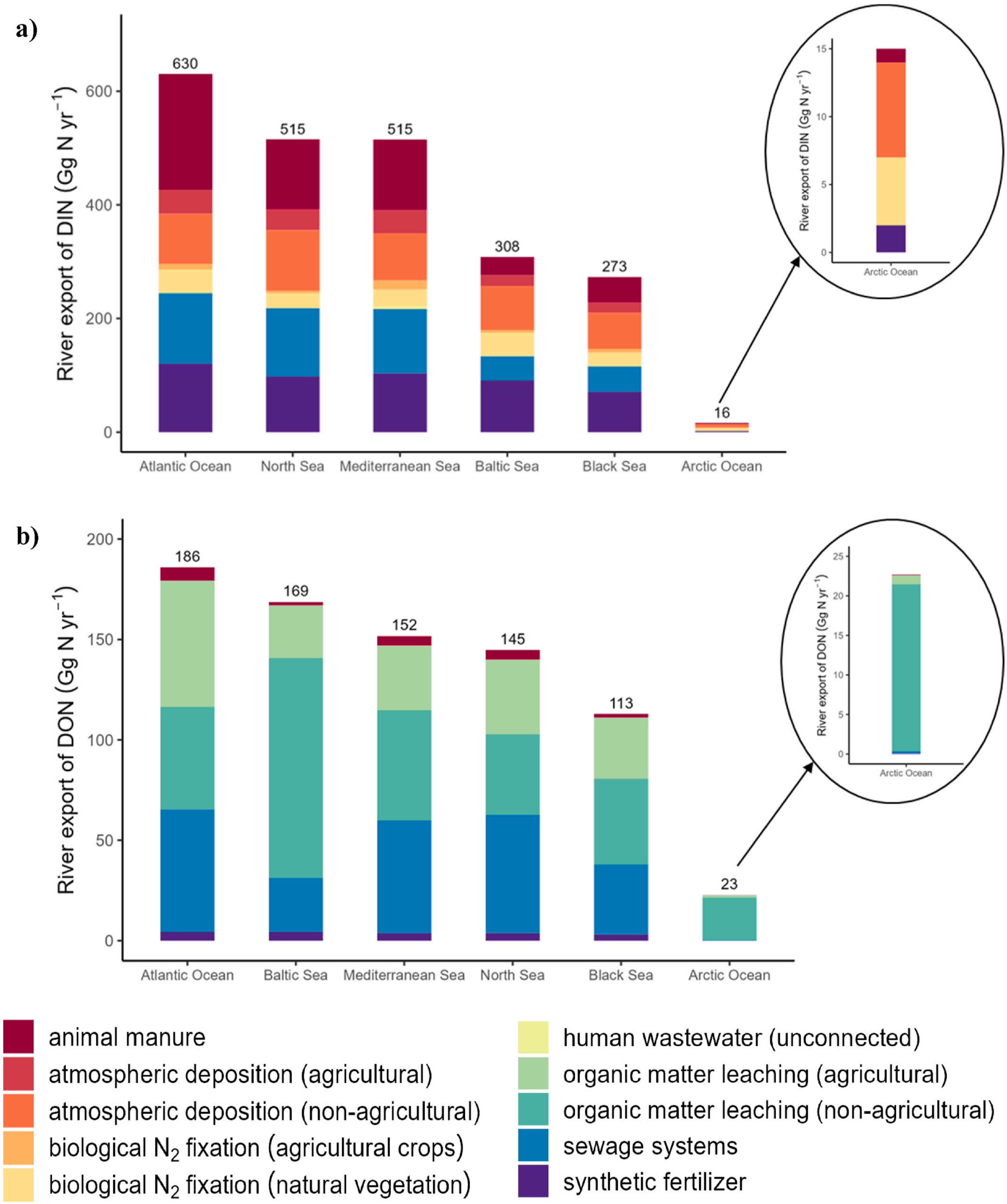

Fig. 6. Future (2050) river export of nitrogen by source to the European seas based on the SSP5-RCP8.5 scenario. (a) River export of dissolved inorganic nitrogen (DIN, Gg N yr^{-1}). (b) River export of dissolved organic nitrogen (DON, Gg N yr^{-1}). Colours represent sources of the river export. SSP5 is short for Shared Socio-economic Pathway 5 (fossil fueled development) and RCP8.5 is short for Representative Concentration Pathways (high-end climate change). Source: MARINA-Nutrients model for Europe (Section 2.1).

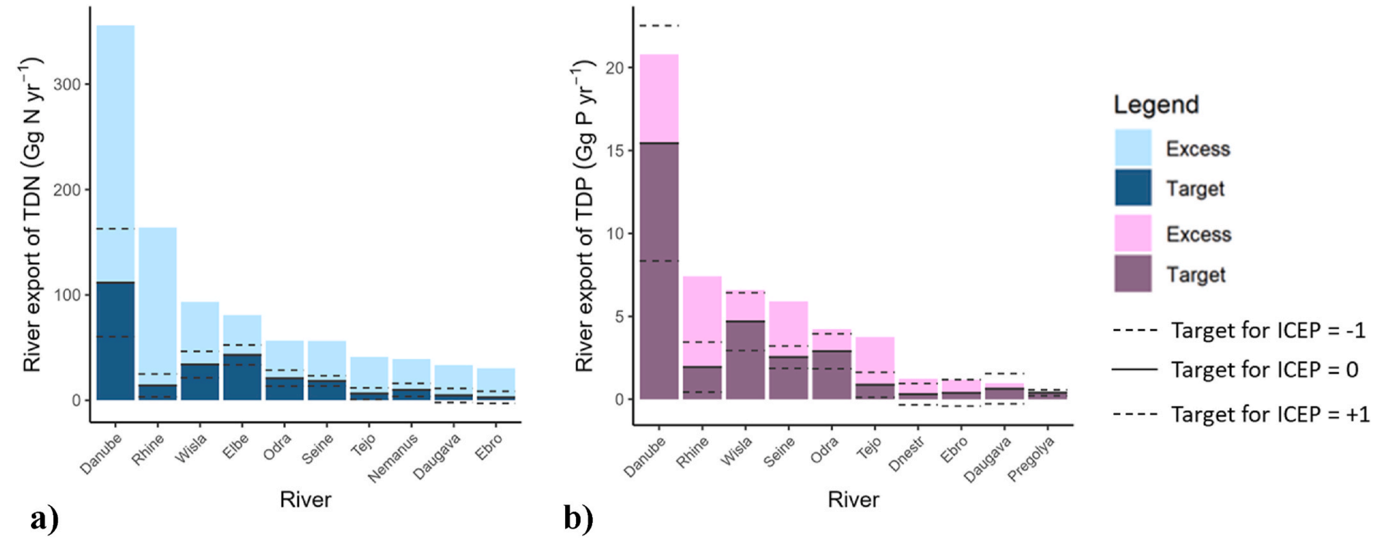

Fig. 7. Future (2050) nutrient export by the top ten polluted rivers of Europe based on the SSP5-RCP8.5 scenario. (a) River export of total dissolved nitrogen (TDN, Gg N yr^{-1}). (b) River export of total dissolved phosphorus (TDP, Gg P yr^{-1}). Targets "0", "-1" and "+1" (kg C-eq. km^{-2} day^{-1}) are for (a) ICEP$_N$ and (b) ICEP$_P$. SSP5 is short for Shared Socio-economic Pathway 5 (fossil fueled development) and RCP8.5 is short for Representative Concentration Pathways (high-end climate change). Source: MARINA-Nutrients model for Europe (Section 2.1).

the European coastal waters. Model validation for the current period was done in our earlier study (Ural-Janssen et al., 2023). To build trust in our future analyses, we compared our model results with available future modelling studies for Europe. In general, our model projections for the river export of nutrients to seas by 2050 are in line with other studies. Many coastal waters are expected to be affected by an increase riverine nutrient delivery in Europe (e.g., up to 40% increase in TDN export to the Black Sea, up to 61% increase in TDP export to the North Sea) relative to today. This is in line with the expected increase in global river exports of N and P by 2050 based on the SSP5-RCP8.5 (Beusen et al., 2022).

The increased nutrient transport to coastal waters by 2050 will be mainly caused by urbanization (e.g., 71% increase for river export of TDN from sewage systems) based on our baseline (SSP5-RCP8.5) scenario. This is mainly due to the river export of nutrients from higher amount of wastewater produced with moderately improved treatment efficiencies (Strokal et al., 2021) (Table S1 and Section 2.2 for details). There will be a shift from synthetic fertilizers to animal manure and that is in line with the SSP5-RCP8.5 scenario assumptions (e.g., reducing synthetic fertilizer application by recycling nutrients from human urine Section 2.2). Diffuse sources of river exports of N (e.g., atmospheric deposition over non-agricultural areas, biological N_2 fixation by natural vegetation) and P (e.g., P weathering from non-agricultural soils) from non-agricultural areas are expected not to change significantly by 2050, similar to global as indicated by Beusen et al. (2022).

3.5. *Uncertainties and limitations*

We discuss the uncertainties and limitations in (1) data, (2) the model and (3) the scenarios. First, we reflect on the limitations related to data availability. Our backcasting approach could only be applied to a limited number of rivers due to data availability for DSi (e.g., regular DSi measurements were not available for European rivers). The DSi data was derived from the Global *NEWS2* model for 2050 based on Global Orchestration scenario (Seitzinger et al., 2010) as this was the closest option to the SSP5-RCP8.5 scenario. The data was not available for all the river basins considered in this study. Thus, we only considered the DSi fluxes of the large and most polluted rivers with N and P in backcasting of maximum allowable nutrient exports by rivers to assess the risk of coastal eutrophication in Europe by 2050. The DSi fluxes to seas might vary depending on socio-economic (e.g., dam constructions (Garnier et al., 2010)) and climate (e.g., precipitation (Garnier et al., 2010) and temperature (Zhang et al., 2023)) changes. Thus, further research on DSi observations and on how the controlling factors could affect the DSi fluxes in future is required.

Second, our model has limitations. Our model inputs and coefficients are from various sources (e.g., MITERRA-Europe model, literature) and this can increase uncertainties. As we do large scale modelling, some parameters are basin-scale spesific (e.g., nutrient removal efficiency in sewage treatment systems), not site specific. The MARINA-Nutrients model for Europe does not account for the inputs of N and P from the industrial wastewater treatment systems (only domestic wastewaters) and N input from atmospheric deposition onto coastal waters. Thus, we underestimate the future river export of nutrients and in turn the required reduction to reach the maximum allowable nutrient exports by the top ten polluted rivers to seas. Nevertheless, our study shows that even with the considered sources, nutrient exports by the top ten polluted rivers will exceed the maximum allowable levels by 2050. Another limitation is not considering particulate forms of nutrients. Our model does not account for particulate N (PN) and P (PP), and nutrient losses associated to erosion explicitly. River export of PN and PP were estimated as around 20% and 50% of the total N and total P for Europe in 2000 by Mayorga et al. (2010). Therefore, the contribution of the river export of PP to the total P (TP = DIP + DOP + PP) pollution in the European seas is as much as the TDP export to seas. P loss from soil erosion is a significant source of PP inputs to rivers and in turn, river export of TP to seas (Alewell et al., 2020; Panagos et al., 2022). However, we need to realize that not all particulate N and P is biologically available, so it could be argued that this omission affects our results and conclusions to only a limited extent. Moreover, we consider the common pathways (e.g., runoff, discharges of sewage effluents after treatment) but our process-based model does not account for the dynamics in retention and release processes of nutrients between soil and sediments, and waters (Strokal et al., 2016). For example, the effect of animal manure (applied on agricultural land and deposited during grazing) on the river export of P might be delayed by dynamic processes (e.g., P accumulation) (Strokal and de Vries, 2012). Similarly, biogeochemical processes in soil and waters can alter the N export by rivers (Beusen et al., 2022). For example, more denitrification results in more N removal from the soil and waters, and thus less N available for export to the river mouth. Denitrification is influenced by several factors such as temperature; precipitation; soil microbial biomass, carbon, N and clay contents; soil texture and pH in soils (Z. Z. Li et al., 2022); temperature, and availability of N and C in rivers (Deng et al., 2020). These all can influence the process of denitrification, and therefore the availability of N in the river. In the MARINA-Nutrients model for Europe, processes of nutrient retention and losses are aggragated to basin scale (Ural-Janssen et al., 2023) which might cause over/underestimation of future nutrient exports to seas. Ideally, more in-depth analyses that should comprise all the relevant sources of nutrient exports by rivers, account for losses in all nutrient forms, and consider all the relevant processes (e.g., morphological and hydrological) are needed for a comprehensive assessment of the future coastal eutrophication in Europe. We nevertheless consider that the level of detail of the MARINA-Nutrients model for Europe fit for purpose in this study: to explore large-scale future trends for relatively long-term future.

Third, scenario related limitations might associate with our baseline scenario assumptions. We chose a SSP-RCP combination with the largest changes (i.e. SSP5: fossil fueled development and RCP8.5: high-end climate change). We derived the actual model inputs to calculate nutrient exports from point sources for 2050 based on the SSP5 scenario from (Strokal et al., 2021), while calculating the model inputs for diffuse sources as a function of the percent changes (per basin) between 2015 and 2050 in the IMAGE model based on the SSP5-RCP8.5 scenario (Beusen et al., 2022). Different from the SSP5 assumptions by Beusen et al. (2022), we do not consider the human urine as a source of fertilizer in agriculture. Our choice to use SSP5-RCP8.5 as a basis determines the required reductions to meet the allowable river export levels to avoid coastal eutrophication. Other SSP-RCP combinations may result in other required reductions. This should be realized when interpreting our results.

4. Conclusions

We estimated the delivery of dissolved N and P by rivers to the seas of Europe (e.g., Arctic Ocean, Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea, North Sea) for the year 2050 based on the SSP5-RCP8.5 scenario. We modelled future nutrient pollution in the coastal waters of Europe by sources and basins. River exports of TDN and TDP are projected to increase by 13% and 28%, respectively, under global change relative to today. Manure and fertilizers contribute to river export of TDN by 35% in 2050. Sewage systems are responsible for 70% of future TDP export by rivers. As a result, more eutrophication is expected in the coastal waters of Europe by 2050. The top ten polluted rivers (N and P) are expected to host 42% of the European population in 2050. This implies that at least 42% of the population in the study area may be affected by coastal eutrophication from 2050 onwards.

We quantified the required reductions in river pollution to avoid the potential risks of coastal eutrophication under global change. For this, we set maximum allowable nutrient exports by rivers to seas using the ICEP approach. We quantified the maximum allowable TDN and TDP fluxes from the top ten most polluted rivers based on the ICEP $= 0$ (with an uncertainty range of -1 to $+1$). Then, we compared the maximum allowable nutrient export levels to the results of SSP5-RCP8.5 scenario to identify the required reductions to avoid future coastal eutrophication in Europe. To avoid the risk of coastal eutrophication, we urgently need to reduce nutrient delivery by rivers to seas. Avoiding future coastal eutrophication requires over 47% less N and up to 77% less P exports by the top ten polluted rivers (e.g., Danube, Rhine, Wisla).

Recycling or upcycling nutrients in agriculture from organic waste could be a promising option to reduce river export of nutrients and avoid future coastal eutrophication, but needs to be studied comprehensively to better understand the synergies and to avoid trade-offs (e.g., pollution swapping). For instance, large amount of nutrients from urban wastewater treatment systems should be recycled more and effectively in agriculture to prevent high nutrient exports by rivers from sewage systems to seas. Our study shows how backcasting approach can be used to define desired futures for reduced pollution and low risks of coastal eutrophication. This could support the implementation of effective environmental policies to avoid coastal eutrophication in future.

Our baseline scenario should be interpreted as a pessimistic future. Considering the abovementioned limitations of this study, future studies can build on the SSP5-RCP8.5 scenario by incorporating the EU policies and targets (e.g., Green Deal, Farm to Fork) to illustrate the effect of their implementation on the riverine nutrient transport and eutrophication in European seas by 2050.

CRediT authorship contribution statement

Aslıhan Ural-Janssen: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Carolien Kroeze:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. **Erik Meers:** Funding acquisition, Supervision, Writing – review & editing. **Maryna Strokal:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

The main model results supporting Figs. 2–7 generated in this study have been deposited in the DANS Easy repository under the Digital Object Identifier: https://doi.org/10.17026/PT/OUJR9H.

Acknowledgements

This study has been developed within the framework of the European Union Horizon 2020 Research and Innovation Programme under Marie Sklodowska-Curie Grant Agreement No. 860127 (FertiCycle project). The authors acknowledge funding from the European Union HORIZON-CL6-2021-ZEROPOLLUTION-01 Grant Agreement No. 101060455 (NutriBudget project). The authors would also like to thank the anonymous reviewers for their comments and suggestions on how to improve this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2024.106446.

References

Alewell, C., Ringeval, B., Ballabio, C., Robinson, D.A., Panagos, P., Borrelli, P., 2020. Global phosphorus shortage will be aggravated by soil erosion. Nat. Commun. 11 (1), 4546. https://doi.org/10.1038/s41467-020-18326-7.

Andersen, J.H., Harvey, E.T., Murray, C., Prins, T., Peterlin, M., Reker, J., 2019. Nutrient Enrichment and Eutrophication in Europe's Seas: Moving towards a Healthy Marine Environment. Retrieved from Luxembourg. Publications Office of the European Union. https://www.eea.europa.eu/publications/nutrient-enrichment-and-eutrophication-in.

Beusen, A.H.W., Doelman, J.C., van Beek, L.P.H., van Puijenbroek, P.J.T.M., Mogollón, J. M., van Grinsven, H.J.M., Stehfest, E., van Vuuren, D.P., Bouwman, A.F., 2022. Exploring river nitrogen and phosphorus loading and export to global coastal waters in the Shared Socio-economic pathways. Global Environ. Change 72, 102426. https://doi.org/10.1016/j.gloenvcha.2021.102426.

Billen, G., Garnier, J., 2007. River basin nutrient delivery to the coastal sea: assessing its potential to sustain new production of non-siliceous algae. Mar. Chem. 106 (1–2), 148–160. https://doi.org/10.1016/j.marchem.2006.12.017.

Billen, G., Garnier, J., 2022. The water-agro-food system: upscaling from the Seine river basin to the global scale. Compt. Rendus Geosci. 355 (S1), 1–15. https://doi.org/10.5802/crgeos.141.

Billen, G., Ramarson, A., Thieu, V., Théry, S., Silvestre, M., Pasquier, C., Hénault, C., Garnier, J., 2018. Nitrate retention at the river–watershed interface: a new conceptual modeling approach. Biogeochemistry 139 (1), 31–51. https://doi.org/10.1007/s10533-018-0455-9.

Boesch, D.F., 2019. Barriers and bridges in abating coastal eutrophication. Front. Mar. Sci. 6 https://doi.org/10.3389/fmars.2019.00123.

Chen, X., Strokal, M., Bai, Z., Ma, L., Kroeze, C., 2019. Multi-scale Modeling of Nutrient Pollution in the Rivers of China, 53.

de Vries, W., Kros, J., Voogd, J.C., Ros, G.H., 2023. Integrated assessment of agricultural practices on large scale losses of ammonia, greenhouse gases, nutrients and heavy metals to air and water. Sci. Total Environ. 857, 159220 https://doi.org/10.1016/j.scitotenv.2022.159220.

Deng, D., Pan, Y., Liu, G., Liu, W., Ma, L., 2020. Seeking the hotspots of nitrogen removal: a comparison of sediment denitrification rate and denitrifier abundance among wetland types with different hydrological conditions. Sci. Total Environ. 737, 140253 https://doi.org/10.1016/j.scitotenv.2020.140253.

Duan, Y.-F., Bruun, S., Jensen, L.S., Gerven, L.v., Hendriks, C., Stokkermans, L., Groenendijk, P., Lesschen, J.P., Prado, J., Fangueiro, D., 2021. Mapping and Characterization of CNP Flows and Their Stoichiometry in Main Farming Systems in Europe. Retrieved from. https://www.nutri2cycle.eu/wp-content/uploads/2022/06/D.1.5-Report-on-the-mapping-and-characterization-of-CNP-flows-and-their-stoichiometry-in-main-farming-systems-in-Europe-.pdf.

European Environment, A., Zal, N., Whalley, C., Christiansen, T., Kristensen, P., Néry, F., 2018. European Waters: Assessment of Status and Pressures 2018. Publications Office.

Garnier, J., Beusen, A., Thieu, V., Billen, G., Bouwman, L., 2010. N:P:Si nutrient export ratios and ecological consequences in coastal seas evaluated by the ICEP approach. Global Biogeochem. Cycles 24 (4). https://doi.org/10.1029/2009gb003583 n/a-n/a.

Garnier, J., Billen, G., Lassaletta, L., Vigiak, O., Nikolaidis, N.P., Grizzetti, B., 2021. Hydromorphology of coastal zone and structure of watershed agro-food system are main determinants of coastal eutrophication. Environ. Res. Lett. 16 (2), 023005 https://doi.org/10.1088/1748-9326/abc777.

Glibert, P.M., Al-Azri, A., Allen, J.I., Bouwman, A.F., Beusen, A.H.W., Burford, M.A., Harrison, P.J., Zhou, M., 2018a. Chapter 12 key questions and recent research advances on harmful algal blooms in relation to nutrients and eutrophication. In: Glibert, P.M., Berdalet, E., Burford, M.A., Pitcher, G.C., Zhou, M. (Eds.), Global Ecology and Oceanography of Harmful Algal Blooms, 232. Ecological Studies.

Glibert, P.M., Berdalet, E., Burford, M.A., Pitcher, G.C., Zhou, M., 2018b. Chapter 2 harmful algal blooms and the importance of understanding their ecology and oceanography. In: Glibert, Patricia M., Berdalet, Elisa, Burford, Michele A., Pitcher, Grant C., Zhou, Mingjiang (Eds.), Global Ecology and Oceanography of Harmful Algal Blooms, 232. Ecological Studies.

Grizzetti, B., Bouraoui, F., Aloe, A., 2012. Changes of nitrogen and phosphorus loads to European seas. Global Change Biol. 18 (2), 769–782. https://doi.org/10.1111/j.1365-2486.2011.02576.x.

Grizzetti, B., Vigiak, O., Udias, A., Aloe, A., Zanni, M., Bouraoui, F., Pistocchi, A., Dorati, C., Friedland, R., De Roo, A., Benitez Sanz, C., Leip, A., Bielza, M., 2021. How EU policies could reduce nutrient pollution in European inland and coastal waters. Global Environ. Change 69, 102281. https://doi.org/10.1016/j.gloenvcha.2021.102281.

Hader, J.D., Lane, T., Boxall, A.B.A., MacLeod, M., Di Guardo, A., 2022. Enabling forecasts of environmental exposure to chemicals in European agriculture under global change. Sci. Total Environ. 840, 156478 https://doi.org/10.1016/j.scitotenv.2022.156478.

Jansson, T., Andersen, H.E., Gustafsson, B.G., Hasler, B., Höglind, L., Choi, H., 2019. Baltic Sea eutrophication status is not improved by the first pillar of the European Union Common Agricultural Policy. Reg. Environ. Change 19 (8), 2465–2476. https://doi.org/10.1007/s10113-019-01559-8.

Khan, Z., Graham, N., Vernon, C., Wild, T., Chen, M., Calvin, K., 2022. A global gridded monthly water withdrawal dataset for multiple sectors from 2010 to 2100 at 0.5° resolution under a range of socioeconomic and climate scenarios. online EGU General Assembly 2021, 19–30. https://doi.org/10.5194/egusphere-egu21-903. *April 2021, EGU21-903*.

Kudela, R.M., Raine, R., Pitcher, G.C., Gentien, P., Berdalet, E., Enevoldsen, H., Urban, E., 2018. Chapter 3 establishment, goals, and legacy of the global ecology and oceanography of harmful algal blooms (GEOHAB) Programme. In: Glibert, Patricia M., Berdalet, Elisa, Burford, Michele A., Pitcher, Grant C., Zhou, Mingjiang (Eds.), Global Ecology and Oceanography of Harmful Algal Blooms, 232. Ecological Studies.

Li, A., Strokal, M., Bai, Z., Kroeze, C., Ma, L., 2019. How to avoid coastal eutrophication - a back-casting study for the North China Plain. Sci. Total Environ. 692, 676–690. https://doi.org/10.1016/j.scitotenv.2019.07.306.

Li, A., Wang, M., Kroeze, C., Ma, L., Strokal, M., 2022. Past and future pesticide losses to Chinese waters under socioeconomic development and climate change. J. Environ. Manag. 317, 115361 https://doi.org/10.1016/j.jenvman.2022.115361.

Li, Z., Tang, Z., Song, Z., Chen, W., Tian, D., Tang, S., Wang, X., Wang, J., Liu, W., Wang, Y., Li, J., Jiang, L., Luo, Y., Niu, S., 2022. Variations and controlling factors of soil denitrification rate. Global Change Biol. 28 (6), 2133–2145. https://doi.org/10.1111/gcb.16066.

Mayorga, E., Seitzinger, S.P., Harrison, J.A., Dumont, E., Beusen, A.H.W., Bouwman, A.F., Fekete, B.M., Kroeze, C., Van Drecht, G., 2010. Global nutrient export from WaterSheds 2 (NEWS 2): model development and implementation. Environ. Model. Software 25 (7), 837–853. https://doi.org/10.1016/j.envsoft.2010.01.007.

Nikolaidis, N.P., Phillips, G., Poikane, S., Várbíró, G., Bouraoui, F., Malagó, A., Lilli, M.A., 2022. River and lake nutrient targets that support ecological status: European scale gap analysis and strategies for the implementation of the Water Framework Directive. Sci. Total Environ. 813 https://doi.org/10.1016/j.scitotenv.2021.151898.

Njock, P.G.A., Zhou, A., Yin, Z., Shen, S.-L., 2023. Integrated risk assessment approach for eutrophication in coastal waters: case of Baltic Sea. J. Clean. Prod. 387 https://doi.org/10.1016/j.jclepro.2022.135673.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environ. Change 42, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004.

Panagos, P., Koningner, J., Ballabio, C., Liakos, L., Muntwyler, A., Borrelli, P., Lugato, E., 2022. Improving the phosphorus budget of European agricultural soils. Sci. Total Environ. 853, 158706 https://doi.org/10.1016/j.scitotenv.2022.158706.

Poikane, S., Salas Herrero, F., Kelly, M.G., Borja, A., Birk, S., van de Bund, W., 2020. European aquatic ecological assessment methods: a critical review of their sensitivity to key pressures. Sci. Total Environ. 740, 140075 https://doi.org/10.1016/j.scitotenv.2020.140075.

Redfield, A.C., Ketchum, B.H., Richards, F.A., 1963. The Influence of Organisms on the Composition of the Sea Water, 2. Interscience Publishers, New York.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environ. Change 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Seitzinger, S.P., Mayorga, E., Bouwman, A.F., Kroeze, C., Beusen, A.H.W., Billen, G., Van Drecht, G., Dumont, E., Fekete, B.M., Garnier, J., Harrison, J.A., 2010. Global river nutrient export: a scenario analysis of past and future trends: global RIVER EXPORT scenarios. Global Biogeochem. Cycles 24 (4). https://doi.org/10.1029/2009GB003587 n/a-n/a.

Shan, X., Zhu, Z., Ma, J., Fu, D., Song, Y., Li, Q., Huang, Z., Pei, L., Zhao, H., 2023. Modeling nutrient flows from land to rivers and seas - a review and synthesis. Mar. Environ. Res. 186, 105928 https://doi.org/10.1016/j.marenvres.2023.105928.

Strokal, M., Bai, Z., Franssen, W., Hofstra, N., Koelmans, A.A., Ludwig, F., Ma, L., van Puijenbroek, P., Spanier, J.E., Vermeulen, L.C., van Vliet, M.T.H., van Wijnen, J., Kroeze, C., 2021. Urbanization: an increasing source of multiple pollutants to rivers in the 21st century. npj Urban Sustainability 1 (1), 1–13. https://doi.org/10.1038/s42949-021-00026-w.

Strokal, M., de Vries, W., 2012. Dynamic Modelling of Phosphorus Export at River Basin Scale Based on Global NEWS. Retrieved from Alterra, Wageningen. https://library.wur.nl/WebQuery/wurpubs/fulltext/213989.

Strokal, M., Kroeze, C., Wang, M., Bai, Z., Ma, L., 2016. The MARINA model (model to Assess River Inputs of nutrients to seAs): model description and results for China. Sci. Total Environ. 562, 869–888. https://doi.org/10.1016/j.scitotenv.2016.04.071.

Strokal, M., Kroeze, C., Wang, M., Ma, L., 2017. Reducing future river export of nutrients to coastal waters of China in optimistic scenarios. Sci. Total Environ. 579, 517–528. https://doi.org/10.1016/j.scitotenv.2016.11.065.

Strokal, M., Strokal, V., Kroeze, C., 2023. The future of the Black Sea: more pollution in over half of the rivers. Ambio 52 (2), 339–356. https://doi.org/10.1007/s13280-022-01780-6.

Ural-Janssen, A., Kroeze, C., Lesschen, J.P., Meers, E., van Puijenbroek, P.J.T.M., Strokal, M., 2023. Hotspots of nutrient losses to air and water: an integrated modeling approach for European river basins. Frontiers of Agricultural Science and Engineering 10 (4), 579–592. https://doi.org/10.15302/J-FASE-2023526.

van Puijenbroek, P.J.T.M., Beusen, A.H.W., Bouwman, A.F., 2019. Global nitrogen and phosphorus in urban waste water based on the Shared Socio-economic pathways. J. Environ. Manag. 231, 446–456. https://doi.org/10.1016/j.jenvman.2018.10.048.

van Vliet, M.T.H., van Beek, L.P.H., Eisner, S., Flörke, M., Wada, Y., Bierkens, M.F.P., 2016. Multi-model assessment of global hydropower and cooling water discharge potential under climate change. Global Environ. Change 40, 156–170. https://doi.org/10.1016/j.gloenvcha.2016.07.007.

van Vuuren, D., Stehfest, E., Gernaat, D., de Boer, H.-S., Daioglou, V., Doelman, J., Edelenbosch, O., Harmsen, M., van Zeist, W.-J., van den Berg, M., Dafnomilis, I., van Sluisveld, M., Tabeau, A., De Vos, L., de Waal, L., van den Berg, N., Beusen, A., Bos, A., Biemans, H., Bouwman, L., Chen, H.-H., Deetman, S., Dagnachew, A., Hof, A., van Meijl, H., Meyer, J., Mikropoulos, S., Roelfsema, M., Schipper, A., Van Soest, H., Tagomori, I., Zapata Castillo, V., 2021. The 2021 SSP Scenarios of the IMAGE 3.2 Model. Retrieved from. http://eartharxiv.org/repository/view/2759/.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. Climatic Change 109 (1–2), 5–31. https://doi.org/10.1007/s10584-011-0148-z.

van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., Doelman, J.C., van den Berg, M., Harmsen, M., de Boer, H.S., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y., Girod, B., Kram, T., Lassaletta, L., Lucas, P.L., van Meijl, H., Müller, C., van Ruijven, B.J., van der Sluis, S., Tabeau, A., 2017. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environ. Change 42, 237–250. https://doi.org/10.1016/j.gloenvcha.2016.05.008.

Velthof, G.L., Oudendag, D., Witzke, H.P., Asman, W.A., Klimont, Z., Oenema, O., 2009. Integrated assessment of nitrogen losses from agriculture in EU-27 using MITERRA-EUROPE. J. Environ. Qual. 38 (2), 402–417. https://doi.org/10.2134/jeq2008.0108.

Vigiak, O., Udias, A., Grizzetti, B., Zanni, M., Aloe, A., Weiss, F., Hristov, J., Bisselink, B., de Roo, A., Pistocchi, A., 2023. Recent regional changes in nutrient fluxes of European surface waters. Sci. Total Environ. 858 (Pt 3), 160063 https://doi.org/10.1016/j.scitotenv.2022.160063.

Wang, M., Kroeze, C., Strokal, M., Vliet, M.T.H., Ma, L., 2020. Global change can make coastal eutrophication control in China more difficult. Earth's Future 8 (4). https://doi.org/10.1029/2019ef001280.

Zhang, P., Xie, J., Zhang, J., Fu, M., Luo, W., Cheng, M., 2023. Tidal variation modulates the dissolved silicate behavior and exchange flux across the semi-enclosed bay-coastal water continuum, China. Front. Mar. Sci. 10 https://doi.org/10.3389/fmars.2023.1229267.