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Key Points:

- Globally, in a “Sustainability-driven Future” (SD) river exports of pollutants will be up to 83% lower in 2100 compared to 2010
- In the world, 56% (SD)—78% (ED) of people are projected to live in more polluted river basins in the future
- Rising coastal water pollution is projected for the Indian Ocean in the “Sustainability-driven” (SD) and the “Economy-driven” (ED) future

Supporting Information:

Supporting Information may be found in the online version of this article.

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Future Scenarios for River Exports of Multiple Pollutants by Sources and Sub-Basins Worldwide: Rising Pollution for the Indian Ocean

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Abstract In the future, rivers may export more pollutants to coastal waters, driven by socio-economic development, increased material consumption, and climate change. However, existing scenarios often ignore multi-pollutant problems. Here, we aim to explore future trends in annual river exports of nutrients (nitrogen and phosphorus), plastics (macro and micro), and emerging contaminants (triclosan and diclofenac) at the sub-basin scale worldwide. For this, we implement into the process-based MARINA-Multi model (Model to Assess River Inputs of pollutaNts to the seAs) two new multi-pollutant scenarios: “Sustainability-driven Future” (SD) and “Economy-driven Future” (ED). In ED, river exports of nutrients and microplastics will double by 2100, globally. In SD, a decrease of up to 83% is projected for river export of all studied pollutants by 2100, globally. Diffuse sources such as fertilizers are largely responsible for increasing nutrient pollution in the two scenarios. Point sources, namely sewage systems, are largely responsible for increasing microplastic pollution in the ED scenario. In both scenarios, the coastal waters of the Indian Ocean will receive up to 400% more pollutants from rivers by 2100 because of growing population, urbanization, and poor waste management in the African and Asian sub-basins. The situation differs for sub-basins draining into the Mediterranean Sea and the Pacific Ocean (mainly less future pollution) and the Atlantic Ocean and Arctic Ocean (more or less future pollution depending on sub-basins and scenarios). From 56% to 78% of the global population are expected to live in more polluted river basins in the future, challenging sustainable development goals for clean waters.

Plain Language Summary In the future, rivers are likely to carry more pollutants to coastal waters as a result of socio-economic development, increased material consumption, and climate change. However, many current scenarios overlook the issue of multiple pollutants. We modeled the future river exports of nutrients, plastics, and emerging contaminants to coastal waters worldwide and identified their main pollution sources and hotspots for the 21st century. We explored future trends with the use of two scenarios focusing on a “Sustainability-driven Future” (SD) and an “Economy-driven Future” (ED). By 2100, the ED scenario projects doubled river exports of nutrients and microplastics, while the SD scenario projects up to 83% reduction in river exports of all studied pollutants. Fertilizers are expected to cause most nutrient pollution, while sewage systems are expected to cause most microplastic pollution. Both scenarios project that the coastal waters of the Indian Ocean will receive up to 400% more pollutants as a result of population growth, urbanization, and poor waste management in Africa and Asia.

1. Introduction

Coastal waters are vital for ecosystems, human well-being, and the economy, but they remain at risk due to pollution and climate change (Alcamo, 2019; Crespo Cuaresma, 2017). Rivers are important exporters of various pollutants such as nutrients (nitrogen and phosphorus), plastics (macro and micro), and emerging contaminants (diclofenac and triclosan). These pollutants contribute to the deterioration of the coastal water quality (Micella, Kroeze, Bak, & Strokal, 2024; M. Strokal et al., 2021; H.-M. Wang et al., 2020; M. Wang et al., 2020). Rivers often export these pollutants from common sources such as agriculture and sewage, resulting in multiple impacts (Kroeze et al., 2016; M. Strokal et al., 2019, 2021).

Nutrients, specifically nitrogen (N) and phosphorus (P), primarily originate from agricultural activities and sewage discharges (Li et al., 2021; M. Strokal et al., 2021). Both nutrients move through water runoff, soil

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leaching, and atmospheric deposition, but their chemical properties affect their transport differently. N is highly mobile and can easily leach into groundwater or volatilize into the atmosphere, while P tends to bind to soil particles and is transported primarily through soil erosion and runoff (Haygarth et al., 2005; Wall et al., 2011). Regional differences in pollutant sources and transfer dynamics are important when formulating reduction strategies. For example, in Western and Northern Europe, P loads primarily come from diffuse agricultural pollution, with point sources managed through sewage treatment (Bartosova et al., 2019). In contrast, urban point sources dominate in Sub-Saharan Africa due to a lack of sewage systems. Nutrient pollution in rivers and coastal waters can have several impacts, such as harmful algal blooms and reduction of oxygen levels in rivers and coastal waters (H.-M. Wang et al., 2020; M. Wang et al., 2020).

Plastics can enter into waters from agricultural runoff (e.g., plastic mulching), urban runoff, and industrial discharges (Li et al., 2023). Plastics are transported to water via runoff (macroplastics), wind, and wastewater (microplastics), settling in sediments or remaining suspended in water (M. Strokal et al., 2021). Plastics may cause physical harm to aquatic organisms through ingestion, leading to blockages, malnutrition, and exposure to toxins. Microplastics accumulate in the food chain, affecting predators, including humans. Additionally, plastics can degrade habitats through mechanisms such as biofouling and can act as vectors for transporting other pollutants like nutrients (Koelmans et al., 2016, 2019; Kooi et al., 2017).

Emerging pollutants such as diclofenac (pain killers) and triclosan (antibacterial agents) enter the environment through human excretion (diclofenac), improper disposal of medications, and veterinary drugs (triclosan) (Font et al., 2019; van Wijnen et al., 2018). They dissolve in water and travel through sewage systems into rivers and lakes, with their transport influenced by their solubility and persistence (van Wijnen et al., 2018). Emerging pollutants, like triclosan or diclofenac, can cause endocrine disruption, antibiotic resistance, altered behavior and reproduction in wildlife, and potential long-term effects on human health (Acuna et al., 2020; Font et al., 2019).

In the future, coastal water pollution will depend on the complex relations between climate change and socioeconomic developments (Haddeland et al., 2014; van Vuuren & Carter, 2013). Climate change could directly affect the global water cycle, influencing precipitation, evaporation, runoff, and snowmelt rates (Konapala et al., 2020). In addition, climate change may cause shifts in temperature, which could have considerable effects on aquatic ecosystems and biological cycling (Beusen et al., 2022; Bodirsky et al., 2014). These changes are not always detrimental. For example, Gervasio et al. (2022) observed that higher temperatures increased denitrification, buffering N loads.

Meanwhile, population and income (gross domestic product, GDP) are expected to grow in the 21st century, but this growth may vary considerably across regions (Crespo Cuaresma, 2017; B. Jones & O'Neill, 2016). Sub-Saharan Africa and Southeast Asia are projected to experience considerable increases in their population by 2050, while Europe and parts of Asia may experience stagnation or decline in their population. These population changes will impact food production, potentially increasing fertilizers, and manure use. Growing populations may also drive rapid urbanization, leading to more sewage connections and potentially more river pollutants if wastewater is not treated efficiently. Similarly, the demand for water supplies may also increase, challenging even more water availability (Flörke et al., 2018; van Vliet et al., 2017; Wada et al., 2016). Increased water consumption can alter river retention and discharge patterns, ultimately altering pollutant export to coastal waters (Haddeland et al., 2014; Schewe et al., 2014). Therefore, to successfully address these challenges and control pollution, it is critical to understand the links between river exports of nutrients, plastics and emerging chemicals, their sources, and future trends driven by global changes.

Another knowledge gap is associated with scenarios for multiple pollutants. Many scenarios for coastal waters often focus on single pollutants (Beusen et al., 2015; Kanter et al., 2020; H.-M. Wang et al., 2020; M. Wang et al., 2020). Existing Shared Socio-economic Pathways (SSPs) were designed to explore socio-economic changes in the 21st century (Jiang & O'Neill, 2017; O'Neill et al., 2017, 2020). However, they were not developed for the water quality sector nor for multiple pollutants and their land-based sources. Although, several studies quantified future water quality using the SSPs in combination with the Representative Concentration Pathways (RCPs), (van Vuuren & Carter, 2013), these analyses mostly addressed individual pollution types such as pathogens (Hofstra & Vermeulen, 2016), and nutrients (Beusen et al., 2022), or analyses are often focused on in-stream water quality (E. R. Jones et al., 2023). There is a lack of comprehensive studies covering simultaneously the river exports of plastics (macro and micro), nutrients (N and P), and emerging contaminants (e.g., diclofenac and triclosan) to coastal waters in the future under the SSPs and RCPs scenarios. Multiple pollutants often coexist and may be influenced by various societal factors (e.g., population growth, urbanization, economy) and depend on technological developments. This highlights a need for a deeper understanding of those aspects affecting future coastal waters in the world (M. Wang et al., 2024).

To bridge this gap, modeling tools for multiple pollutants can be used. Global models exist for nutrients (Beusen et al., 2022), pathogens (Hofstra & Vermeulen, 2016), diclofenac (Acuna et al., 2020; Font et al., 2019), triclosan (van Wijnen et al., 2018), and plastics (M. Strokal, Strokal, & Kroeze 2023; M. Strokal, Vriend, et al., 2023). Only a few models exist that simultaneously simulate multiple pollutants in rivers (Li et al., 2021; M. Strokal et al., 2021) and in streams (E. R. Jones et al., 2023). The family of the MARINA (Model to Assess River Inputs of pollutaNts to seAs) models has been developed to address multi-pollutant issues for rivers and coastal waters at the sub-basin scale in the world. One of these models, called MARINA-Multi, has been developed to simulate simultaneously river exports of plastics (macro and micro), nutrients (N and P), and emerging contaminants (e.g., triclosan) to coastal waters from sub-basins and by sources (Micella, Kroeze, Bak, & Strokal, 2024). The model ran for the year 2010 and allowed modelers to identify and compare pollution hotspots and their sources between pollutants and sub-basins worldwide. The model has consistent spatial and temporal levels of detail facilitating multi-pollutant comparisons and has the potential to be applied for future analyses because of its ability to integrate societal factors into the simulations of river exports of multiple pollutants. This integration makes it possible to examine synergies and trade-offs between the releases of multiple pollutants to rivers and other factors such as population growth, technology development, and economic development. While models like SWAT for Africa (Nkwasa et al., 2024) and GREEN for Europe (Grizzetti et al., 2021) offer valuable insights, MARINA-Multi's integrated approach serves as a foundation for developing multi-pollutant scenarios (e.g., "what-if" scenarios) and assessing future trends.

In this study, aim to explore future trends in annual river exports of nutrients (nitrogen and phosphorus), plastics (macro and micro), and emerging contaminants (triclosan and diclofenac) at the sub-basin scale in the world. For this, we implement into the process-based MARINA-Multi model (Model to Assess River Inputs of pollutaNts to the seAs) two new multi-pollutant scenarios: "Sustainability-driven Future" (SD, based on the combination of SSP1-RCP2.6) and "Economy-driven Future" (ED, based on the combination of SSP5-RCP8.5). We chose these scenarios to focus on environmental actions. Regarding socio-economic development, SSP1 and SSP5 follow similar trends (e.g., high urbanization and economic growth) but have different attitudes toward environmental management. SSP1 focuses on proactive approaches and mitigation, whereas SSP5 focuses on reactive approaches and adaptation. We selected SSP1-RCP2.6 for the multi-pollutant SD scenario because it represents a future in which sustainable development is prioritized and climate change mitigation measures are implemented. In contrast, we chose SSP5-RCP8.5 for the multi-pollutant ED scenario because it represents a future in which economic growth takes precedence over climate change mitigation measures. Our research contributes to the achievement of Sustainable Development Goals (SDGs) 6 (clean freshwater) and 14 (clean coastal waters). We emphasize the role of socio-economic changes in future pollution trends to support SDG14 on coastal water pollution.

2. Materials and Methods

2.1. The MARINA-Multi Model

We use the MARINA-Multi model (Micella, Kroeze, Bak, & Strokal, 2024) to quantify future river export of multiple pollutants by source from sub-basins into coastal areas in the 21st century covering the period of 2010–2100. The MARINA-Multi is a process-based, steady-state model that integrates modeling approaches for nutrients (N and P), plastics (macro and micro), and emerging contaminants (triclosan and diclofenac). This is the first application of MARINA-Multi for future analyses under consistent socio-economic and climate scenarios, for three pollution types (nutrients, plastics, and chemicals) and for both point and diffuse sources. The model is run at the sub-basin scale in the world for the years 2010, 2050, and 2100. The model has been already validated for 2010 (Micella, Kroeze, Bak, & Strokal, 2024). Here, we further evaluate the model for the future (see Section 4).

The MARINA-Multi model includes multiple pollutants entering rivers from diffuse and point sources. The model considers nutrient forms: dissolved inorganic (DIN, DIP) and dissolved organic (DON, DOP) nitrogen (N) and phosphorus (P). Total dissolved N (TDN) is the sum of DIN and DON, while total dissolved P (TDP) is the sum of DIP and DOP. These nutrients originate from point sources such as sewage systems, direct discharges of untreated human waste, and direct discharges of untreated animal manure to rivers (this source is only relevant for Chinese rivers). The diffuse sources of these nutrients in rivers are classified into anthropogenic and non-anthropogenic. Anthropogenic diffuse sources include the use of synthetic fertilizers and animal manure in crop production (for DIN, DON, DIP, and DOP), atmospheric N deposition (for DIN), biological N_2 fixation by legumes (for DIN), leaching of organic matter (for DON, DOP), and weathering of P-contained minerals (for DIP) from agricultural areas. Non-anthropogenic diffuse sources include atmospheric N deposition (for DIN), biological N_2 fixation by natural vegetation (for DIN), leaching of organic matter (for DON, DOP), and weathering of P-contained minerals (for DIP) from non-agricultural areas. For plastics the model distinguishes between macro- (MAP) and microplastics (MIP). Diffuse sources of MAP in rivers include Mismanaged Plastic Waste (MPW) that undergoes weathering, fragmentation, and embrittlement, entering river systems as secondary MIP. Thus, MPW is also a diffuse source of MIP in rivers. Point sources of MIP in rivers include sewage effluents that contain MIP from car tire wear, personal care products (PCPs), laundry fibers, and household dust. For emerging contaminants, the model considers triclosan (TCS) and diclofenac (DCL) in rivers. These are emerging contaminants in aquatic environments. In the model, these emerging contaminants enter rivers from sewage systems that collect wastewater from households. This wastewater contains TCS from the use of PCPs (e.g., soap) and DCL as excreted in human feces and urine.

The overall description of the MARINA-Multi model is provided in "Supporting Information S1." Here, we describe the main equation to quantify annual river exports of pollutants to coastal waters by source and sub-basin. This is done as follows:

$$M_{i.y.j} = \left(\mathrm{RSpnt}_{i.y.j} + \mathrm{RSdif}_{i.y.j}\right) \cdot \mathrm{FE}_{\mathrm{riv}.i.\mathrm{out}.j} \cdot \mathrm{FE}_{\mathrm{riv}.i.\mathrm{mouth}.j} \tag{1}$$

where,

$M_{i.y.j}$ is the annual river export of pollutant i from source y and sub-basin j (kg/year)**;**

$\mathrm{RSpnt}_{i.y.j}$ is the annual input of pollutant i to rivers from point source y and sub-basin j (kg/year) (see Equation 2);

$\mathrm{RSdif}_{i.y.j}$ is the annual input of pollutant i to rivers from diffuse source y and sub-basin j (kg/year) (see Equations 3–6);

$\mathrm{FE}_{\mathrm{riv}.i.\mathrm{out}.j}$ is the fraction of the annual input of pollutant i in rivers reaching the outlet of sub-basin j (0–1) (see Equation 7). This fraction accounts for the retention and losses of pollutants in the river network of the sub-basin, including denitrification, river damming, and sedimentation, as well as water removal from the rivers, resulting in losses of pollutants from rivers (for all pollutants; see details in Tables S6 and S7 of the Supporting Information S1).

$\mathrm{FE}_{\mathrm{riv}.i.\mathrm{mouth}.j}$ is the fraction of pollutant i reaching the river mouth from the outlet of sub-basin j (0–1). This fraction includes retention and losses of pollutants during export from the sub-basin outlet to the river mouth (or coastal waters, more details are in Tables S8 and S9 of the Supporting Information S1).

To quantify $\mathrm{RSpnt}_{i.y.j}$ *for all considered pollutants* the following equation is used:

$$\mathrm{RSpnt}_{i.y.j} = \mathrm{RSpnt}_{i.\mathrm{dir}.j} + \mathrm{RSpnt}_{i.\mathrm{sew}.j} + \mathrm{RSpnt}_{i.\mathrm{ma}.j} \tag{2}$$

where,

$\mathrm{RSpnt}_{i.\mathrm{dir}.j}$ is the annual input of pollutant i (DIN, DON, DIP, or DOP) to rivers from direct discharges of human waste (open defecation) in sub-basin j (kg/year).

$\mathrm{RSpnt}_{i.\mathrm{sew}.j}$ is the annual input of pollutant i (DIN, DON, DIP, DOP, TCS, DCL, or MIP) to rivers from sewage systems in sub-basin j (kg/year).

$\mathrm{RSpnt}_{i.\mathrm{ma}.j}$ is the annual input of pollutant i (DIN, DON, DIP, or DOP) to rivers from direct discharges of animal manure (ma) in sub-basin j (kg/year). This source is only for Chinese sub-basins.

To quantify $\mathrm{RSdif}_{i.y.j}$ *for nutrients* (N and P) we use the following equations agricultural and non-agricultural areas:

$$\mathrm{RSdif}_{i.y.j} = \mathrm{WSdif}_{i.y.j} \cdot G_{i.j} \cdot \mathrm{FEws}_{i.j} \qquad \text{agricultural areas} \tag{3}$$

$$\mathrm{RSdif}_{i.y.j} = \mathrm{WSdif}_{i.y.j} \cdot \mathrm{FEws}_{i.j} \qquad \text{non-agricultural areas} \tag{4}$$

where,

$\mathrm{WSdif}_{i.y.j}$ is the annual input of pollutant i (N and P) on agricultural and non-agricultural land from animal manure (agricultural land, for N and P), synthetic fertilizers (agricultural land, for N and P), atmospheric N deposition (agricultural and non-agricultural land, for N) and biological N_2 fixation (for crops and natural vegetation, for N) in sub-basin j (kg/year).

$G_{i.j}$ is the fraction of pollutant i (DIN, DON, DIP, or DOP) that is applied to agricultural land and is remained in soils after animal grazing and crop harvesting in sub-basin j (0–1).

$\mathrm{FEws}_{i.j}$ is the export fraction of pollutant i (DIN, DON, DIP, or DOP) entering rivers in sub-basin j (0–1). The fraction is calculated as a function of annual surface runoff from land to streams in sub-basin j (0–1).

To quantify $\mathrm{RSdif}_{i.y.j}$ *for macroplastics (MAP) and microplastics* (MIP) from mismanaged plastic waste (MPW), the following equations are used:

$$\mathrm{RSdif}_{\mathrm{map.MPW}.j} = \left(\mathrm{RSdif}_{\mathrm{MPW}.j} - \mathrm{RSdif}_{\mathrm{mip.MPW}.j}\right) \tag{5}$$

$$\mathrm{RSdif}_{\mathrm{mip.MPW}.j} = \left(\mathrm{RSdif}_{\mathrm{MPW.fast}.j} \cdot t_{\mathrm{res.fast}.j} + \mathrm{RSdif}_{\mathrm{MPW.slow}.j} \cdot t_{\mathrm{res.slow}.j}\right) \cdot F_{\mathrm{map}} \tag{6}$$

where,

$\mathrm{RSdif}_{\mathrm{MPW}.j}$ is the annual input of mismanaged macroplastic waste (diffuse source) to river systems in sub-basin j (kg/year).

$\mathrm{RSdif}_{\mathrm{mip.MPW}.j}$ is the annual input of microplastics (mip) to rivers as a result of fragmentation of macroplastics from mismanaged plastic waste (MPW, diffuse source) in sub-basin j (kg/year).

$\mathrm{RSdif}_{\mathrm{MPW.fast}.j}$ and $\mathrm{RSdif}_{\mathrm{MPW.slow}.j}$ are the annual inputs of macroplastics from mismanaged plastic waste (MPW, diffuse source) into the fast and slow fractions (water column) in sub-basin j (kg/year).

$t_{\mathrm{res.fast}.j}$ and $t_{\mathrm{res.slow}.j}$ are the average residence times of macroplastics in the fast and slow fractions in sub-basin j (year).

To quantify $\mathrm{FE}_{riv.i.out.j}$ *for all considered pollutants,* the following equation is used:

$$\mathrm{FE}_{\mathrm{riv}.i.\mathrm{out}.j} = (1 - D_{i.j}) \cdot (1 - L_{i.j}) \cdot (1 - \mathrm{FQrem}_j) \tag{7}$$

where,

FQrem_j is the fraction of losses of pollutant i (generic for all pollutants) from rivers via water removals in sub-basin j (0–1).

$D_{i.j}$ is this fraction of pollutant i (DIN, DIP, and TCS) retained in dammed reservoirs in sub-basin j (0–1). For all pollutants see details in Tables S6 and S7 of the Supporting Information S1.

$L_{i.j}$ is the retention fraction of pollutant i (DIN, DON, DIP, DOP, DCL, TCS, MIP, and MAP) in rivers because of the biogeochemical processes in sub-basin j (0–1). For all pollutants see details in Tables S6 and S7 of the Supporting Information S1.

$\mathrm{FE}_{\mathrm{riv}.i.\mathrm{mouth}.j}$ calculation is based on the river network and routing scheme. Our routing scheme distinguishes between sub-basins that include only tributaries (T) and sub-basins that include the main channel (C) of the river. This is done for up- (ju), middle- (jm) and downstream (jd) sub-basins. Tributaries discharge multiple pollutants into the main channel, which then transports them to the river mouth (see Figure S15, Tables S6 and S7 in Supporting Information S1).

2.2. Scenario Description

We develop two multi-pollutant scenarios based on the combinations of two SSPs and RCPs (Jiang & O'Neill, 2017). SSPs typically describe various future socio-economic developments, including changes in population, urbanization, land use, and gross domestic product (GDP) (B. Jones & O'Neill, 2016). RCPs typically reflect future climate change with a range of radiative forcing values projected for 2100, ranging from 2.6 to 8.5 W/m^2 (van Vuuren & Carter, 2013). Our scenarios combine SSP1 with RCP2.6 (sustainability-driven with low global warming) and SSP5 with RCP8.5 (economy-driven with high global warming), resulting in two different futures for multiple pollutants: "Sustainability-driven Future" (SD) and "Economy-driven Future" (ED). We translate the storylines of SSP1-RCP2.6 and SSP5-RCP8.5 into our two multi-pollutant scenarios. These two scenarios share largely the trends in high urbanization and economic developments but taking reactive (ED under high global warming) and proactive (SD under low global warming) perspectives toward reductions of coastal water pollution with multiple pollutants. These scenarios are useful in the context of water pollution as they provide contrasting perspectives on how the attitude toward the environment and policy can influence the future of coastal water quality. The SD scenario highlights the potential benefits of sustainable development and proactive environmental action, while the ED scenario underscores the challenges associated with economy-driven markets and reactive environmental management. By examining these scenarios, we can gain insights into the two potential societal responses to future coastal water pollution, and from there, we can learn. Below, we describe each scenario (Table 1).

2.2.1. "Sustainability-Driven Future" (SD) for Multiple Pollutants

SD assumes a transition to sustainable practices and a proactive attitude toward environmental policies. This scenario is characterized by moderate to low population growth, efficient resource use, advanced technology adoption, and enhanced environmental policies (inspired by B. Jones and O'Neill (2016)) (Table 1). The Human Development Index (HDI) and Gross Domestic Product (GDP) are both measures of a country's development, but they address distinct aspects. While GDP measures a country's economic growth, the HDI considers factors such as health, education, and income to provide a more comprehensive picture of human well-being. GDP and HDI show an increasing trend in the 21st century (Klugman et al., 2011). Future estimates indicate that by 2050, sewage connections are expected to reach up to 50% of the global population, increasing to 60% by 2100. Technological advances in SD include innovative wastewater treatment and transitioning to advanced treatments in well-developed areas (Van Puijenbroek et al., 2023). As a result, in 2100, removal fractions (global averages) during treatment in the wastewater treatment plants (WWTPs) based on the scenario storylines are estimated at 71%–76% for N and P (based on Beusen et al. (2022) and Van Puijenbroek et al. (2019)), 44% for MIP, and 66%–68% for TCS and DCL (based on calculations for 2010 in Micella, Kroeze, Bak, and Strokal (2024)). Nutrient excretion rates follow GDP growth (Van Drecht et al., 2009). After 2050, all detergents are assumed to be P-free (Van Puijenbroek et al., 2018). Per capita consumption of MIP is assumed to decrease by 50% between 2010 and 2050–2100 years globally. This demonstrates a commitment to cut the generation of waste, prohibit the use of single-use plastics, and achieve a global reduction of MPWs by over 50% by 2050 years on a global scale (based on Lebreton and Andrady (2019)). We assume that per capita consumption of TCS and DCL will stay at the level of 2010 in the future because people will likely continue using painkillers and antibacterial agents. SD encourages a shift to less meat-intensive diets, a gradual increase in synthetic fertilizer use between 2010 and 2050, and stable practices thereafter. Hydrology (water discharge) aligns with the RCP2.6 scenario, assuming low global warming (Table 1).

2.2.2. "Economy-Driven Future" (ED) for Multiple Pollutants

In contrast, ED assumes an economy-driven future but with less attention to reducing pollution. This implies that people will take a reactive attitude toward environmental issues. This scenario is characterized by globalization and moderate population growth (Table 1). GDP and HDI are projected to be higher in the future compared to 2010 because of a market-driven approach, and technology investments. Around half of the global population is projected to be connected to sewage systems in the year 2050. This is somewhat like the trends in the SD scenario. However, treatment in this ED scenario is poorer compared to the SD scenario. For example, following the

Table 1
Scenario Assumptions for 2050 and 2100

Input	Unit	SD 2050	SD 2100	ED 2050	ED 2100
Population growth	people/year	+20%	+1%	+20%	+7%
GDP* (****)	US$/cap/year (2005 exchange rate)	+57%	+77%	+60%	+80%
HDI**	0–1	+10%	+20%	+10%	+20%
Sewage connection rates	0–1	+50%	+60%	+50%	+60%
Removal fractions***	0–1				
• N removal		Mean: 0.43	Mean: 0.71	Mean: 0.49	Mean: 0.75
		Range: (0.02–0.88)	Range: (0.06–0.88)	Range: (0.0004–0.87)	Range: (0.0004–0.88)
• P removal		Mean: 0.47	Mean: 0.76	Mean: 0.55	Mean: 0.82
		Range: (0.003–0.95)	Range: (0/08–0/95)	Range: (0.0004–0.95)	Range: (0.0004–0.95)
• MIP removal		Mean: 0.34	Mean: 0.44	Mean: 0.38	Mean: 0.46
		Range: (0.01–0.49)	Range: (0.01–0.09)	Range: (0.0004–0.49)	Range: (0.0004–0.49)
• DCL removal		Mean: 0.48	Mean: 0.68	Mean: 0.54	Mean: 0.72
		Range: (0.006–0.8)	Range: (0.11–0.8)	Range: (0.0002–0.8)	Range: (0.0002–0.8)
• TCS removal		Mean: 0.47	Mean: 0.66	Mean: 0.53	Mean: 0.71
		Range: (0.007–0.78)	Range: (0.22–0/78)	Range: (0.10–0.78)	Range: (0.10–0.78)
MIP Consumption	kg/cap/year	−50%	−50%	No changes	No changes
MPW Generation	kg/cap/year	−50%	−80%	+50%	+50%
DCL and TCS Consumption	g/cap/year	No changes	No changes	No changes	No changes
Open Defecation	–	No open defecation	No open defecation	No open defecation	No open defecation
Use of synthetic fertilizers					
• N	kg/year	+14%	+36%	+54%	+100%
• P	kg/year	+20%	+55%	+36%	+88%
Use of animal manure (on land)					
• N	kg/year	−10%	−20%	+25%	+45%
• P	kg/year	−12%	−19%	+25%	+50%
Hydrology (e.g., river discharges)****	–	RCP2.6	RCP2.6	RCP8.5	RCP8.5

Note. SD is a Sustainability-driven Future, ED is an Economy-driven Future (see their description in Section 2.2). Percentage changes for 2050 and 2100 are relative to 2010. Increases are indicated with "+" and decreases with "−." N is nitrogen, P is phosphorous, MIP is microplastics, MAP is macroplastics, DCL is diclofenac and TCS is triclosan. The values in the brackets show the ranges among 10,226 sub-basins (spatial heterogeneity). The values outside the brackets indicate the averages over those sub-basins. These assumptions are supported by literature (Beusen et al., 2022; Lebreton & Andrady, 2019; Micella, Kroeze, Bak, & Strokal, 2024; O'Neill et al., 2017; Van Puijenbroek et al., 2019, 2023). *GDP (Gross Domestic Product), averaged over the sub-basins; **HDI (Human Development Index), averaged over the sub-basins; ***Averaged removal fractions over the sub-basins (0–1); ****N and P excretion rates depend on GDP following van Drecht et al. (2009). *****RCP is short for Representative Concentrative Pathways.

scenario storylines in 2100, the global averages of the removal fractions during treatment in wastewater treatment plants (WWTPs) are estimated at 75%–82% for N and P (based on Beusen et al. (2022) and Van Puijenbroek et al. (2019)), 46% for MIP, and around 70% for TCS and DCL (based on calculations for 2010 in Micella, Kroeze, Bak, and Strokal (2024)). While some of these removal rates in the ED scenario are higher than those in the SD scenario, Table 1 highlights that there is greater local variability in removal rates, with some areas experiencing lower minimum values. Nutrient excretion rates follow the future trend in GDP growth (Van Drecht et al., 2009). After 2050, all detergents are assumed to be P-free (Van Puijenbroek et al., 2018). Assuming only reactive policies, global per capita MIP consumption remains unchanged from 2010 to 2050 and 2100. Despite this, population growth, economic development, and no policies are anticipated to double MPW generation in this scenario (based on Lebreton and Andrady (2019)). We assume that per capita consumption of TCS and DCL will stay at the level of 2010 in the future because people will likely continue using painkillers and antibacterial agents. Livestock production will intensify, resulting in an increase in crop production in the future. Agriculture intensification is projected to be higher in 2050 than in 2100 (Beusen et al., 2022). In ED, higher global warming and intensified extremes could impact runoff and river export of pollutants, following the RCP8.5 scenario (Table 1).

2.3. Data

Various data sources are used as inputs to the scenarios. The sources differ among pollutants. In addition, input data that are available at the grid level or other higher resolutions are aggregated to sub-basins as described in Tables S10 and S11 of the Supporting Information S1. Most of our model inputs and parameters are uncalibrated. This uncalibrated modeling approach has been applied and evaluated at different scales and for different regions (Li et al., 2022; Micella, Kroeze, Bak, & Strokal, 2024; Ural-Janssen et al., 2024). For nutrients, model inputs for diffuse sources are taken from previous MARINA model studies and other sources. For example, model inputs for the fractions of direct discharges of animal manure and human waste are based on M. Strokal et al. (2016), H.-M. Wang et al. (2020), and M. Wang et al. (2020) (Table S11 in Supporting Information S1, letter G). The practice of directly discharging animal manure was predominantly observed in China until 2007, after which there was a notable reduction in this practice. As a result, it is assumed that this practice will cease in the future. This assumption is grounded in the policy implemented in China since 2010 and supported by evidence of local reductions in manure dumping practices (Zhu et al., 2022). Direct discharges of untreated human waste for other regions are based on M. Strokal et al. (2021). Model inputs for the runoff coefficient needed to quantify inputs of nutrients from land to rivers are from Li et al. (2021) (Table S11 in Supporting Information S1, letter M). Other agricultural data such as synthetic fertilizers, animal manure, atmospheric N deposition, and biological N_2 fixation are from the Integrated Model to Assess the Global Environment–Global Nutrient Model (IMAGE–GNM) model (Beusen et al., 2022) (Table S11 in Supporting Information S1, letter N). Model inputs for point sources of nutrients include the fraction of nutrient removals during treatment (based on Beusen et al. (2022) and Van Puijenbroek et al. (2019)). The fraction of the population with sewage connections is based on SSP-RCP scenarios (Van Puijenbroek et al., 2023), with adjustments for the sub-basin scale (Micella, Kroeze, Bak, & Strokal, 2024) (Table S11 in Supporting Information S1, letter D–F).

For plastics, model inputs for MPWs are derived from Lebreton and Andrady (2019). These inputs are aggregated from the country scale to sub-basins (Table S11 in Supporting Information S1, letter O). Removal fractions for MIP during treatment are estimated using the removal efficiencies from the literature (based on the calculation for 2010 in Micella, Kroeze, Bak, and Strokal (2024)). The fractions of the population with primary, secondary, tertiary, and quaternary technologies and no treatment are based on the information of Van Puijenbroek et al. (2023) and adjusted to the sub-basin scale. The same holds for the removal fractions of TCS and DCL for which estimates are based on existing studies for removal efficiencies (calculation for 2010 in Micella, Kroeze, Bak, and Strokal (2024)) and the information of Van Puijenbroek et al. (2023) for the population with different treatment types (Table S11 in Supporting Information S1, letter E, and H–I).

Model inputs for retention in the soil and river systems (e.g., reservoirs, hydrology) are from the previous MARINA versions. For example, our model covers over 10,000 sub-basins that are delineated using the river flow and land mask from a hydrological model (Variable Infiltration Capacity, VIC) in an earlier study (M. Strokal et al., 2021) (Table S11 in Supporting Information S1, letter T). This hydrological data (e.g., river discharges) is a 30-year average derived from five global circulation models (GCMs) as part of the CMIP5/ISIMIP 2b (Frieler et al., 2017) (Coupled Model Intercomparison Project/Intersectoral Impact Model Intercomparison Project) (van Vliet et al., 2016). Our choice for the 30-year average of river discharges is based on expert knowledge. It is justified by the fact that the 30-year averages are sufficient enough to avoid the influence of extremes and outliers in our long-term water quality assessments (van Vliet et al., 2016). Data for future water consumption projections, covering sectors like residential and irrigation is from Khan et al. (2023) and aggregated to sub-basins (Table S11 in Supporting Information S1, letter W).

2.4. Model Evaluation

The MARINA-Multi model was developed through the integration of existing modeling approaches, and evaluated for nutrients (Li et al., 2021; M. Strokal et al., 2016), plastics (V. Strokal, Kurovska, & Strokal, 2023; M. Strokal, Strokal, & Kroeze 2023; M. Strokal, Vriend, et al., 2023), emerging contaminants (M. Strokal et al., 2021) independently and multiple pollutants simultaneously (see more details in Micella, Kroeze, Bak, and Strokal (2024)). We further evaluate our model for the future following the "building trust" approach (M. Strokal et al., 2016), including (a) comparisons with observations for the past year, (b) comparisons with other studies for the past and future years and (c) sensitivity analysis on climate change and socio-economic drivers. We perform four runs to test how sensitive the model results are to different scenario assumptions for the baseline year (2010). Each sensitivity run involves changing either socio-economic or climate-associated hydrological conditions while keeping the other factors constant in the model. Sensitivity run 1 assumes sustainable socio-economic development in the 21st century (reflecting the storyline of SSP1) with hydrology at the level of 2010. Sensitivity run 2 assumes a fossil-fueled socio-economic development in the 21st century (reflecting the storyline of SSP5) with hydrology at the level of 2010. Sensitivity run 3 assumes changes in hydrology in the 21st century because of "low global warming" (RCP2.6) but with socio-economic development at the level of 2010. Sensitivity run 4 assumes changes in hydrology in the 21st century because of "high global warming" (RCP8.5) but with socio-economic development at the level of 2010.

2.5. Classification of Multi-Pollutant Hotspots for Coastal Waters

We classify multi-pollutant hotspots for coastal waters to better understand where (sub-basins) and why (pollutants) multi-pollutant issues are expected in the future. This information could facilitate the policy to prioritize pollution reduction strategies for multiple pollutants. We define three classes using the pollution trends in river exports over time: Class A, Class B, and Class C. Classes A and C stand for coastal waters for which river exports of at least four different pollutants are modeled to increase (Class A) or decrease (Class C) during the periods of 2010–2050 and/or 2010–2100. Class B includes the remaining situations, namely mixed responses where river exports of less than four pollutants are modeled to increase or decrease during the periods of 2010–2050 and/or 2010–2100. This implies that Class A indicates increasing trends for most pollutants, Class C indicates decreasing trends for most pollutants and Class B (in the middle) indicates varied trends among pollutants for coastal waters.

3. Results

3.1. Future Multiple Pollutants in Coastal Waters Globally

Many coastal waters in the world are expected to receive multiple pollutants in the near (2050) and far (2100) future (Figure 1). This especially holds for the ED ("Economy-driven Future") scenario in which global river export of microplastics will double by 2100, for TDP and TDN there is also an increase (+18% to +34% respectively). In this scenario, river export of MAP is projected to increase by 30% during 2010–2050 and by 10% during 2050–2100. This is different for river exports of TCS and DCL where the ED scenario projects a slight increase by 2050 (2%–12%) and then a decrease by 2100 (8%–24%, Figure 1).

In contrast, the SD scenario ("Sustainability-driven Future") projects up to 83% less sea pollution by 2100 than in 2010 (Figure 1). These decreases vary among pollutants. Greater decreases are projected for river exports of MAP (−74% to −83%), TCS (−5% to −32%), and DCL (−15% to −45%) between 2010 and the future years globally. For river exports of TDN and TDP, the projected decreases range from −3% to −10% depending on the year. For river export of MIP, this decrease ranges from −8% to −13% depending on the year (Figure 1).

The coastal waters of the Indian Ocean are expected to become much more polluted in the future compared to the year 2010. This is because river exports of pollutants to the Indian Ocean are projected to exceed those to the other oceans. In both scenarios, the Indian Ocean will receive up to 400% more pollutants from rivers by 2100 because of growing population, urbanization, and poor waste management in the African and Asian basins. In the SD scenario, in 2010, 70% of total river exports of most pollutants went to the coastal waters of the Pacific and Atlantic Oceans. However, this is expected to drop to less than 60% by 2050 and 2100. Conversely, the Indian Ocean's coastal waters are projected to receive more pollutants in this SD future, increasing their global share (Figure 1). In the ED scenario, the majority of MAP (+55%) will be exported by rivers into the coastal waters of

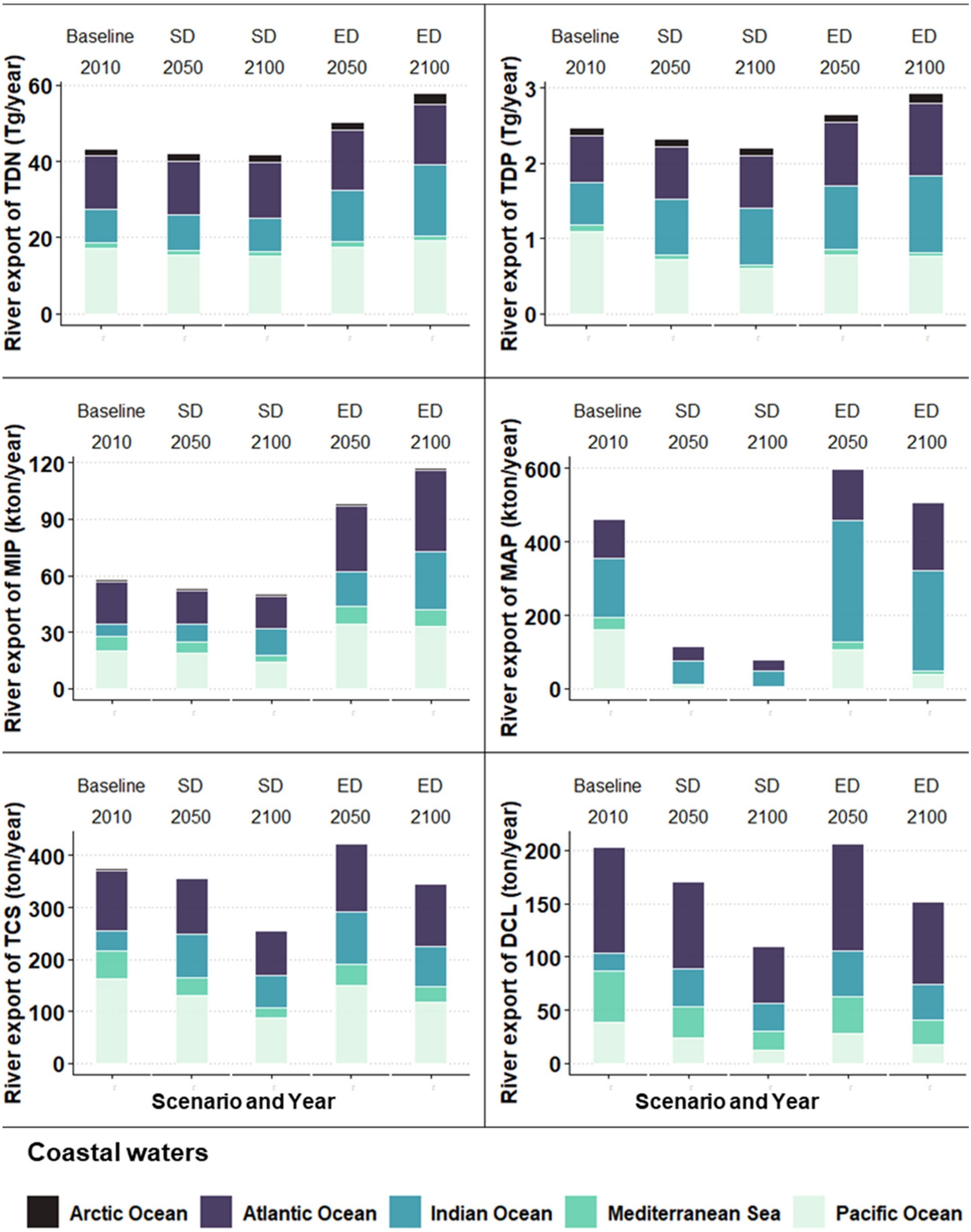

Figure 1. River exports of pollutants to coastal waters in 2010, 2050, and 2100 under the two scenarios (Tg/year, kton/year, or ton/year). Scenarios are "Sustainability-driven Future" (SD) and "Economy-driven Future" (ED). TDN and TDP are short for total dissolved nitrogen, and phosphorus, respectively. MIP and MAP are short for microplastics and macroplastics, respectively. TCS and DCL are short for triclosan and diclofenac, respectively. Source: The MARINA-Multi model (see Section 2 for the model and scenario description).

the Indian Ocean by 2100. This was different in 2010 when most of MAP was exported by rivers to the Pacific Ocean globally (Figure 1).

3.2. From Sources to Seas

3.2.1. Anthropogenic Pollution in the SD Scenario

We analyze dominant anthropogenic (diffuse and point) sources for river exports of TDN, TDP, and MIP for 2100. Globally, around two-thirds of the sub-basin areas will be dominated by diffuse anthropogenic sources contributing to river exports of TDN and TDP in 2100 (pie charts in Figure 2). For TDN the largest share is from atmospheric N deposition, and biological N_2 fixation on a global scale (pie charts in Figure 2). For TDP, the largest share is from synthetic fertilizers and sewage systems (pie charts in Figure 2). For MIP export by rivers, this situation is different. Around 95% of sub-basin areas globally are expected to be dominated by point sources namely due to car tire wear (80%) and laundry fibers (14%) in sewage systems.

The share of point and diffuse sources in anthropogenic-associated river exports of TDN and TDP varies among sub-basins (maps in Figure 2). In many sub-basins draining into the coastal waters of South America, North America, Australia, and Central Africa, atmospheric N deposition and biological N_2 fixation by crops are expected to dominate in river exports of TDN in 2100. This could be due to the large share of agricultural areas in those regions and the reduced share of the other sources in the SD scenario in 2100. Under the SD scenario, from 2010 to 2100, coastal water pollution from point sources is expected to decrease due to improved wastewater treatment and higher connection rates. Likewise, diffuse pollution from animal manure is projected to decline with more efficient agricultural practices. These reductions will notably influence the balance of point and diffuse source contributions across sub-basins by 2100. Additionally, direct discharges of human waste are assumed to be reduced to zero (van Puijenbroek et al., 2023). Consequently, in South America, North America, Australia, and Central Africa, human waste as the diffuse source of nutrient pollution in coastal waters may become less important compared to atmospheric N deposition and biological N_2 fixation by crops in agriculture.

Synthetic fertilizers are expected to be the major sources in many sub-basins of Europe, India, North China Plain, and Sub-Saharan Africa, while West African coasts are expected to be influenced primarily by animal manure on land. This is largely due to the reduction of the share of the other point sources, such as sewage systems, in Europe, India, and the North China Plain between 2010 and 2100. In Africa, the increasing trends in the use of synthetic fertilizers and animal manure (diffuse sources) may also contribute considerably to more river exports of nutrients in those regions by 2100 under the SD scenario. Sewage systems will only be dominant in a few sub-basins draining into the coastal waters of the Mediterranean Sea (Europe and North Africa), Africa, the Middle East, and polar regions (maps in Figure 2). Under the SD scenario, point sources are expected to be dominant in areas with rapid population growth or increased connections to sewage systems, such as in Africa and the Middle East. For river exports of TDP, synthetic fertilizers will be dominant, especially for the coastal waters of Africa, South America, India, and North America in 2100. In these regions, there will be a substantial reduction in river export of TDP from sewage systems (e.g., around a 30% decrease in South America and India between 2010 and 2100). However, the use of synthetic fertilizers in Africa is expected to continue increasing between 2010 and 2100, even under the SD scenario. Sewage will be dominant in Europe by the end of the century and under SD, and weathering and leaching will also contribute to the river export of TDP to the coastal waters of regions draining into the Mediterranean Sea (maps in Figure 2). This pattern between 2010 and 2100 is influenced by the extensive agricultural areas and the relatively minimal impact of hydrology-driven climate change in these regions.

Dominant sources for the river export of MIP in 2100 include car tire wear in sewage systems for the coastal waters of North and South America, Oceania, and most of Europe and Asia (Figure 2). MIP from laundry is expected to be slightly more dominant than household dust in sewage systems in the coastal waters of Central Africa in 2100. While for many African and Indian coastal waters, the fragmentation of MPWs into MIP will be also relevant in the future.

3.2.2. Anthropogenic Pollution in the ED Scenario

In 2100, about 64%–67% of sub-basin areas globally will be dominated by anthropogenic diffuse sources contributing to river export of TDN and TDP. These sources include synthetic fertilizers (for TDN and TDP),

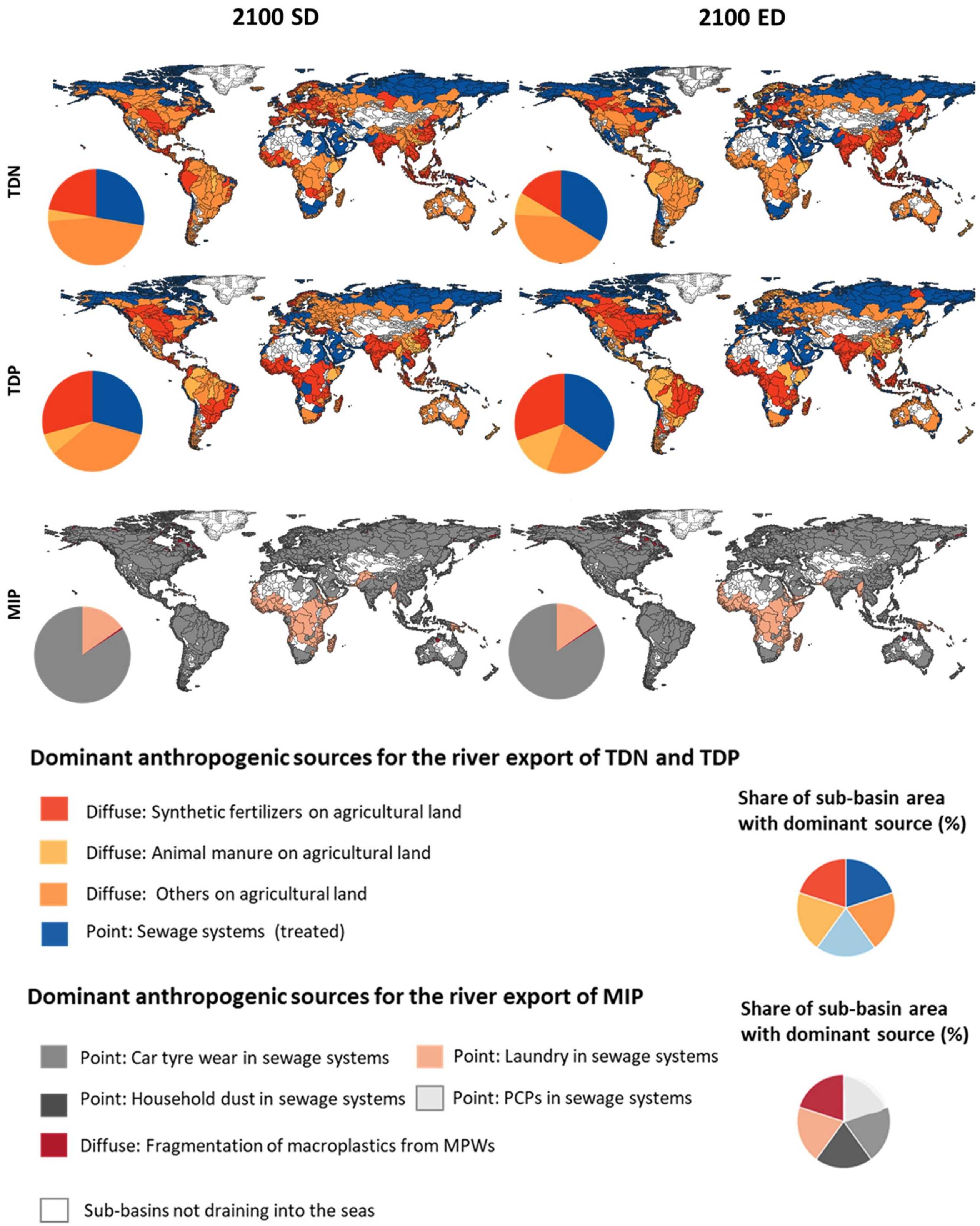

Figure 2. Dominant sources in anthropogenic-associated river exports of pollutants at the sub-basin scale in 2100 under the two scenarios SD and ED (%). Scenarios are "Sustainability-driven Future" (SD) and "Economy-driven Future" (ED). TDN and TDP are short for total dissolved nitrogen, and phosphorus, respectively. MIP and MPWs are short for microplastics and mismanaged plastic waste, respectively. All the sources described here are extensively presented in Section 2. Source: The MARINA-Multi model (see Section 2 for the model and scenario description).

atmospheric N deposition (for TDN), biological N_2 fixation (for TDN), leaching (for TDP), weathering (for TDP), and animal manure (for TDP, see pies in Figure 2). For the river export of MIP, 98% of sub-basin areas globally are dominated by sewage mainly from car tires (82%) and laundry fibers (16%). Secondary microplastics, originating from MPWs fragmentation, will only account for 2% of the total river export of MIP globally (pie charts in Figure 2).

There is a spatial variability in the share of diffuse and point sources in anthropogenic-associated river exports of TDN and TDP in 2100 (maps in Figure 2). For TDN, projected dominant sources are atmospheric N deposition and biological N_2 fixation in coastal waters of South–West America, Central America, Australia, and Central Africa, synthetic fertilizers in North America, Southeast America, East Africa, Eastern Europe, India, and Southeast Asia. This is because some of these areas may experience major improvements in wastewater treatment plants by 2100, whereas at the same time, there is a large increase in the inputs from diffuse sources. Sewage systems are projected as dominant sources of TDN in coastal waters of Central Europe, Eastern Asia, and Mediterranean Africa. For TDP, a similar regional pattern is found as synthetic fertilizers are dominant sources for East Africa, South America, India, and North America, weathering and leaching for Eastern Europe, and sewage systems for other regions. In these regions, limited improvements in sewage treatment may lead to a higher contribution to coastal water pollution from point sources. In the future, some areas are projected to be drier than in the past (e.g., Europe, Mediterranean Africa). At the same time, those areas are projected to have more inputs of nutrients from synthetic fertilizers in the future under ED. As the net-effect, less nutrients may enter rivers and be exported to coastal waters in the future due to decreases in runoff (Figure S7 in Supporting Information S1).

For river exports of MIP, our model projects car tire wear in sewage systems to be dominant sources for North and South America, Oceania, and Europe in 2100. Laundry fibers remain the primary contributor, but household dust is also a considerable source in Central Africa. Both contribute small amounts compared to major pollution sources in other parts of the world. For certain sub-basins in Africa and India MPW fragmentation is projected to be a relevant source of MIP, this is due to the lack of garbage collection under this scenario.

3.3. Multi-Pollutant Hotspots for Coastal Waters

We analyze future multi-pollutant hotspots for coastal waters. We use Class A (increasing trends for most pollutants), Class B (varied trends among pollutants), and Class C (decreasing trends for most pollutants) (Section 2.4). Increasing trends in river exports of most studied pollutants are projected for the coastal waters of the Indian Ocean in the future (Figure 3, Class A). This holds for both scenarios. For example, the SD scenario projects a 130% increase in the river export of MIP by 2100. This increase is 400% in the ED scenario (Figure 3). The river export of TDN, TDP, TCS, and DCL are projected to increase by 50%–150% in the ED scenario between 2010 and 2100, with MAP expected to slightly decrease under SD due to improved plastic waste management (Figure 3). These increasing trends are associated with pollution sources (Figure 4). In both scenarios, the share of natural sources contributing to river exports of TDN and TDP is expected to decrease by the end of the 21st century due to increased food production demands driven by population growth. As a result, anthropogenic diffuse sources, including synthetic fertilizers, are expected to make up 75% of TDN and 90% of TDP in the Indian Ocean's coastal waters by 2100. Increasing river exports of MIP by 2100 are associated with more MIP from car tires in sewage systems and the fragmentation of MAP from mismanaged municipal solid waste.

The drainage area contributing to more pollution in the coastal waters of the Indian Ocean covers many African and Asian sub-basins. Around 91%–94% of the population is projected to live in those polluted sub-basins in 2100 in both scenarios (Figure 5). This is associated with more sewage connections from rapid urbanization, leading to more waste in rivers. Although some improvements in wastewater treatment and solid waste management are anticipated in the SD scenario, more actions are still necessary to counterbalance the overall increasing pollution trend for the sub-basins that bring multiple pollutants into the coastal waters of the Indian Ocean.

Varying trends among pollutants are projected for the coastal waters of the Arctic and Atlantic Oceans (Figure 3, Class B). In the ED scenario, river exports of some pollutants are expected to increase to the coastal waters of the Atlantic and Arctic Oceans. Exceptions are MAP and TCS for the Arctic Ocean (by

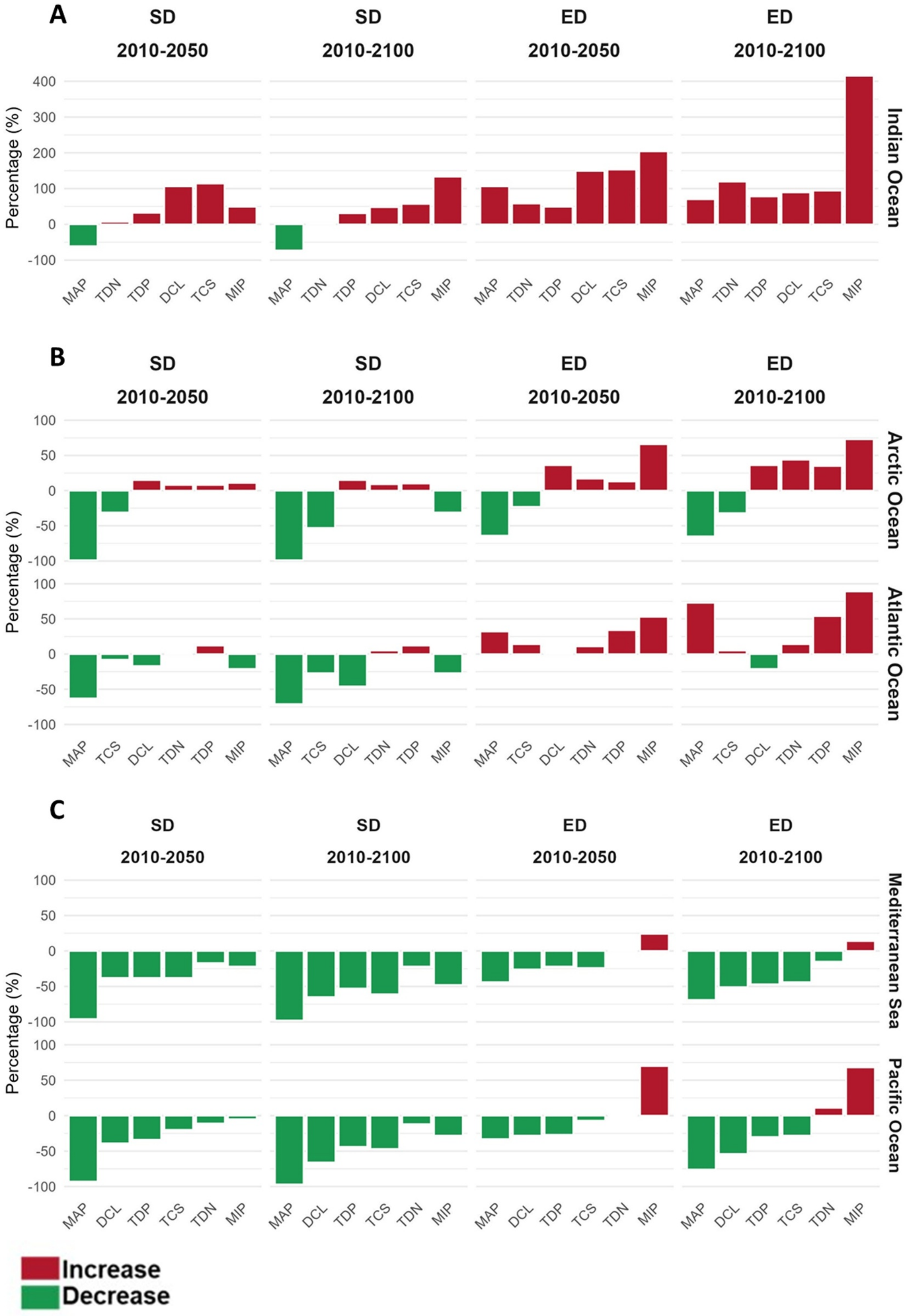

Figure 3. Changes in future river exports of pollutants to coastal waters of the oceans and seas under the two scenarios (% during the periods of 2010–2050 and 2010–2100). Scenarios are "Sustainability Future" (SD) and "Economy-driven Future" (ED). N and P are short for total dissolved nitrogen (TDN) and phosphorus (TDP), respectively. MIP and MAP are short for microplastics and macroplastics, respectively. TCS and DCL are short for triclosan and diclofenac, respectively. Trends in river exports of multiple pollutants are clustered by Class A (increasing trends for most pollutants), Class B (varied trends among pollutants) and Class C (decreasing trends for most pollutants). Source: The MARINA-Multi model (see Section 2 for the description of the model, scenarios, and classes).

2050 and 2100) and DCL for the Atlantic Ocean (by 2100). The SD scenario generally projects lower river exports of emerging contaminants and plastics to the Atlantic Ocean when compared to the ED scenario in the future, even though there is a slight increase for nutrients, which is still lower than for ED (Figure 3). However, the share of the sources differs among the oceans. For the coastal waters of the Arctic Ocean, over 80% of TDN and TDP will still originate from non-anthropogenic sources, despite the projected increase in synthetic fertilizers and animal manure on the land during the period of 2010–2100. In contrast, for the coastal waters of the Atlantic Ocean, over 50% of TDN and TDP will result from anthropogenic sources in 2100. For MIP in the coastal waters of the both oceans, car tires are projected to be important sources in the SD scenario, while car tires and sewage-associated to laundry fibers in the ED scenario (Figure 4).

The drainage area of these Arctic and Atlantic oceans occupies the sub-basins located in North America or Europe. Many of these sub-basins will become more polluted. As a result, 55% of the population in the drainage areas of the Atlantic Ocean will live in areas experiencing major increases (>30%) in river exports of at least one pollutant during 2010–2100 in the SD scenario. This is 90% in the ED scenario. In the ED scenario, 80% of the population in the Arctic Ocean's drainage area is expected to reside in the most polluted regions, a considerably higher proportion compared to the SD scenario (only 2%).

Decreasing trends in river exports of most studied pollutants are projected for the coastal waters of the Mediterranean Sea and Pacific Ocean (Figure 3, Class C). In the SD and ED scenarios, river export of MAP is projected to decrease from 70% (ED) to 80% (SD), and river export of TDP is projected to decrease from 20% (ED) to 50% (SD) during the period of 2010–2100. Exceptions are increasing trends for river exports of TDN (10%) and MIP (80%). Important sources of nutrients in those coastal waters of the Pacific Ocean are related to food production: for example, 45%–55% of TDN in the SD and ED scenarios (considerable amount from manure, Figure 4). For the coastal waters of the Mediterranean Sea, the SD scenario projects that sewage and synthetic fertilizers are responsible for 15%–20% of TDN and 25% of TDP in 2100. In contrast, in the ED scenario, sewage systems are expected to contribute 47% of TDP in the Mediterranean Sea. For river exports of MIP, car tire wear in sewage will be an important source in the future (Figure 4). As a result of these trends, 12% (SD) and 55% (ED) of the population are expected to inhabit more polluted sub-basins (>30% increase for at least one pollutant) draining into the Mediterranean Sea. Similarly, 42% (SD) and 89% (ED) are projected to live in more polluted sub-basins in the future, draining into the Pacific Ocean (Figure 5).

4. Discussion

4.1. Model Evaluation and Uncertainties

The core novelty of our study lies in developing future scenarios for multiple pollutants. These scenarios represent a step forward in large-scale water quality assessment. While existing studies typically model single pollutants using SSPs and RCPs, and the WWQA (World Water Quality Alliance) has attempted pollutant-specific scenarios using individual models (World Water Quality Alliance, 2021), our approach uniquely interprets SSPs and RCPs for multiple pollutants simultaneously. We developed two scenarios focused on environmental actions, highlighting the similar socio-economic trends but differing environmental attitudes. This simultaneous multi-pollutant scenario approach is a major effort in understanding and projecting future water quality trends.

Our process-based MARINA-Multi model was developed by integrating the existing modeling approaches for nutrients, plastics, and emerging chemicals. In total, there are more than 10 versions of the MARINA models. Their development started around 10 years ago. All those models were evaluated for different regions, lakes and years using the "building trust" approach. This approach considers several options to build trust in large-scale water quality models for which observations are limited or scarce. These options include comparing model results with empirical observations, comparing model trends with other empirical studies, sensitivity analysis, comparing model inputs with independent data sets, using expert knowledge, and comparing results with other modeling studies (M. Strokal et al., 2016). Examples of model evaluations using the building trust approach include the MARINA models for nutrients in Chinese rivers (Li et al., 2023; M. Strokal et al., 2016), nutrients for Europe (Ural-Janssen et al., 2024), plastics in rivers draining into the Black Sea (V. Strokal, Kurovska, & Strokal, 2023; M. Strokal, Strokal, & Kroeze 2023; M. Strokal, Vriend, et al., 2023),

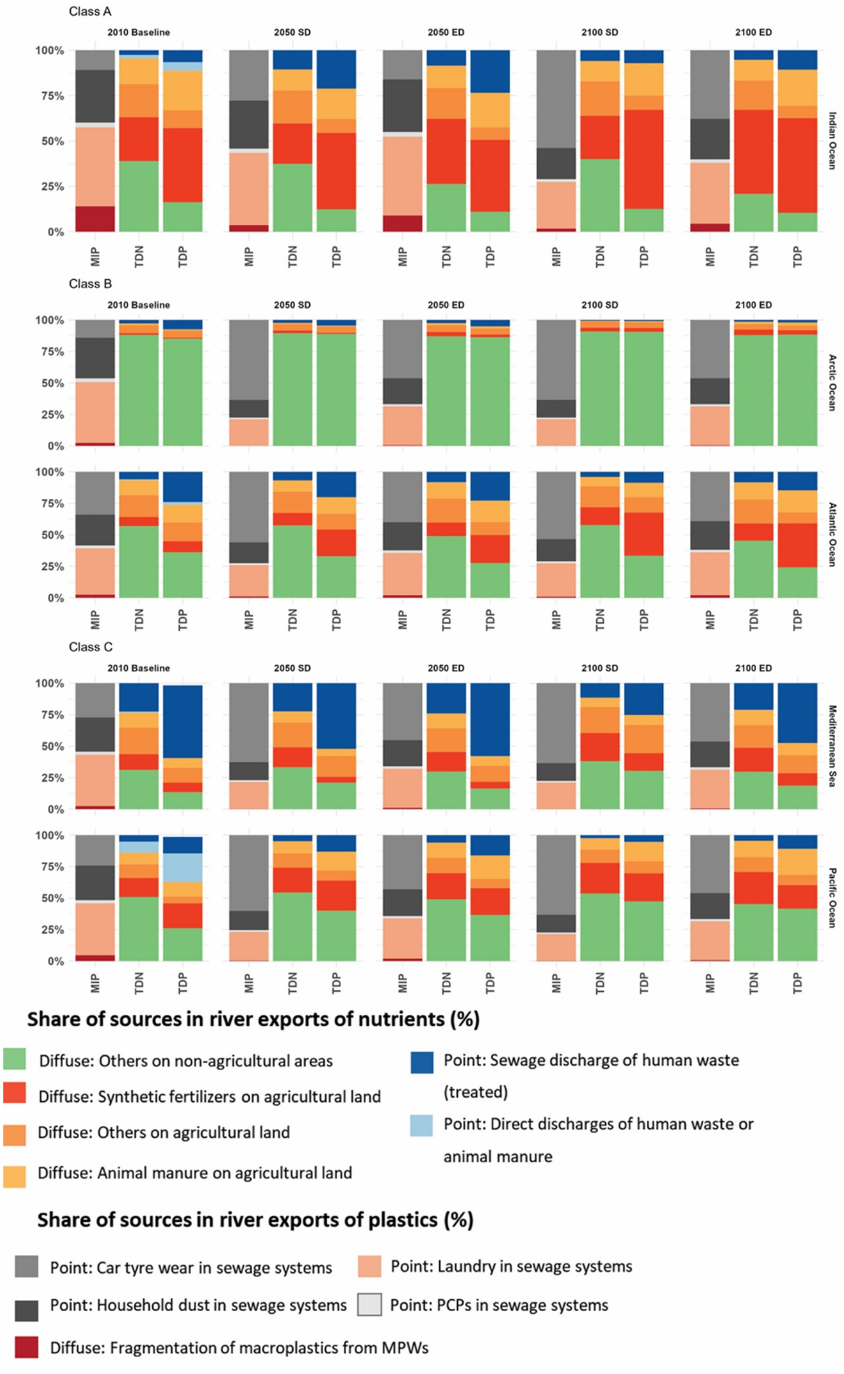

Figure 4. The relative share of sources in river exports of pollutants to coastal waters by sea in 2010, 2050, and 2100 under two scenarios: "Sustainability Future" (SD) and "Economy-driven Future" (ED). The shares are classified in Class A–C. The share of sources for microplastics (MIP, %), total dissolved nitrogen (TDN, %); total dissolved phosphorus (TDP, %). TDN is the sum of dissolved inorganic (DIN) and organic (DON) nitrogen. TDP is the sum of dissolved inorganic (DIP) and organic (DOP) phosphorus. TCS (triclosan), DCL (diclofenac) and MAP (macroplastics) are not in the figure as we only account for one source for them in the model. All the sources described here, and Classes A–C are described in Section 2. Source: The MARINA-Multi model (see Section 2 for the model description).

and plastics and other contaminants in rivers globally (V. Strokal, Kurovska, & Strokal, 2023; M. Strokal, Strokal, & Kroeze 2023; M. Strokal, Vriend, et al., 2023; M. Strokal et al., 2021). We built trust in our global MARINA-Multi model for nutrients, plastics, and emerging contaminants for the year 2010 in Micella, Kroeze, Bak, and Strokal (2024).

In this study, we build on the previously evaluated MARINA modeling approaches. We further evaluated our model outputs against observations for nutrients and plastics (see details in Supporting Information S1). We also compared our model results with other studies (this section) and performed a sensitivity analysis (Section 4.2).

For model validation, the GEMStat database provided around 2000 observations for TDN, DIN, DON and TDP, DIP for the years 2000–2020 worldwide (UNEP, 2018) (Figures S8 and S9 in Supporting Information S1). Other existing studies provided the available observations for MIP (Figure S10 in Supporting Information S1). We converted the observations into loads (e.g., kg/year). Then, we compared our modeled loads at the river mouth with the observed loads for which we obtained measurements. We calculated the coefficient of determination (R^2) to present our validation results. R^2 values range from 0.73 to 0.76 for river exports of DIN, DON, and TDN. We also calculated the Nash Sutcliffe efficiency (NSE). NSE values range from 0.61 to 0.63 for river exports of DIN, DON, and TDN. In addition, we calculated the ratio of root mean square error (RMSE) and standard deviation of measured data (RSR), with values ranging from 0.33 to 0.38 for DIN, DON, and TDN. For P, observations were available for DIP and TDP. We calculated the same statistical indicators as for N. Results indicate that R^2 values range from 0.57 to 0.61, NSE values range from 0.45 to 0.53, and RSR values range from 0.43 to 0.56 for river exports of DIP and TDP. We calculated R^2 for river exports of MIP using available observations. R^2 equals to 0.94 (Figures S8–S10 in Supporting Information S1). Thus, our validation results generally indicate an acceptable model performance based on the interpretation of the statistical indicators following Moriasi (2015).

However, the number of observations is rather limited especially for MIP and some nutrient forms. Most observations, used in our model evaluation, were available from well-monitored areas located in Europe and North America. Observations are particularly limited for regions like Africa. As shown in Figure S8 of the Supporting Information S1, the majority of observations (72%) are for North America, with considerably fewer observations for regions like Africa (2%) and South America (2%). This imbalance indicates a data scarcity in certain regions, which may challenge the model's evaluation. E. R. Jones et al. (2024) reported similar findings also for other types of pollution, showing that 71% of available water quality observations come from monitoring stations in North America and Western Europe, revealing significant data gaps in other regions. Their analysis indicates that only 0.05% of global surface water quality observations are from North Africa and the Middle East, with an even lower share in sub-Saharan Africa, where vast areas lack any observations. This shortage of data presents a major challenge for large-scale water quality modeling, highlighting the urgent need for expanded monitoring efforts globally.

Other options to build trust in the large-scale model are needed and should be considered together with validation to determine the model plausibility. We further built trust in our model by comparing our estimates with other existing modeling studies. Our global river exports of TDN and TDP were compared with the Global NEWS (Nutrient Export from WaterSheds, Mayorga et al., 2010; Seitzinger et al., 2010) and IMAGE-GNM models (Beusen et al., 2015, 2022). Our results are 35% higher than in Global NEWS and 10% lower than in IMAGE-GNM. This discrepancy between us and others is in time and space. We focus on 2010 with the sub-basin scale modeling approach, while Global NEWS focused on 2000 with the basin-scale modeling approach. Our lower results compared to IMAGE-GNM are due to our focus on dissolved nutrients, whereas IMAGE-GNM considered total nutrients (Table S15 in Supporting Information S1). In addition, IMAGE-GNM considered legacy effects whereas our model is a steady-state model. Regarding point sources, our river exports of TDN and TDP are generally aligned with other modeling studies (Van Puijenbroek et al., 2019). To cover data-scarce regions such as Africa, we compared model results with the model results of IMAGE-GNM (Beusen et al., 2022) and SWAT+ (Nkwasa et al., 2024) for four large African rivers (see Table S21 in Supporting Information S1). Our results are generally lower than the results from those two models because of our focus on dissolved N and P. Our future trends for the world are also comparable with IMAGE-GNM (Beusen et al., 2022): for example, our decreasing trends under SD and increasing trends under ED are in line with SSP1-RCP2.6 and SSP5-RCP8.5 in IMAGE-GNM (Beusen et al., 2022). Like IMAGE-GNM, our model projects higher contributions of agriculture and sewage systems in nutrient pollution, especially for the Indian Ocean in 2050.

We compared river exports of emerging chemicals (TCS and DCL) with other modeling studies. Our river exports of TCS for selected sub-basins (e.g., Danube, Ganges) are generally lower than in other studies for 2010 (Table S16 in Supporting Information S1) (M. Strokal et al., 2021; van Wijnen et al., 2018). This result might be associated with the fact that the model of van Wijnen et al. (2018) was based on the basin-scale approach, which is different from our sub-basin-scale approach which considers more retention in the river system. Our hotspots for

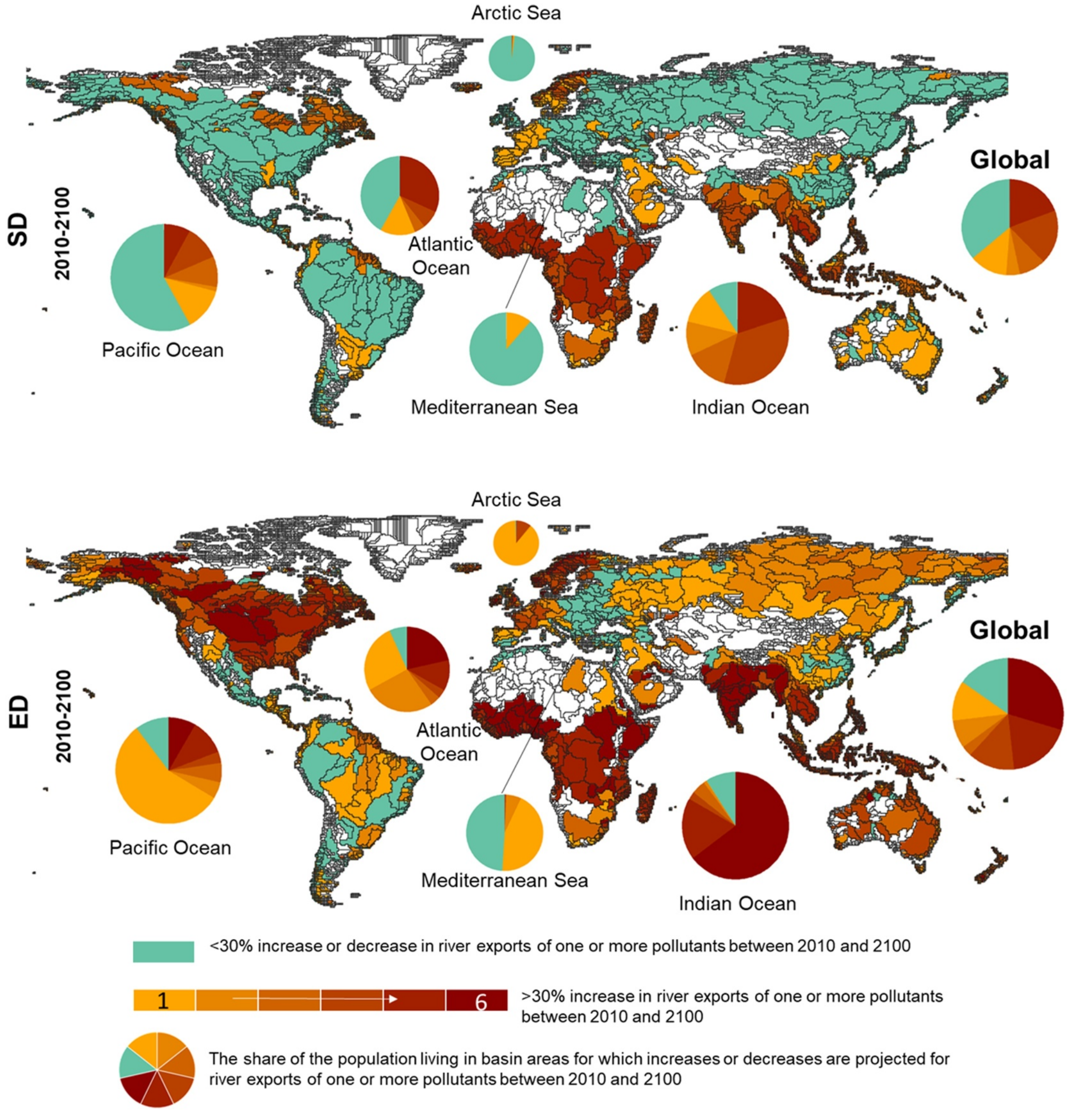

Figure 5. Changes in river exports of multiple pollutants to the coastal waters of five seas during the period 2010–2100 according to two scenarios (%). Scenarios are "Sustainability-driven Future" (SD) and "Economy-driven Future" (ED). We classify the sub-basins based on the number of pollutants for which the increases are higher than 30%. If it is lower, or there is a decrease, the given number is 0. The pollutant includes TDN (total dissolved nitrogen), TDP (total dissolved phosphorous), MIP (microplastics), MAP (macroplastics), TCS (triclosan), and DCL (diclofenac). The description of the two scenarios is in Section 2 and Supporting Information S1. Source: The MARINA-Multi model (see Section 2 for the model and scenario description).

river exports of DCL in 2010 align reasonably well with hotspots from existing studies (Acuna et al., 2020; Font et al., 2019), but global river export is generally lower than in the model of Font et al. (2019). This result could be linked to differences in the scales and modeling approaches.

We also made comparisons with other modeling studies for MIP and MAP. Our river exports of MIP are generally comparable with studies for European rivers (Siegfried et al., 2017; van der Wal et al., 2015) (Table S18 in Supporting Information S1). Our river exports of MAP fall within a similar range as shown in studies like Mai et al. (2020, 2023), Nakayama and Osako (2023), Schmidt et al. (2017), Y. Zhang et al. (2023), Meijer et al. (2021), and Lebreton and Andrady (2019). However, our MAP exports by rivers were lower when compared to Geyer et al. (2017), Borrelle et al. (2020), Lau et al. (2020), and Law et al. (2020). The same holds for our future trends. This result is due to the differences in the years that were considered in our study and other existing studies (Table S17 in Supporting Information S1). Discrepancies observed in these comparisons are coherent with recent findings by González-Fernández et al. (2023) and Weiss et al. (2021) indicating variations up to five orders of magnitudes in plastic inputs to the ocean from rivers. For example, model structure differences, as indicated by Roebroek et al. (2022), can lead to substantial differences in results.

Our projected results have limitations and uncertainties. Structural uncertainties may result from the simplifications in our modeling approach. This includes the steady-state approach, which assumes constant conditions and overlooks the accumulation and slow release of pollutants like P and MIP from soils into rivers. Unlike N, those pollutants bind strongly and are gradually released over time (Haygarth et al., 2005; Qi et al., 2020; Wall et al., 2011). Additionally, there is a need to better understand how to include biogeochemical interactions explicitly in the modeling approaches. Our biogeochemical interactions between pollutants are limited and simplified, but not entirely excluded. For example, for wastewater treatment, we implicitly include interactions between pollutants by accounting for removal efficiencies of pollutants during primary, secondary, tertiary, and quaternary treatments. In other words, secondary treatment is less effective for nutrient and chemical reduction (synergetic effect of secondary treatment between the two pollution types) but can be more effective for microplastic reduction (antagonistic effect of the secondary treatment between nutrient/chemical and macroplastic pollution types). Such interactions are complex, differ in space and time, and can be influenced by external factors like climate change and temperature increases (Gervasio et al., 2022). Our model lacks consideration of interannual variability and seasonality, making it important for future work to incorporate these fluctuations for more accurate long-term projections of pollutant dynamics (van Vliet et al., 2023).

Uncertainties may also result from model inputs. For instance, our model uses inputs from other models such as VIC for hydrology (van Vliet et al., 2016) and IMAGE for land use and agriculture. Those two models also have uncertainties. In our model, we use 30-year averages for hydrology. On one hand, it leads to a large simplification because we lump the temporal variability. On the other hand, we avoid the influence of extremes on our annual pollutant releases. These 30-year averages have been widely accepted and applied for large-scale water quality assessments (V. Strokal, Kurovska, & Strokal, 2023; M. Strokal, Strokal, & Kroeze 2023; M. Strokal, Vriend, et al., 2023; Ural-Janssen et al., 2024; H.-M. Wang et al., 2020; M. Wang et al., 2020; M. Wang et al., 2024). In future work, we propose to explore methods to incorporate variability in runoff and discharge to improve the accuracy of nutrient load estimations under different climate change scenarios. Our model is also uncalibrated, which has advantages and disadvantages. Disadvantages are related to the fact that our model is not calibrated to a certain period in the past. Advantages are related to the fact that we can use our model for future analysis because our model inputs and parameters describe processes and basin characteristics that can change over time and do not rely heavily on observations that are only for specific times in the past. This makes our model flexible in its application to other regions that do not have enough observations (Krysanova et al., 2018; La Follette et al., 2021).

There are uncertainties in our future projections due to future socio-economic developments and climate changes. By definition, a future is uncertain. We can explore a variety of possible futures to answer research questions on what may happen with coastal water pollution in the future if certain socio-economic developments and climate changes are assumed. In our study, we develop two multi-pollutant scenarios to answer similar research questions. We look at two scenarios with proactive and reactive environmental management for multiple pollutants. In this way, we explore two different attitudes toward water pollution. Within our scenarios, we made assumptions regarding the future excretion and consumption of multiple pollutants based on the storylines of the SSP1 (for SD) and SSP5 (for ED), supported by existing literature (Beusen et al., 2022; Bodirsky et al., 2014). Some of our assumptions are more uncertain than others. For instance, we did not account for potential changes in regulations governing the use of pharmaceuticals or emerging contaminants, as these are contingent upon evolving policy regulations and the emergence of substitute drugs. Similarly, we did not explicitly account for the possibility of rapid technological advancements in the future. We only considered the advances that are available today in literature. More technological opportunities may arise in the future. We also did not account for the effects of poverty and conflicts on agricultural practices and water quality management. Some first steps in this direction have been recently done for specific regions (V. Strokal, Kurovska, & Strokal, 2023; M. Strokal, Strokal, & Kroeze 2023; M. Strokal, Vriend, et al., 2023). We do not explicitly include policy measures such as the Green Deal or the newly adopted Nature Restoration Law. Incorporating these measures is particularly challenging due to data limitations and the global scale of our model. However, we acknowledge their importance and the need to consider them in future work. It is important to mention that our study may also be influenced by the amplification of uncertainties due to the modeling chain. In large-scale water quality modeling, as we listed above, uncertainties arise for example, from inputs, from downscaling processes, and from assumptions in our scenarios. This amplification of uncertainties, where single uncertainties accumulate and interact, is well-studied in fields like hydrology and disaster science (H.-M. Wang et al., 2020; M. Wang et al., 2020). It poses a significant challenge for global multi-pollutant models like ours. To minimize the amplification of uncertainties, further research is needed.

Comparisons with other modeling studies offer valuable insights and help build confidence, but they cannot eliminate uncertainties, especially in data-scarce regions like sub-Saharan Africa. The fact that many studies consistently model these regions as pollution hotspots presents an opportunity (E. R. Jones et al., 2023; Nkwasa et al., 2024). This alignment across models could motivate policymakers to prioritize the development of monitoring networks in these areas. By implementing such networks, we can validate model projections, improve water quality data, and support more decision-making for the future.

Our multi-pollutant approach is strong in the way of modeling the sources of multiple pollutants and their trends over time simultaneously. Our multi-pollutant model is transparent and offers an opportunity to add more pollutants to identify the common sources and multi-pollutant hotspots. Our scenario results should be interpreted as trends and patterns to explore possible futures. Despite the uncertainties, scenarios are valuable tools for understanding potential pollution patterns in coastal waters across potential future changes. This is highlighted by collaborative efforts within the global water quality community such as the UN World Water Quality Alliance and ISIMIP. Scenarios help harmonize and compare large-scale water quality models to identify robust pollution hotspots and better understand uncertainties in future projections.

4.2. Sensitivity Analysis

To address the model uncertainties, we conducted a sensitivity analysis. We ran MARINA-Multi two times to evaluate the sensitivity of the model outputs to changes in socio-economic aspects. In these two runs, we changed socio-economic features to the level of 2050 and 2100 from the SD (sensitivity run 1) and ED (sensitivity run 2) scenarios and kept hydrology at the level of 2010 (Table S19 in Supporting Information S1). We compared the results of these runs to the original baseline (the year 2010) (Figures S11 and S12 in Supporting Information S1). Our sensitivity results confirm the importance of socio-economic aspects in river exports of multiple pollutants. In sensitivity run 1 (SD socio-economy), river exports of all pollutants are lower than in the baseline ranging from a decrease of 5% (TDN) to 83% (MAP) globally. These decreasing trends are comparable with the SD scenario that we presented in Section 3 (e.g., Figure 3). In sensitivity run 2 (ED socio-economy), river exports of emerging contaminants (TCS and DCL) are lower (5%–20%) while river exports of nutrients (TDN and TDP) and plastics (MAP and MIP) are higher (6% TDP–120% MIP) than in the baseline. These trends are generally comparable with trends in Figure 3.

We ran the MARINA-Multi model two times to evaluate the sensitivity of model outputs to changes in hydrology due to climate changes. In those two runs, we changed hydrology reflecting RCP2.6 (sensitivity run 3) and RCP8.5 (sensitivity run 4) and kept socio-economic aspects at the level of 2010 (Table S19 in Supporting Information S1). We compared the results with the original baseline of the year 2010. The difference aims to show the effects of changes in hydrology due to climate change on river exports of pollutants. The results vary among sub-basins and pollutants. In sensitivity run 3 (RCP2.6, low global warming), global river exports of pollutants increased between 1% (for MIP) and 6% (for TDP) relative to the baseline. In sensitivity run 4 (RCP8.5, high global warming), river exports of pollutants increased from 8% (for TDN) to 12% (for TDP) relative to the baseline year. In general, the sensitivity of model outputs is higher when we consider hydrology under RCP8.5 (run 4) compared to RCP2.6 (run 3). This indicates the influence of hydrology on river exports of pollutants. Furthermore, the sensitivity of nutrient exports by rivers is relatively higher than that of other pollutants (Tables S19 and S20 in Supporting Information S1). In general, our results show that hydrology impacted by future climate change may increase nutrient inputs into seas due to reduced nutrient retention on land and in rivers, particularly in "high climate change" scenarios (RCP8.5). Future studies could build on these insights and explore interactions in pollution control for multiple pollutants (van Vliet et al., 2023).

4.3. Future Research and Implications for Pollution Control

We developed two scenarios representing two different attitudes toward multi-pollutant problems. We focused on nutrients (TDN and TDP), plastics (MIP and MAP), and emerging contaminants (TCS and DCL) for the period of 2010–2100. Our scenarios and modeling tool can be used for further research to explore interactions in pollution control options for multiple pollutants in coastal waters. Our study also provides valuable research insights on increasing (Class A), decreasing (Class C), and varying (Class B) trends in multi-pollutant problems for coastal waters in the world. We identified sub-basins in which rivers are expected to export more (Class A), and less (Class C) pollutants in the future. For example, many rivers draining into the coastal water of the Indian Ocean are expected to export much more pollutants in the future (Class A). This is different for some rivers draining into the coastal waters of the Mediterranean Sea and Pacific Ocean that may export less pollutants (Class C). In contrast, the coastal waters of the Atlantic and Arctic Oceans may receive more or less pollution from rivers depending on scenario and pollutant (e.g., Figure 3, Class B). These valuable insights could help identify a range of mitigation and adaptation measures tailored to the sub-basins and their rivers. Consequently, this would contribute to achieving SDG 14. To support this, we believe that pollution control strategies are needed in food production and urban activities to mitigate simultaneously future multi-pollutant issues.

For sustainable food production, transitioning toward practices that reduce reliance on synthetic fertilizers (Wei et al., 2021), and increase the recycling of animal manure based on crop needs is important (Si et al., 2019). For example, farmers may require targeted guidance through the adoption of smart agricultural tools, such as precision agriculture systems facilitated by agricultural information management (Navarro et al., 2020). Another notable example is the Science Technology Backyard (STB), widely implemented in China, which fosters collaboration between scientists and farmers to enhance crop yields with minimal environmental impact (W. Zhang et al., 2022). These measures not only promote sustainable agriculture but also resilience against the impacts of climate change. These food production strategies are especially needed to reduce increasing multi-pollutant problems in sub-basins draining into the coastal waters of the Indian Ocean. Many of these sub-basins are in African and Asian continents where food demand and production are high. Addressing food security challenges in those sub-basins is well aligned with poverty alleviation and equality objectives (SDGs 2, 6, 11, 12, and 13) (Alcamo, 2019; Van Puijenbroek et al., 2019).

For urbanization activities, making sanitation sustainable with advanced treatment is important. Our results show that increasing point-source pollution levels are projected for sub-basins, for example, in India and Africa (Class A) that gain more sewage connections with poor treatment. Therefore, transitioning from conventional wastewater treatment methods to facilities adopting multi-pollutant approaches is crucial (Z. Zhang & Chen, 2020). Advanced technologies are needed to reduce not only nutrients in wastewater but also plastics and pharmaceuticals. This is relevant for sub-basins in Africa and Asia (Class A) as well as for European and North American sub-basins (Class B and C). This can be facilitated through policy incentives to avoid mismanaged solid waste with better collection strategies and behavioral changes to reduce the consumption of plastic products and avoid (Vuori & Ollikainen, 2022). In some sub-basins belonging to Class B (e.g., located in Europe), wastewater treatment plants are already established or upgraded with advanced technologies. However, further investment is necessary to implement UV and ozone-based advanced oxidation techniques (AOP) for enhanced removal of micropollutants such as microplastics and pharmaceuticals (Adeel et al., 2024). For sub-basins that belong to Class C (e.g., located in North America and Europe), urban stormwater management has effectively reduced river pollution compared to the past. However, a comprehensive approach is needed to further decrease coastal water pollution, involving technological investments, regulatory measures, and collaborative efforts. These measures are crucial for mitigating pollution levels, particularly in regions where pollution is expected to remain high despite decreasing trends (Class C), such as coastal waters of the Mediterranean Sea and Pacific Ocean.

5. Conclusions

We developed the MARINA-Multi model and for two multi-pollutant scenarios: a “Sustainability Future” (SD) and an “Economy-driven Future” (ED). They offer valuable tools for estimating future river exports to coastal waters from sub-basins worldwide taking the period of 2010–2100. In the ED scenario, river exports of microplastics are projected to double globally by 2100. In contrast, the SD scenario projected a decrease of up to 83% for all pollutants by 2100. Increasing trends in river exports of nutrients are largely associated with increased contributions of anthropogenic diffuse sources such as the use of synthetic fertilizers as assumed in our scenarios. Increasing trends in river exports of microplastics are associated with more microplastics from car tire wear in sewage systems (point sources) as assumed in our scenarios.

Our scenario results highlight alarming pollution levels for coastal waters of the Indian Ocean in the future. Our ED scenario projects an increase of up to 400% in river exports of pollutants by 2100 due to population growth, urbanization, and inadequate waste management in many African and Asian basins. In contrast, our SD scenario projects that the coastal waters of the Mediterranean Sea and the Pacific Ocean are expected to receive less pollutants in 2100 than in 2010 because of better wastewater treatment and waste management. For the coastal waters of the Atlantic Ocean, Arctic Ocean, and Baltic seas, future trends depend on sub-basin, pollutant, and scenario. Globally, from 56% to 78% of people are projected to live in more polluted river basins (ED and SD scenarios), posing a challenge to achieving Sustainable Development Goal 14 for clean marine waters.

Data Availability Statement

Gridded data of global population count are available in B. Jones and O'Neill (2016). Sanitation and wastewater treatment data is available in van Puijenbroek et al. (2023). Nitrogen and phosphorous inputs to the land from diffuse sources are available in Beusen et al. (2022). Natural river discharges are available in van Vliet et al. (2016). Global monthly sectoral water uses for 2010–2100 at 0.5° resolution across alternative futures are presented in Khan et al. (2023). Global monthly sectoral water uses data can be obtained from: Khan et al. (2022). The model used in this article is also available in Micella, Kroeze, Bak, and Strokal (2024) and Micella, Kroeze, Bak, Tang, et al. (2024). A list of all sources of model input data and the data supporting this study's findings are publicly available in the DANS-EASY repository Micella, Kroeze, Bak, Tang, et al. (2024).

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