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Global river nutrient export: A scenario analysis of past and future trends

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[1] An integrated modeling approach was used to connect socioeconomic factors and nutrient management to river export of nitrogen, phosphorus, silica and carbon based on an updated Global NEWS model. Past trends (1970–2000) and four future scenarios were analyzed. Differences among the scenarios for nutrient management in agriculture were a key factor affecting the magnitude and direction of change of future DIN river export. In contrast, connectivity and level of sewage treatment and P detergent use were more important for differences in DIP river export. Global particulate nutrient export was calculated to decrease for all scenarios, in part due to increases in dams for hydropower. Small changes in dissolved silica and dissolved organics were calculated for all scenarios at the global scale. Population changes were an important underlying factor for river export of all nutrients in all scenarios. Substantial regional differences were calculated for all nutrient elements and forms. South Asia alone accounted for over half of the global increase in DIN and DIP river export between 1970 and 2000 and in the subsequent 30 years under the Global Orchestration scenario (globally connected with reactive approach to environmental problems); DIN river export decreased in the Adapting Mosaic (globally connected with proactive approach) scenario by 2030, although DIP continued to increase. Risks for coastal eutrophication will likely continue to increase in many world regions for the foreseeable future due to both increases in magnitude and changes in nutrient ratios in river export.

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1. Introduction

[2] The production of food and energy to support the increasing human population have markedly altered biogeochemical cycles of nitrogen (N), phosphorus (P), carbon (C) and silica. The rate at which biologically available nitrogen enters the terrestrial biosphere has more than doubled in the past 5 decades through activities such as fertilizer production and use, fossil fuel combustion, and cultivation of leguminous crops [*Galloway et al.*, 2004]. P inputs to the environment over natural, background P from weathering have more than doubled from mining and use of rock phosphate as fertilizer, detergent additives, animal feed supplement and other technical uses [*Bennett et al.*, 2001; *Mackenzie et al.*, 1998; *United States Geological Survey*, 2008]. Much of this N and P is recycled through the terrestrial biosphere after consumption by animals and humans.

[3] These changes in global nutrient cycles have had both positive and negative effects. The increased use of N and P fertilizers has allowed food production to keep pace with rapid human population growth [*Galloway and Cowling*, 2002]. However, significant fractions of anthropogenically

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mobilized N and P in watersheds enter groundwater and surface water and are transported by rivers to coastal marine systems. At the same time there are many observations of decreasing river export of silicon dioxide (SiO_2) [*Conley*, 2002]. Decreased dissolved silica export may be related to numerous factors including increased growth and burial of diatomaceous algae associated with N and P enrichment and longer water residence times in reservoirs behind dams. Changes in the amount, form (dissolved inorganic, organic, particulate), and ratios in nutrient inputs to coastal ecosystems contribute to numerous negative human health and environmental impacts, such as loss of habitat and biodiversity, increase in blooms of certain species of harmful algae, eutrophication, hypoxia and fish kills [*Billen and Garnier*, 2007; *Diaz and Rosenberg*, 2008; *Howarth et al.*, 1996; *Rabalais*, 2002; *Turner et al.*, 2003].

[4] There have been considerable gains in knowledge of amounts and sources of N and P entering the terrestrial biosphere, and biogeophysical factors that control the amount of N and P ultimately exported by rivers to coastal ecosystems. Considerably less work has addressed how various socioeconomic factors and approaches to nutrient management affect N and P inputs to the terrestrial biosphere and subsequent impacts on river nutrient export. For example, population, income, per capita food consumption (e.g., amount of food, animal protein intake), agricultural practices (fertilizer application rates, nutrient use efficiency, amount and type of crop produced), sewage treatment, climate and hydrology (e.g., irrigation, reservoirs) have not generally been addressed, in particular at the global scale or with an integrated approach. Neither have effects of these factors in controlling river export of multiple elements (N, P, C and Si) and the different forms of these elements (dissolved inorganic, dissolved organic, particulate) been addressed [*Seitzinger et al.*, 2005]. Several of these factors have been studied alone or in combination earlier to address past or future changes in global river export [*Alcamo et al.*, 2006; *Boyer et al.*, 2006; *Galloway et al.*, 2004; *Kroeze and Seitzinger*, 1998; *Seitzinger and Kroeze*, 1998]. Here we seek to address how a suite of socioeconomic, nutrient management and biogeophysical factors are related and how in combination they affect river export of multiple nutrients globally.

[5] An integrated modeling approach connecting socioeconomic, nutrient management and biogeophysical factors to river export of nitrogen, phosphorus, silica and carbon was undertaken using an updated version of the Global Nutrient Export from Watersheds (NEWS) model [*Mayorga et al.*, 2010]. Past (1970–2000), and future trends (2000–2030–2050) in river export of nutrients from watersheds globally based on four Millennium Ecosystem Assessment (MEA) scenarios, were analyzed. Other papers in this special section present details of development of the nutrient inputs to watersheds from agricultural [*Bouwman et al.*, 2010] and urban wastewater [*Van Drecht et al.*, 2009] sources, climate and hydrological alterations [*Fekete et al.*, 2010] for the past and future trends, and detailed patterns in river nutrient export among watersheds within a continent [*Yasin et al.*, 2010; *Van der Struijk and Kroeze*, 2010; W. Ludwig et al., Past and future trends in flux of river nutrients to the Mediterranean and Black Seas, submitted to Global Biogeochemical Cycles, 2009], regional and downscaled global scenarios of future river export [*Thieu et al.*, 2010], application of the NEWS model at high resolution in specific river basins [*Yan et al.*, 2010; J. Harrison, Applying NEWS-DIP at a half-degree resolution using U.S. river basins as test sites: Challenges, insights, and possibilities, submitted to Global Biogeochemical Cycles, 2009], scenario consequences for autotrophy and heterotrophy in world watersheds [*Billen et al.*, 2010], and nutrient ratio changes over time and their implications for coastal ecosystem effects [*Garnier et al.*, 2010].

[6] This paper presents an overview of (1) past and future trends in river nutrient export at global, continental and regional scales, (2) effects of socioeconomic, agricultural nutrient management, and sewage treatment trends on nutrient export, and (3) implications of patterns in nutrient ratios over time for coastal ecosystems. The paper is structured as follows: First, an overview of assumptions for the MEA scenarios and development of input databases for the NEWS model are presented. Second, global drivers and trends in nutrient export by rivers for the period 1970–2000 and for the MEA scenarios are discussed. Third, continental-scale and regional-scale patterns of drivers and trends for river nutrient export are presented. Finally, implications of the scenarios for watershed heterotrophy/autotrophy and patterns in nutrient export ratios for coastal ecosystem effects are summarized. Discussion of MEA future scenario results primarily focuses on the period 2000–2030 due to space limitations. Other papers in this section cover 2050 results more extensively.

2. Data and Methods

[7] The global NEWS system includes river-basin-scale models for predicting export at river mouths to the coastal ocean of dissolved inorganic nitrogen and phosphorus (DIN, DIP), dissolved organic carbon, nitrogen and phosphorus (DOC, DON, DOP), total suspended solids (TSS), particulate organic carbon (POC), particulate nitrogen and phosphorus (PN and PP), and dissolved silica (DSi). These models are referred to as NEWS-DIN, NEWS-DON, NEWS-DIP, NEWS-DOP, NEWS-DOC, and NEWS-PNU (particulate nutrients). Natural and anthropogenic nutrient sources in watersheds, hydrological and physical factors, and in-river N and P removal are important model components. NEWS generally operates on inputs and forcings aggregated to the basin scale. However, most of these inputs are spatially distributed at resolutions finer than the mean basin area used in global applications [*Seitzinger et al.*, 2005] (Text S1 provides a list of input data sets (Table A-1)).[1] In addition, some factors, such as basin-wide reservoir retention, are calculated using highly specific within-basin information. There are numerous differences in the model parameters among the different nutrient forms, but as an example, the DIN model

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[1] Auxiliary materials are available with the HTML. doi:10.1029/2009GB003587.

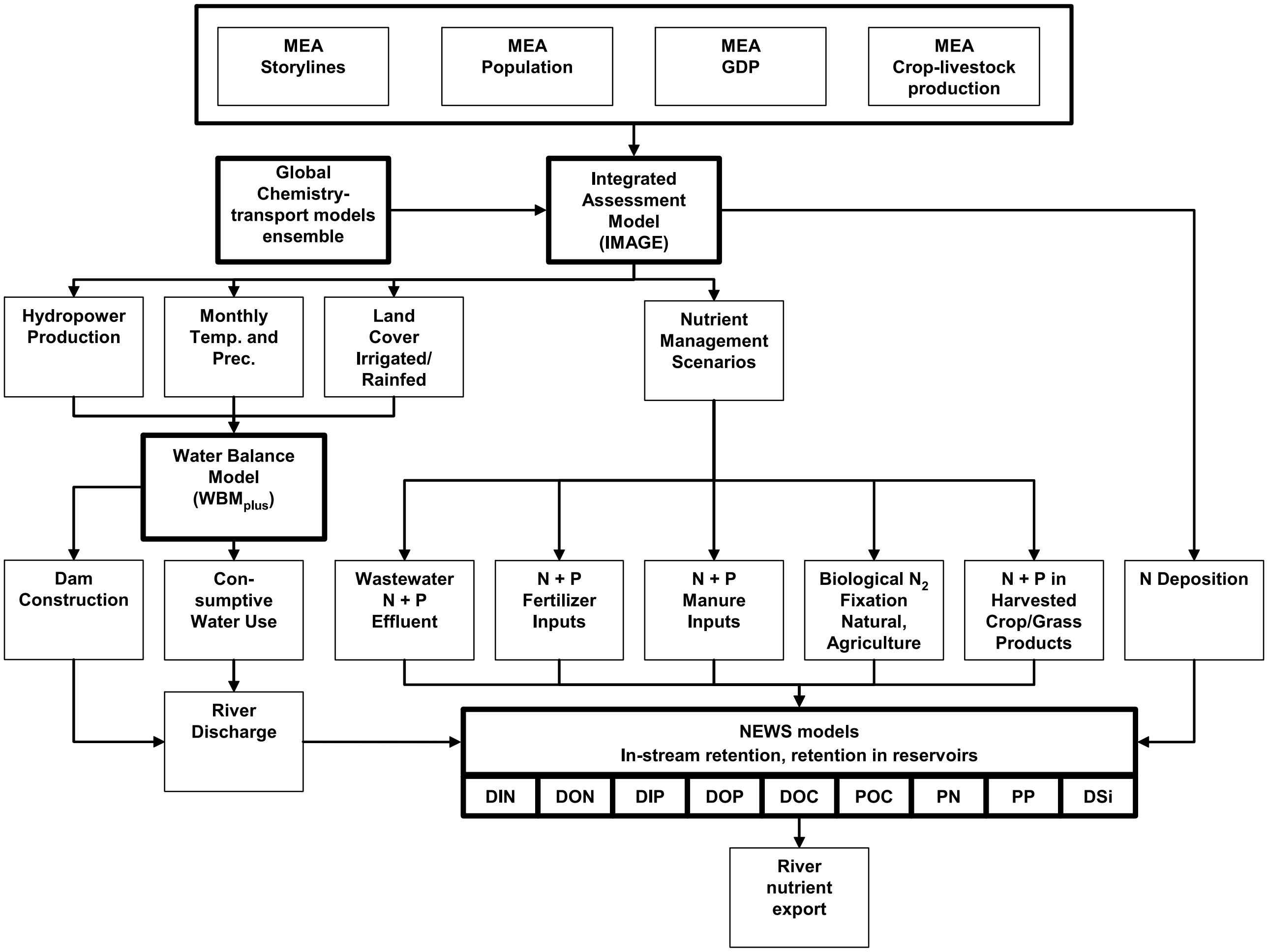


Figure 1. Scheme showing the input data and information flows into the NEWS model for the retrospective analysis 1970–2000 and assessment of scenarios for 2030 and 2050 based on the Millennium Ecosystem Assessment (MEA). See Text S1 (section A1) and *Mayorga et al.* [2010] for full list of spatially explicit data sets used in the NEWS model.

incorporates diffuse N inputs from fertilizers, manure, biological N_2 fixation, and atmospheric N deposition, as a function of specific crop types, land use, animal type, etc.; and point-source emissions of N into streams as a function of national and regional socioeconomic (e.g., per capita income) and sanitation information. N removal within the river includes denitrification in river channels and in dammed reservoirs as a function of water residence time, and through consumptive water use primarily for irrigation. Basins are defined using a consistent global river systems data set (*Vörösmarty et al.*, 2000). Global NEWS assumes that nutrient elements are in steady state and do not accumulate on land or in the river system; retained nutrients are lost or sequestered permanently. Details of the NEWS model are described elsewhere [*Beusen et al.*, 2005; *Dumont et al.*, 2005; *Harrison et al.*, 2005a, 2005b]. However, since these publications there have been a number of revisions as outlined in Text S1 (section A1) and in the work of *Mayorga et al.* [2010], and a model for simulating dissolved inorganic silica (NEWS-DSi) was developed [*Beusen et al.*, 2009]. Details of NEWS model calibration, validation and uncertainty analysis are included in Text S1 (section A1.2).

[8] Nutrient export at river mouths was computed using historical input data for 1970 and 2000.

[9] Model inputs for future scenarios (2030 and 2050) were developed based on the four MEA scenarios [*Alcamo et al.*, 2006]: Global Orchestration, Order from Strength, Technogarden and Adapting Mosaic. Global Orchestration portrays a globally connected society that focuses on global trade and economic liberalization and takes a reactive approach to ecosystem problems, but also takes strong steps to reduce poverty and inequality and to invest in public goods, such as infrastructure and education. In contrast, Order from Strength is a regionalized and fragmented world, concerned with security and protection, with the emphasis primarily on regional markets, paying little attention to public goods, and taking a reactive approach to ecosystem problems. Technogarden is a globally connected world,

relying strongly on environmentally sound technology, using highly managed, often engineered, ecosystems to deliver ecosystem services, and taking a proactive approach to the management of ecosystems in an effort to avoid problems. In Adapting Mosaic, the fourth scenario, regional watershed-scale ecosystems are the focus of political and economic activity. Local institutions are strengthened and local ecosystem management strategies are common; societies develop a strongly proactive approach to the management of ecosystems based on simple technologies. Some key differences among the scenarios relevant for the NEWS model are related to the total crop and livestock production, efficiency of nutrient use in agriculture, nutrient emissions from sewage, energy use, per capita income, and river discharge in particular as it relates to consumptive water use for irrigation.

[10] We used several of the anthropogenic drivers from MEA directly as input to the NEWS model (Figure 1). However, not all required NEWS model inputs were available from MEA. Therefore, additional input data sets were developed by interpreting the original MEA scenarios (Figure 2). Details of the assumptions used and resulting data sets are described elsewhere [*Bouwman et al.*, 2010; *Fekete et al.*, 2010; *Van Drecht et al.*, 2009] and in Text S2 (section A2). A brief summary of how some key nutrient inputs for the scenarios were developed is presented below.

[11] Agricultural areas in NEWS-DIN and NEWS-DIP use net surface N and P balances as input. These surface balances are based on N and P inputs from fertilizer use, animal manure application, N_2-fixation by crops, atmospheric N deposition (NOy+NHx), and sewage N and P, minus N and P removal from crop harvest and animal grazing (Figure 1) [see also *Bouwman et al.*, 2010, Figure 5]. The surface nutrient balances form the basis of the scenario assumptions for nutrient management in agriculture. The original MEA storylines and scenarios lack descriptions, however, of nutrient management in agriculture. We therefore interpreted the MEA storylines (Figure 2) to generate four quantitative nutrient management scenarios on the scale of the 24 IMAGE regions (Figure 1) using an updated Integrated Model for the Assessment of the Global Environment (IMAGE) (version 2.4) [*Bouwman et al.*, 2006, 2010].

[12] Regional scenarios for N and P fertilizer use are based on efficiency of N and P in crop production [*Bouwman et al.*, 2010] (Figure 2). For constructing the regional scenarios we distinguish countries with a current nutrient surplus (industrialized countries and a number of developing countries like China and India) and countries with a deficit, i.e., crop uptake exceeds inputs leading to degradation of soil fertility. Generally, in Technogarden and Adapting Mosaic, farmers in countries with a surplus are motivated to be increasingly efficient in the use of fertilizers, while in Global Orchestration and Order from Strength, a slower efficiency increase was assumed. In deficit countries, N and P use efficiency for upland crops gradually decreased to a varying degree. The spatial distribution and magnitude of change in N and P use efficiency (Figure 3e), N and P fertilizer use, and soil N and P balances are presented in detail by *Bouwman et al.* [2010]. As an example, at the global scale, N and P fertilizer use in Global Orchestration increased between 2000 and 2030 from 78 (2000) to 97 (2030) Tg N yr^{-1} and 13 to 25 Tg P yr^{-1}. For comparison, in Adapting Mosaic fertilizer use in 2030 for N (62 Tg N yr^{-1}) is less than in 2000 and for P (15.6 Tg P yr^{-1}) use increases less than in Global Orchestration.

[13] Manure production is computed from livestock production (Figure 3d), animal numbers and excretion rates, and distributed over different animal manure management systems [*Bouwman et al.*, 2010]. Livestock production is related to a number of factors including human population and diet. As with fertilizer, there are substantial differences among scenarios (e.g., N in global manure increases from 83 Tg N yr^{-1} in 2000 to, by 2030, 132 Tg N yr^{-1} in Global Orchestration but only to 110 in Adapting Mosaic). Atmospheric N deposition from natural and anthropogenic sources to all watersheds is detailed in [*Bouwman et al.*, 2010]. For natural ecosystems inputs include biological N_2−fixation and atmospheric nitrogen deposition.

[14] N and P flows in urban wastewater (Figure 1) for the period 1970 to 2000 are based on country-scale data. For the years 2030 and 2050 calculated influents to wastewater treatment systems are computed from per capita incomes, and stem from human N and P emissions and P-based detergent use [*Van Drecht et al.*, 2009]. The MEA storylines were interpreted to generate scenarios differing in degree of access to improved sanitation, connection to sewage systems (Figure 3f) and nutrient removal in wastewater treatment systems (Figure 2) [*Van Drecht et al.*, 2009].

[15] Scenarios for hydropower production, monthly temperature and precipitation data, and land use, irrigated and rainfed crop production areas from the IMAGE model are used by the Water Balance Model (WBM_{plus}) to develop scenarios for the construction of reservoirs (dams) and consumptive water use and irrigation, to generate monthly river water discharge [*Fekete et al.*, 2010] (Figure 1).

[16] Information from the gridded input data (0.5 × 0.5 degree) is passed to the NEWS model. In total 5761 exoreic basins are included. NEWS predicts nutrient export at the mouth of rivers as a function of these inputs and biophysical properties of their basins. The contribution of watershed nutrient sources to river nutrient export is analyzed and linked back to changing socioeconomic, agricultural, and other watershed characteristics.

3. Results and Discussion

3.1. Global Trends in Nutrient Export by Rivers

3.1.1. Period 1970–2000

[17] River export of all forms of N, P and C increased during the thirty year period between 1970 and 2000 at the global scale (Figure 4). However, the forms responded differently. Relatively large increases (about 30%) were calculated for dissolved inorganic N and P, while particulates loads increased by only about 10% (Table 1b). For dissolved organics the increases were very modest (<5%). For the year 2000 we calculate 43 Tg of total N (TN = DIN + DON + PN) exported by rivers globally compared to 37 Tg TN in 1970 (Table 1a).

[18] Our estimate for 1970 is in good agreement with global river TN export for 1970 based on compilation of measured data for world rivers by *Meybeck* [1982]. This

	Reactive environmental management	Proactive environmental management
Globalization	**Global Orchestration** Agricultural trends [a] - high productivity increase - 4% of cropland area for energy crops - Fertilizer N efficiency: no change in countries with a surplus; rapid increase in N and P fertilizer use in countries with soil nutrient depletion (deficit) Sewage [b] - Towards full access to improved sanitation and sewage connection - Rapid increase in N and P removal by wastewater treatment Hydrology[c] Irrigation water demand, efficiency of irrigation systems, reservoir capacity and consumptive water use are computed from agricultural production, hydropower demand and demography	**Technogarden** Agricultural trends [a] - medium-high productivity increase - 28% of cropland area for energy crops Fertilizer N efficiency: rapid increase in countries with a surplus; rapid increase in N and P fertilizer use in countries with soil nutrient depletion (deficit) Sewage [b] - Towards full access to improved sanitation and sewage connection - Rapid increase in N and P removal by wastewater treatment Hydrology[c] See GO
Regionalization	**Order from Strength** Agricultural trends [a] - low productivity increase - 1% of cropland area for energy crops - Fertilizer N efficiency: no change in countries with a surplus; moderate increase in N and P fertilizer use in countries with soil nutrient depletion (deficit) Sewage [b] - Constant fraction of population with access to sanitation and sewage connection - Moderate increase in N and P removal by wastewater treatment Hydrology[c] See GO	**Adapting Mosaic** Agricultural trends [a] - medium productivity increase - 2% of cropland area for energy crops - Fertilizer N efficiency: moderate increase in countries with a surplus; moderate increase in N and P fertilizer use in countries with soil nutrient depletion (deficit); better integration of animal manure and re-cycling of human N and P from households with improved sanitation but lacking a sewage connection Sewage [b] - As in OS Hydrology[c] See GO

Figure 2. Overview of additional MEA scenario assumptions as implemented for the NEWS model (agricultural trends [*Bouwman et al.*, 2010]; sewage [*Van Drecht et al.*, 2009]; hydrology [*Fekete et al.*, 2010]. Footnotes in Figure 2 indicate the following: Scenarios on the scale of 24 world regions of the IMAGE model, with a downscaling procedure used to construct spatially explicit scenarios (0.5 by 0.5 degree resolution): when aggregated to country scale, our estimates for fertilizer use and livestock production reflect differences between countries in FAO's Agriculture Towards 2030 [*Bruinsma*, 2003]; our scenario outcomes vary around the FAO values (footnote a). Data and scenarios on the country-scale (footnote b). The WBM$_{plus}$ model uses 0.5 by 0.5 degree resolution land use, irrigated areas, cropping intensities and monthly mean precipitation and temperature data generated by IMAGE model (footnote c).

increase in TN over time can be largely explained by a 35% increase in DIN export from 14 to 19 Tg N/y (Table 1b and Figure 4). About 40% of the N in river export is DIN. DIP shows a trend similar to DIN (Figure 4): a 29% increase between 1970 and 2000 (Table 1b). The largest absolute increase in P load, however, is calculated for particulate P (Table 1a and Figure 4), the dominant form (5.9 Tg P in 2000) of total P export (7.6 Tg P in 2000) by world rivers. Our 1970 estimates for DIN, DON (14 and 10 Tg N, respectively) and dissolved P (1.7 Tg P) are similar to global river export for 1970 estimated by *Meybeck* [1982] (12 Tg DIN, 10 Tg DON, 2 Tg dissolved P). Our estimates for PN and PP (12 Tg N and 6 Tg P) are considerably lower than Meybeck's (21 Tg N and 20 Tg P) which were based

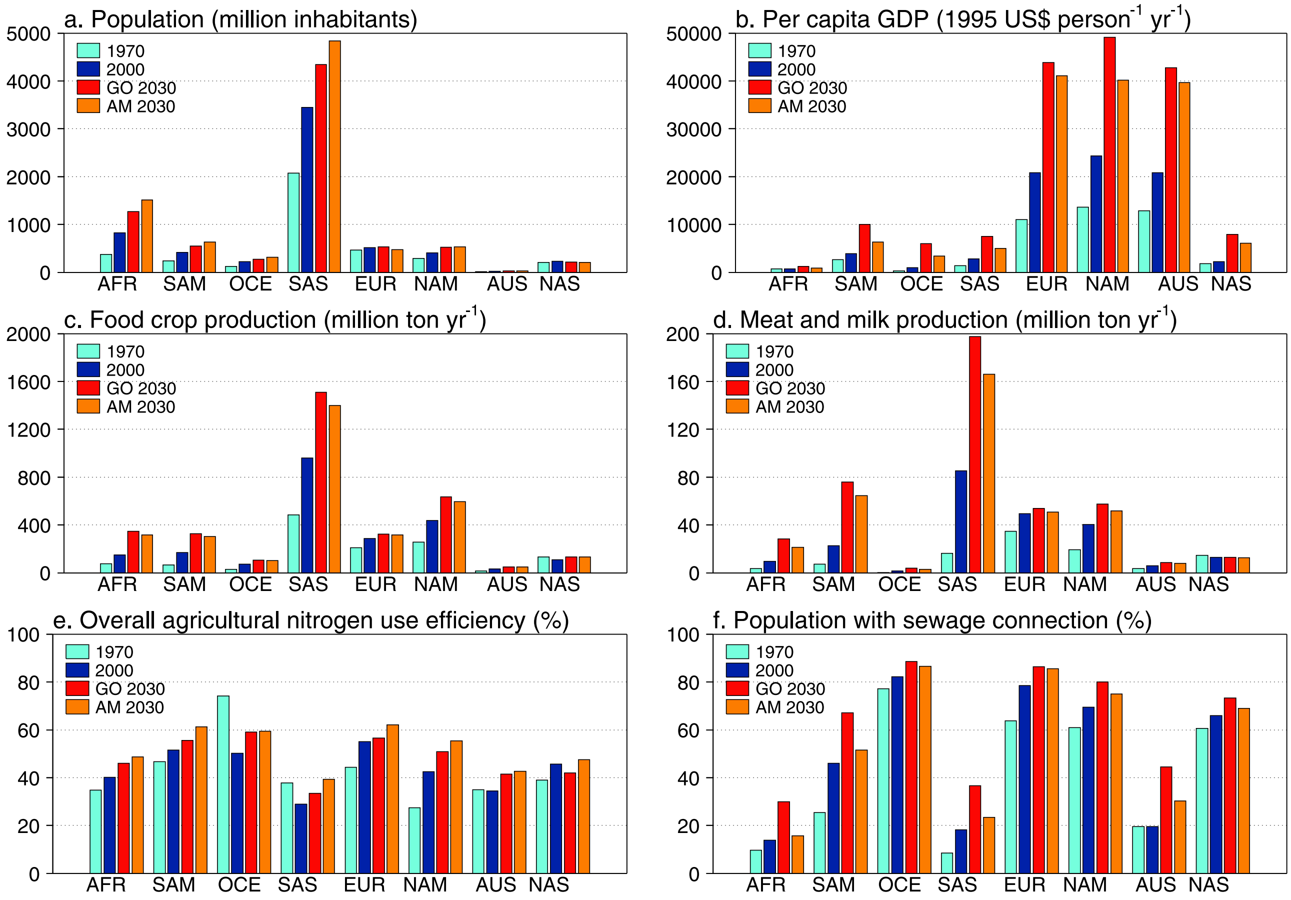


Figure 3. Anthropogenic drivers of nutrient flows for eight world regions for 1970, 2000, and 2030 for the Global Orchestration (GO) and Adapting Mosaic (AM) scenarios. Data taken directly from MEA [*Alcamo et al.*, 2006] on the scale of the 24 world regions of IMAGE include (a) population, (b) per capita gross domestic product, (c) crop production expressed as dry matter, and (d) meat and milk production in dry matter. Values computed in this study, used as indirect drivers, include (e) overall agricultural nitrogen use efficiency (including crop and livestock production systems) [*Bouwman et al.*, 2010]; this efficiency is from a surface balance perspective, ignoring imports and exports of fertilizers, feedstuffs, agricultural products, etc.; and (f) percentage of population with sewage connection [*Van Drecht et al.*, 2009]. AFR, Africa; SAM, South America; OCE, Oceania; SAS, South Asia; EUR, Europe; NAM, North America; AUS, Australia; NAS, North Asia.

on a POC budget and assuming fixed N:C:P ratios. NEWS calculates PN and PP as a function of TSS in rivers, which we consider a more appropriate approach. (See Text S3 (section A3) for additional comparisons). Increased export of PN, PP and POC (Figure 4) is associated with erosion and land use change. Increased PN, PP and POC river export is not as large as expected from erosion trends alone, because increased damming of rivers traps part of the particulates, preventing them from being transported to coastal waters.

[19] The global estimate for river DSi export for 2000 [*Beusen et al.*, 2009] is in good agreement with *Treguer et al.* [1995] and, according to NEWS-DSi, has been nearly constant between 1970 and 2000 (Table 1). Simulated changes result from an increase in dams (decrease DSi export) and changing river runoff, but there are no global-scale studies to compare with.

3.1.2. Period 2000–2030

[20] Differences among scenarios in river nutrient export are considerable (Figure 4). For DIN an increase in global river export is projected for Global Orchestration and Order from Strength scenarios which assume a reactive approach toward environmental change (up to an 18% increase; Table 1b). In contrast, a decrease in global river DIN export is projected for both scenarios with a proactive approach toward environmental change (Technogarden and Adapting Mosaic).

[21] Manure is the most important contributor to the increase in river DIN export between 2000 and 2030 in Global Orchestration (Figure 5f), which is the result of assumed high per capita meat consumption in this scenario (Text S2 (section A2)). Although the contribution from manure also increases in the Adapting Mosaic scenario, the

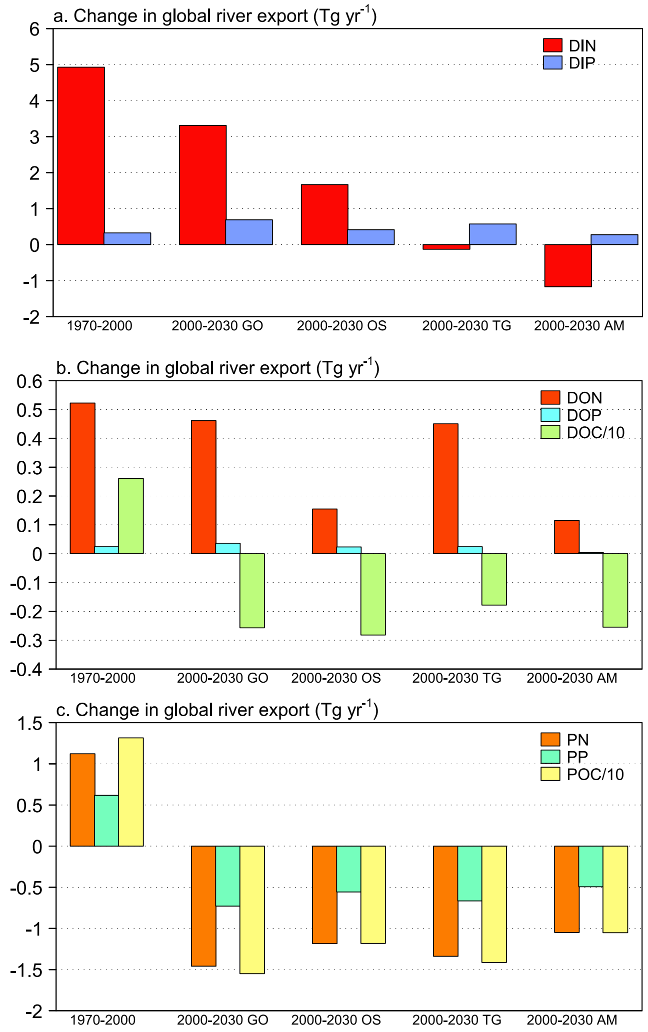


Figure 4. Change in river export of (a) DIN and DIP, (b) dissolved organic (DON, DOP, DOC), and (c) particulate (PN, PP, POC) nutrients, to coastal waters between 1970 and 2000, and between 2000 and 2030 for the four MEA scenarios. Note differences in scales. Units: Tg N, P or C yr^{-1}.

contribution from fertilizer shows an even larger decrease, resulting in the net decrease in river DIN export (Figure 5f). This follows from assumptions in Adapting Mosaic which focus on cheap and simple solutions such as better integration of animal manure in agricultural production systems, and to a lesser extent recycling of human excreta, leading to a reduction of synthetic fertilizer use (Figure 2).

[22] Increases in global river DIP export are projected in all scenarios (Figure 4). Increases in sewage, fertilizer, P-based detergents, and manure all contribute to the increase in DIP river export in Global Orchestration (Figure 5l). All these sources increase in Adapting Mosaic, but to a lesser extent, resulting in a smaller increase in river DIP export by 2030 than in Global Orchestration. As noted above, reduction in fertilizer use in Adapting Mosaic is the result of better integration of nutrient sources in agriculture. The smaller contribution to DIP export from sewage in Adapting Mosaic relative to Global Orchestration results from the much slower increase of connection of households to sewage systems. In Global Orchestration this development is much faster, leading to concentration of nutrients in wastewater streams that is not compensated by a rapid increase in N and P removal (Figure 2).

[23] For DON and DOP we project increasing trends in all four scenarios, but global trends are small: projected 2030 loads differ 1%–6% from 2000 loads (Table 1b and Figure 4b). Although absolute increases in DON and DOP loads are small, the relative magnitude of different sources change which may affect the proportion of DOM export that is bioavailable once it enters coastal ecosystems [*Seitzinger et al.*, 2002]. For DOC small decreases are projected for the period 2000–2030 mainly associated with small changes in the scenarios in the extent of wetlands and river discharge, both important drivers of DOC export [*Harrison et al.*, 2005b].

[24] For particulate forms we project decreasing river export for all scenarios. By 2030 the loads of PN, PP and POC are calculated to be up to 11% lower than in 2000 (Figure 4c and Table 1b). This contrasts with the period 1970–2000, for which we calculate a 10% increase. Both decreasing trends in the past, and increasing trends in the future are the net effect of increasing inputs of particulates in rivers associated with land use change and erosion, and

Table 1a. Global Nutrient Export by Rivers to Coastal Waters[a]

Year/Scenario	DIN	DON	PN	TN	DIP	DOP	PP	TP	DOC	POC	TSS/100	DSi
1970	14.0	10.3	12.4	36.7	1.1	0.6	5.9	7.6	161	127	123	141
2000	18.9	10.8	13.5	43.2	1.4	0.6	6.6	8.6	164	140	145	144
2030 GO	22.2	11.3	12.0	45.5	2.1	0.6	5.8	8.6	161	124	127	137
2030 OS	20.6	11.0	12.3	43.9	1.9	0.6	6.0	8.5	161	128	135	136
2030 TG	18.8	11.3	12.1	42.2	2.0	0.6	5.9	8.5	162	126	129	136
2030 AM	17.7	10.9	12.4	41.1	1.7	0.6	6.1	8.4	161	129	136	136
2050 GO	24.4	11.5	11.6	47.5	2.3	0.6	5.6	8.5	160	120	120	136
2050 OS	22.0	11.1	12.2	45.3	2.0	0.6	6.0	8.6	159	127	134	137
2050 TG	19.1	11.5	11.9	42.5	2.3	0.6	5.8	8.6	162	123	124	137
2050 AM	18.5	11.1	12.4	42.0	2.0	0.6	6.0	8.6	160	129	135	138

[a]Exoreic basins only. Scenarios for Global Orchestration (GO), Order from Strength (OS), Technogarden (TG) and Adapting Mosaic (AM) for 2030 and 2050[a] Units are Tg N, P, C, TSS or Si yr^{-1}.

Table 1b. Global Nutrient Export by Rivers to Coastal Waters[a]

Year/Scenario	DIN	DON	PN	TN	DIP	DOP	PP	TP	DOC	POC	TSS/100	DSi
2000	35.2	5.1	9.1	17.9	29.3	4.3	10.4	12.7	1.6	10.4	17.2	2.0
2030 GO	17.5	4.3	−10.8	5.3	48.0	6.2	−11.1	0.0	−1.6	−11.1	−12.3	−5.2
2030 OS	8.8	1.4	−8.8	1.5	29.0	4.0	−8.5	−1.4	−1.7	−8.5	−6.8	−5.2
2030 TG	−0.7	4.2	−9.9	−2.4	39.8	4.1	−10.1	−0.8	−1.1	−10.1	−10.9	−5.2
2030 AM	−6.2	1.1	−7.8	−4.9	19.3	0.6	−7.5	−2.5	−1.6	−7.5	−6.2	−5.4
2050 GO	29.2	5.8	−13.9	9.9	56.9	8.8	−14.4	−0.9	−2.3	−14.4	−16.9	−5.3
2050 OS	16.4	2.2	−9.5	4.7	39.1	5.7	−9.2	−0.1	−2.6	−9.2	−7.4	−4.7
2050 TG	0.9	6.0	−11.5	−1.7	57.0	6.9	−11.9	0.9	−1.2	−11.9	−13.9	−4.8
2050 AM	−2.0	2.2	−8.1	−2.9	36.7	1.6	−7.9	0.2	−2.2	−7.9	−6.8	−3.9

[a] Exoreic basins only. Percent change relative to 2000 (for the year 2000 relative to 1970).

increased trapping of particulates in reservoirs in rivers. In future years, the scenarios assume increasing numbers of reservoirs in rivers from construction of dams for irrigation and hydropower. The minor changes in global DSi export are comparable to those of TSS and particulate nutrient forms, and primarily a result of increased dams.

[25] Contrasting trends between dissolved inorganic, dissolved organic and particulate N, P and C compounds reflect the differential effect of various drivers (both anthropogenic and natural) in controlling river export of different elements and forms. It also illustrates the importance of an integrated approach to develop effective nutrient management strategies to control river nutrient export to coastal systems.

[26] NEWS projections for 2030 can be compared with earlier assessments of future global trends in river nutrient export. A preliminary assessment of river TN export under the MEA scenarios indicated a 10%–23% increase at the global scale in the coming 3 decades [*Alcamo et al.*, 2006]. Our results are different, indicating a 2%–5% increase for scenarios with a reactive approach to the environment (Global Orchestration and Order from Strength) and a decrease of 2%–5% for proactive scenarios (Adapting Mosaic and Technogarden). The *Alcamo et al.* [2006] estimate was based on global trends, did not account for spatial variation in future trends, nor consider large differences that the scenarios have on river export of different N forms (DIN, DON, PN). It was not based on results of spatially explicit watershed models such as the NEWS model, and as discussed below, there are major differences among basins and continents which can only be captured with spatially explicit modeling and which affect assessments of global trends.

[27] Using the IPCC IS92a scenarios, *Kroeze and Seitzinger* [1998] suggested that global DIN export by world rivers could more than double between 1990 and 2050. The IS92a IPCC scenario is most similar to the Global Orchestration scenario for which we calculate a 29% increase in DIN export by world rivers between 2000 and 2050. The difference between the two studies is a combined effect of differences among scenario assumptions, and important improvements in the NEWS-DIN model compared to the model used by *Kroeze and Seitzinger* [1998]. Virtually all model parameters and inputs have been updated, including improved estimates of biological N_2-fixation in natural ecosystems, surface nutrient balances in agriculture, wastewater management, nutrient retention in rivers, improved hydrology, higher spatial resolution, and a more extensive data set of observed DIN export rates for calibration. We consider the current version of NEWS-DIN a major improvement. It not only better represents river DIN export, but our analysis also illustrates the importance of analyzing a number of contrasting scenarios.

[28] Another recent study [*Bouwman et al.*, 2005] used the Agriculture Toward 2030 projection of FAO [*Bruinsma*, 2003] to estimate river export of TN. Their TN estimate (52 Tg yr^{-1}) for 2030 is ~10% higher than Global Orchestration's, the highest among the MEA scenarios. Although input data were prepared in a similar way, the major difference is the impact of dam construction on nutrient retention in river basins, which was ignored by *Bouwman et al.* [2005]. *Galloway et al.* [2004] presented an outlook for river TN export increasing from the 48 to 63 Tg per year between the early 1990s and 2050. Again, this study did not consider various changes that were included in our study, such as improved agricultural efficiencies, wastewater treatment, and dam construction.

3.2. Continental and Regional Trends in Nutrient Export by Rivers

[29] Existing spatial patterns in human drivers and geophysical properties, in combination with regional differences in application of the MEA scenario assumptions, result in substantial differences among watersheds (Figure 6), and when aggregated, among continents in magnitude, and in some scenarios, direction of change in river nutrient export. These spatial patterns are also reflected in variation in the relative contribution of different watershed sources and human drivers to river export. Here we discuss continental-scale historical trends (1970–2000) and for future trends focus on Global Orchestration and Adapting Mosaic scenarios because they showed the strongest contrast among the four scenarios at the global scale (Figure 4). We also primarily discuss results for DIN and DIP export because they generally showed largest changes over time, and are rapidly used by coastal plankton communities, leading to degradation of coastal ecosystems.

3.2.1. DIN River Export

[30] On all continents under the Global Orchestration scenario river DIN export increased between 1970 and 2000 and is projected to increase still further during the next 30 years (Figures 7 and S1). In contrast, the Adapting Mosaic scenario showed a decrease in river DIN export between 2000 and 2030 for most continents. Largest changes in DIN export during all time periods and in all scenarios were in South Asia. DIN export in South Asia accounted for

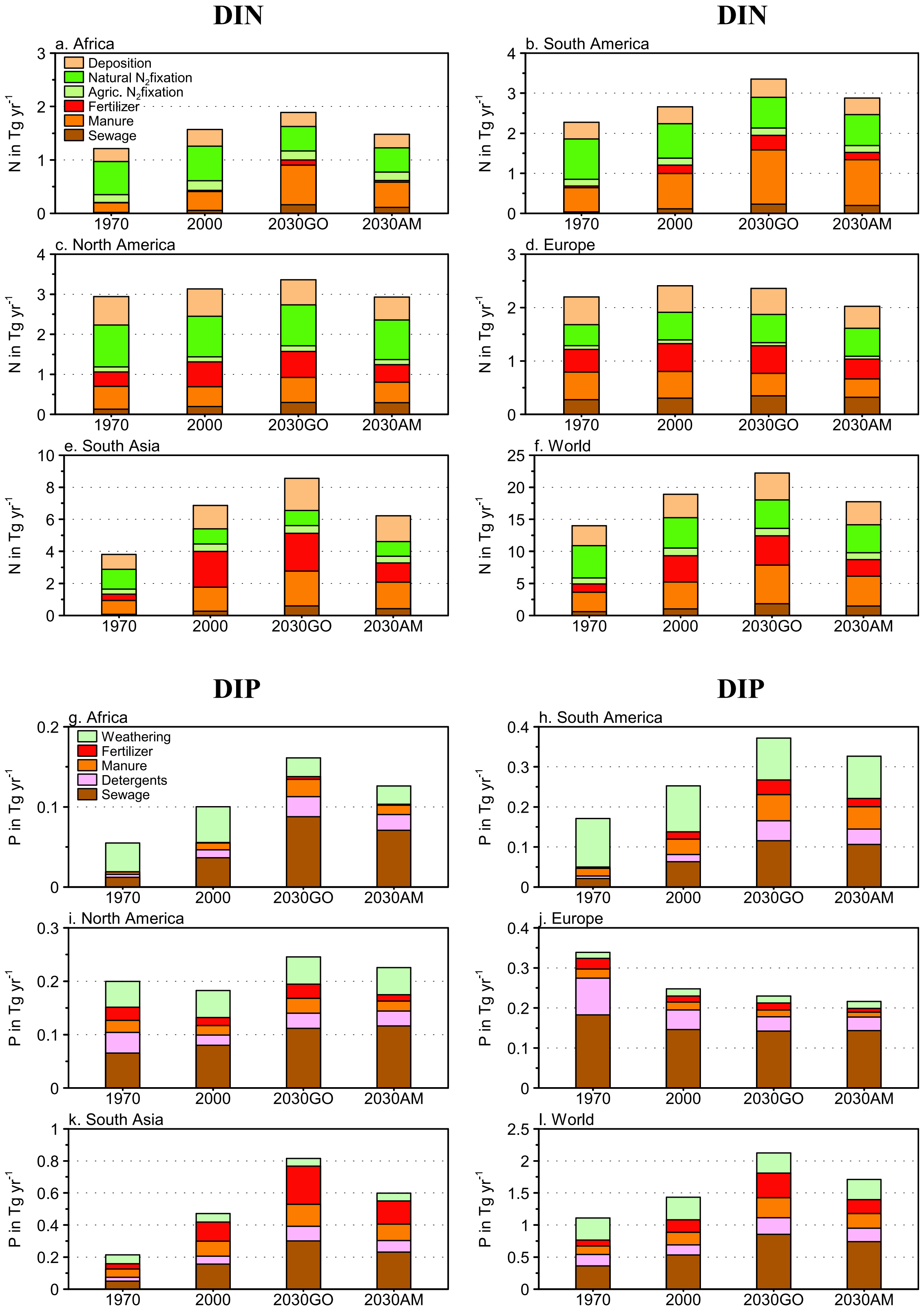
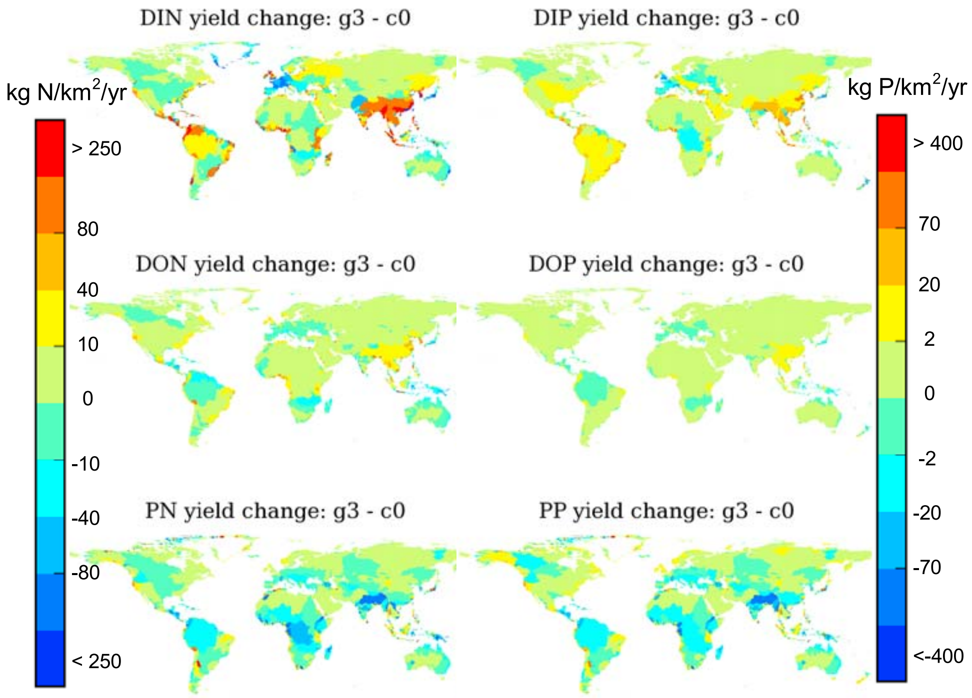


Figure 5. Model predicted contribution of (a–f) nitrogen sources in watersheds to DIN river export and (g–l) phosphorus sources in watersheds to DIP river export, for various continents, regions, and the world.



DIN yield change: g3 - c0

DIP yield change: g3 - c0

DON yield change: g3 - c0

DOP yield change: g3 - c0

PN yield change: g3 - c0

PP yield change: g3 - c0

Figure 6. Change in yields (kg km^{-2} yr^{-1}) between 2000 and 2030 from the 5761 basins in the NEWS model for DIN, DON, and PN and DIP, DOP, and PP under the Global Orchestration scenario.

61% (3 Tg) of global river DIN increase between 1970 and 2000, and 51% (1.7 Tg) of the global increase during the next 30 years under the Global Orchestration scenario, followed by South America (21% of global increase). For Adapting Mosaic, South Asia again accounted for a major portion of the global trend (54% of global DIN decrease), followed by Europe (33% of decrease) and North America (17%).

[31] While similar trends (in direction) in river DIN export were projected for most continents, there are substantial differences in the relative contributions of various watershed sources. Continents with primarily developing countries indicate different patterns compared to continents with primarily industrialized countries.

3.2.1.1. Continents With Primarily Low to Medium-Income Countries

[32] Africa and South America have primarily low to medium-income countries and show similar relative contributions of watershed N sources to DIN export. This holds for 1970 and 2000 and into the next 30 years under Global Orchestration and Adapting Mosaic 2030 scenarios (Figure 5). Biological N_2-fixation plus manure account for about two thirds of DIN export, although their relative contributions change over time. Biological N_2-fixation in natural ecosystems was the single largest source in 1970, but decreases in importance as anthropogenic sources increase. Animal manure, in particular, increases and by 2030 in both Global Orchestration and Adapting Mosaic scenarios exceeds the contribution of N_2-fixation in natural ecosystems to DIN export. Nitrogen deposition (natural plus anthropogenic) is the third largest contributor to DIN export in all scenarios and all years.

[33] Sewage from wastewater treatment systems has not been a major source of river DIN, at the continental scale, for Africa and South America in the past 30 years and is not projected to be a major source under either Global Orchestration or Adapting Mosaic in the next 30 years. Contrasting developments in Africa and South America cause a similar development of the sewage contribution to DIN. In Africa population growth is faster (Figure 3a), while in South America the increase in the percentage of the population with a sewage connection is more rapid than in Africa (Figure 3f). In neither Africa nor South America does the increase in N removal in wastewater treatment prevent an increase of the N effluent.

[34] Attention on reducing DIN river export in Africa and South America should be on agriculture, apart from those river basins where sewage is dominant [*Van der Struijk and Kroeze*, 2010; *Yasin, et al.*, 2010]. Particularly animal manure will be increasingly important, reflecting fast growth of livestock production (Figure 3d). Considerable increases in overall nutrient efficiency in agriculture are achieved in Africa and South America, particularly in Adapting Mosaic and Technogarden but much less so in Global Orchestration and Order from Strength (Figure 3e). However, overall nutrient use efficiencies are not as high as in industrialized countries. The combination of fast growth in crop and livestock production and improvement in agricultural nutrient efficiency is reflected in the contribution of fertilizer and manure to river DIN export, which increases rapidly in Global Orchestration and much less so in Adapting Mosaic.

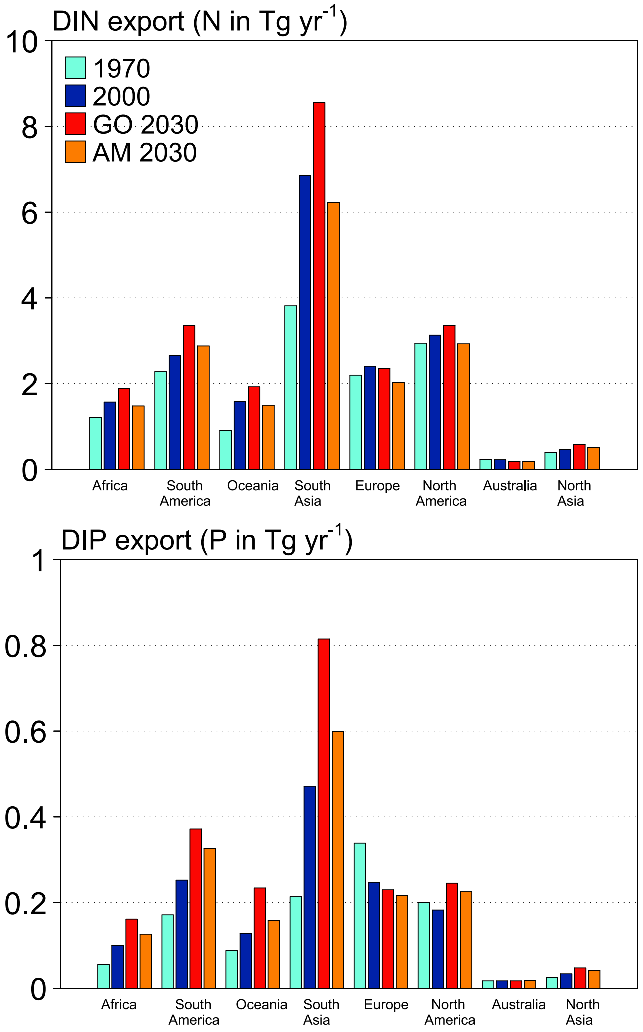


Figure 7. River export at continent/regional scale for (a) DIN and (b) DIP in 1970, 2000, and 2030 for the Global Orchestration and Adapting Mosaic scenarios.

3.2.1.2. Continents With Primarily Industrialized Countries

[35] In Europe and North America small increases in river DIN export were calculated between 1970 and 2000 (Figure 7). The increase in DIN export for North America between 1970 and 2000 is consistent with observed trends in rivers in the northeastern [*Van Breemen et al.*, 2002] and eastern United States [*Howarth et al.*, 2002], and in observed changes in net N inputs and runoff in the Mississippi basin [*McIsaac et al.*, 2001]. For Europe, at the continental scale, our modeled increase of DIN by 10% is consistent with observed trends. However, there has been considerable variability among European rivers over the past 30 years in trends in river nutrient export [e.g., *Billen et al.*, 2007; *de Wit et al.*, 2002; *Garnier et al.*, 2002; *Stalnacke et al.*, 2003]. The reader is referred to papers by *Thieu et al.* [2010] and Ludwig et al. (submitted manuscript, 2009) for a comparison of the NEWS modeled and measured trends for N and P export by individual rivers in Europe.

[36] Under the Global Orchestration 2030 scenario, DIN export is projected to continue to increase in North America but stabilize in Europe. DIN export for both continents is projected to decrease under Adapting Mosaic by 2030 relative to 2000. There are many similarities between these two continents in the relative contribution of watershed N sources to DIN export across all years and scenarios (Figures 5c and 5d). Overall, numerous sources contribute about equally, including natural N_2-fixation, fertilizer, manure, and atmospheric deposition, plus, for Europe, sewage.

[37] In future scenarios, differences in trends in sewage are due primarily to differences in population growth. In Europe and North America the proportion of inhabitants with a sewage connection in 2000 is high (79% and 70%, respectively) (Figure 3f). Further increases in connection are projected in all scenarios, although there is also increased removal of N in wastewater treatment. In Europe, however, because the population remains relatively steady, only a slight increase in the sewage DIN source is projected (Figures 3a and 5d). In contrast, the U.S.A population increases somewhat in all scenarios, and with the increasing percentage of the population connected to sewage systems, the sewage DIN source grows slightly in all scenarios.

[38] Future changes (increases and decreases) in DIN river export projected for Europe and North America are mainly due to changes in agriculture. Overall N use efficiency in agricultural production in Europe increases in all scenarios, particularly Adapting Mosaic (Figure 3e), and this leads to an overall reduction of DIN river export. In the U.S.A. there is also an improvement in agricultural efficiency (Figure 3e). However, in Global Orchestration there is also a much faster increase of crop and livestock production in the U.S.A. than in Europe (Figures 3c and 3d) causing an increasing agricultural DIN source. In Adapting Mosaic, U.S.A. population growth is similar to that in Global Orchestration between 2000 and 2030, but DIN export decreases (Figure 7). This is caused by a combination of parallel developments, including lower meat consumption and a higher nutrient use efficiency in Adapting Mosaic than in Global Orchestration (Figure 3e) the latter of which is the result of a major effort in better incorporating animal manure in the agricultural system (Figure 2).

3.2.1.3. Continental Regions With Countries in Rapid Economic Transition

[39] Largest changes in DIN export during all time periods and in all scenarios were in South Asia, which accounted for over half of the global increase (1970–2000 and Global Orchestration 2030) or decrease (Adapting Mosaic) in river DIN export (Figure 7). Large increases in DIN export in South Asia between 1970 and 2000 are consistent with measured increases in DIN export by the Changjiang River [*Yan et al.*, 2010].

[40] South Asia also shows the largest change in the relative contribution of watershed N sources to DIN export of all continents (Figure 5). In 1970, the pattern of source contributions was closer to that on the lesser developed continents (South America and Africa). However, by 2000 and for projections to 2030 under both Global Orchestration and Adapting Mosaic, the pattern in South Asia was very

similar to Europe and North America, as the contribution from fertilizer and manure increases markedly.

[41] Sewage remains a relatively small contributor to river DIN export in all scenarios in South Asia, even though population growth is high (Figures 3 and 5). In Adapting Mosaic population increases by 40%, and in Global Orchestration by 25%, by 2030 relative to 2000. There are rapid increases in sewage N loading, as a result of increasing urbanization and development of sewage systems, but lagging wastewater treatment. However, relative to agricultural sources, sewage remains a small source of river DIN.

[42] Agricultural sources are dominant in South Asia by 2000. Fertilizer is a major source of river DIN export by 2000, and accounts for about half of the fertilizer contribution of river export globally. This is consistent with the fact that about half of the global N fertilizer use is in South Asia to produce the food for 3750 million inhabitants. In the future continued development of agricultural sources is of major concern in Global Orchestration. Both fertilizer and manure production increase rapidly. In this scenario there is a major change in the crop and livestock production sectors by 2030 (Figure 3d) inducing rapid increases in fertilizer use and manure production. In Global Orchestration there is an increase in overall N use efficiency, but this increase is much faster in Adapting Mosaic (Figure 3e). This is the result of better integration of livestock and crop production in Adapting Mosaic than in Global Orchestration which leads to a reduction in fertilizer use. Also, in Adapting Mosaic there is a considerable amount of human excreta being recycled in agriculture to replace synthetic fertilizers. This N comes from the large number of people with access to improved sanitation, but outside urban areas with connection to sewage systems (Figure 2). Hence, this Adapting Mosaic scenario suggests that in this part of the world a lot can be achieved with regard to recycling to improve agricultural nutrient efficiency and thus to reduce river DIN export to coastal systems.

3.2.2. DIP River Export

[43] DIP export by rivers generally increased on all continents between 1970 and 2000 (Figure 7). An exception was Europe which showed a substantial decrease in DIP export; North America also had a small decrease. As with N, there has been considerable variation among basins within continents in observed river P export trends [e.g., *Billen et al.*, 2007; *de Wit et al.*, 2002; *Garnier et al.*, 2002; *Stalnacke et al.*, 2003]. For example, in North America many river basins show decreasing TP export due to improved wastewater treatment, while others show increasing export due to increasing P inputs in agriculture [*Howarth et al.*, 2002]. The slight increase in DIP river export from North America based on the NEWS model is consistent with conclusions for TP export of *Howarth et al.* [2002].

[44] Under Global Orchestration, DIP export continues to decrease in Europe between 2000 and 2030, although North America and all other continents showed quite substantial increases (Figure 7). South Asia accounts for 50% of the increase in global river DIP export under the Global Orchestration 2030 scenario; South America and Oceania (17% and 15%, respectively) are also important contributors. The Adapting Mosaic 2030 scenario suggests that increases in DIP river export would be less than under the Global Orchestration for all continents, although substantial increases relative to 2000 are still predicted for all continents, with Europe again being the exception. South Asia (46%) and South America (27%) account for 73% of the global increase in DIP river export relative to 2000 under the Adapting Mosaic scenario.

3.2.3. Dissolved Silica

[45] In contrast to N and P flows the scenarios for river export of DSi show no increases or slight decreases as a result of increased reservoirs from global dam construction in river systems [*Beusen et al.*, 2009]. This will inevitably lead to a shift in the N:P:Si stoichiometry as discussed in section 3.3.

[46] The ultimate source for DSi in river systems is rock weathering, with a major biological control in agricultural and natural ecosystems [*Beusen et al.*, 2009]. While the DSi flow from land to river systems may change as a result of climate and land use changes, the major anthropogenic control on river DSi export to the coastal zone is retention in reservoirs. These retention processes cannot be controlled, except for an indirect control on retention through N and P. Overall changes in primary production in river systems and reservoirs through changing N and P inputs will change diatom production. A decrease of N and P in river systems and reservoirs may therefore lead to a decreased retention of DSi. Hence, humans exert an indirect influence on river export of DSi.

3.3. Coastal Eutrophication

[47] Using the indicator of coastal eutrophication potential (ICEP) concept [*Billen and Garnier*, 2007], we can now use the scenarios for river nutrient export to assess the potential risk that nondiatom algal growth may lead to harmful algal blooms in coastal marine ecosystems. ICEP is an indicator for the potential of riverine nutrients to sustain new production of nondiatom phytoplankton biomass; it is calculated by comparing the N, P and Si loading to the Redfield ratios expressing the requirements of marine diatom growth. Positive values of ICEP indicate an excess of N or P over Si which may lead to blooms of nondiatom, possibly harmful species.

[48] We have already shown that in many world regions it is difficult to avoid an increase of river export of N and P. Si river export is decreasing globally as a result of eutrophication and retention in the increasing number of reservoirs in the world's river systems. *Garnier et al.* [2010] indicate that the result of these simultaneous changes of N:P:Si is an increasing ICEP value in all scenarios, indicating an increasing risk that severe problems associated with eutrophication will occur (Figure 8). River basins with positive ICEP values, expressed by the land area draining into the world's oceans, increase in all scenarios. This increase is more rapid in the Global Orchestration than in the Adapting Mosaic scenario, particularly for rivers draining into the Atlantic, Indian and Pacific oceans (Figure 8).

[49] Local physical and environmental conditions will, apart from nutrient loading and element ratios used in the ICEP concept, determine the propensity of a coastal marine

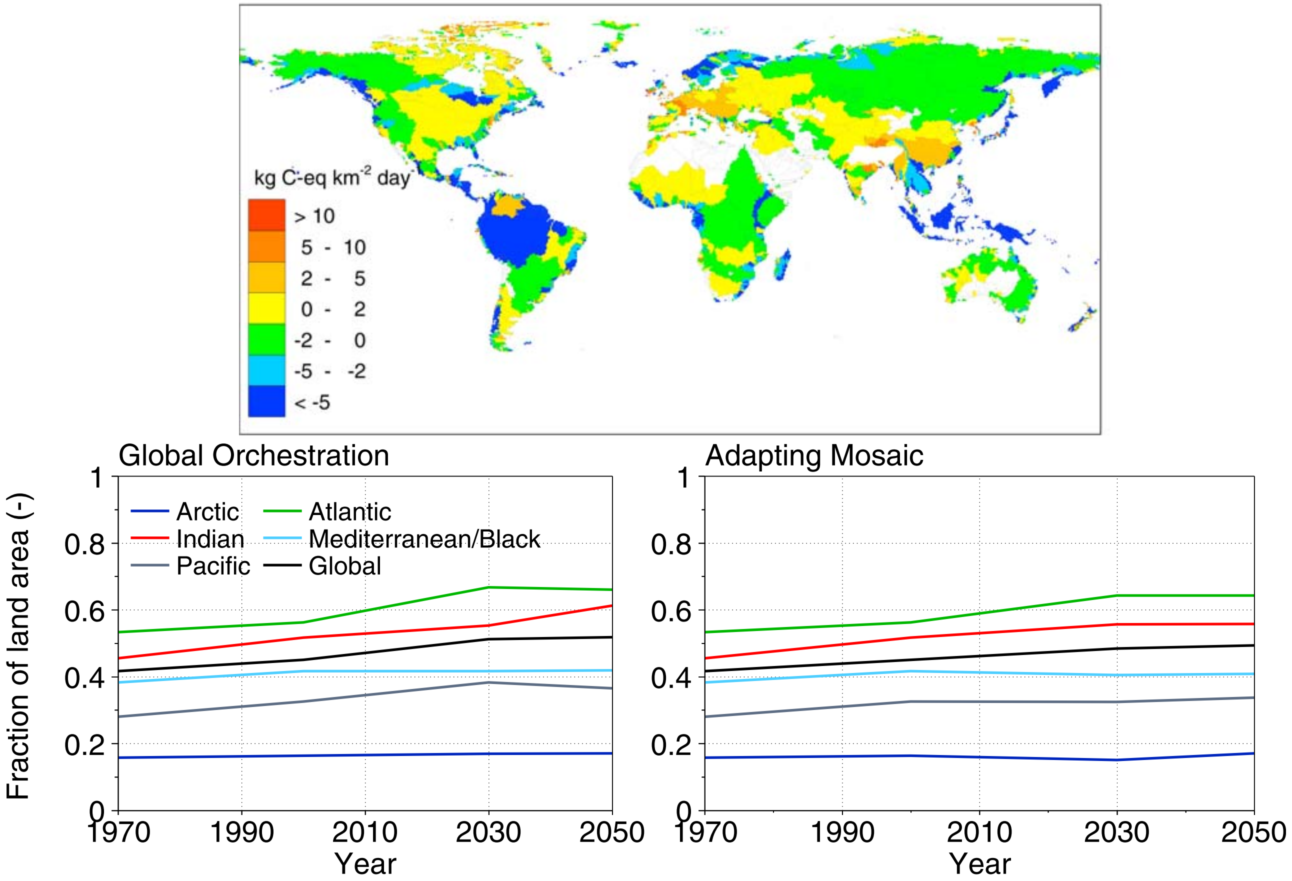


Figure 8. Indicator of Coastal Eutrophication Potential (ICEP) calculated for (top) the year 2000 and fraction of land area with river basins draining into the world's oceans with ICEP > 0 for 2000–2050 for (bottom left) Global Orchestration and (bottom right) Adapting Mosaic scenarios. From *Garnier et al.* [2010].

ecosystem for developing high biomass and otherwise harmful algal blooms, or hypoxia.

3.4. Nitrogen Autotrophy and Heterotrophy

[50] Nitrogen autotrophy of a watershed is defined as the flux of nitrogen associated with local production of harvested crops and of grass directly grazed by livestock (expressed in kg N km^{-2} yr^{-1}) [*Billen et al.*, 2010]. Heterotrophy is defined as the nitrogen flux associated with local food and feed consumption by humans and domestic animals. These two synthetic characteristics summarize the degree of anthropogenic perturbation of the nitrogen cycle by agriculture: their balance indicates either the potential for commercial export or the need for import of agricultural goods.

[51] The concept of nitrogen autotrophy and heterotrophy of watersheds offers very synthetic information about the organization of agricultural activities in a given region and the resulting perturbation they induce on the nitrogen cycle. *Billen et al.* [2010] showed that not only the intensity of autotrophy and heterotrophy of a watershed, but also the degree of imbalance between them, are important factors of nitrogen loss to hydrosystems. During the last 30 years, most watersheds shifted from relatively balanced situations toward either more autotrophic or more heterotrophic conditions. This trend is predicted to reinforce during the next 50 years, with differences among the scenarios.

4. Conclusions

[52] In the current study, an integrated modeling approach was used to connect socioeconomic factors and nutrient management to river export of nitrogen, phosphorus, silica and carbon using the updated Global *NEWS* model. Past trends (1970–2000) and four future scenarios were analyzed for river nutrient export globally, including dissolved inorganic (N, P, Si), dissolved organic and particulate (N, P, C) forms.

[53] An important conclusion from our work is that the risk for coastal eutrophication and associated effects has increased markedly over the past 30 years and will likely continue to increase in many world regions for the foreseeable future. Not only is river nutrient loading expected to increase in many world regions, but changing nutrient ratios are also anticipated implying an increase in the potential risk of harmful algal blooms in coastal marine ecosystems (Figure 8).

[54] This work highlights the need for an integrated approach to evaluate the net effect of the multiple factors (e.g., socioeconomic trends, food consumption, agricultural nutrient management, sewage treatment) affecting trends in river nutrient export. Explicitly modeling the different elements and nutrient forms (dissolved inorganic, dissolved organic, particulate) is also required as their future trends in river export differ in magnitude and direction as a result of differences in the relative magnitude of controlling factors. The effect of nutrient loading on coastal ecosystems depends not only on the magnitude but also the nutrient form and nutrient ratios, among other factors.

[55] During the past 30 year period (1970–2000), at the global scale, increases in river export of all forms of N, P and C were calculated by the NEWS model (Figure 4). Increases in river N export were dominated by DIN (80%), followed by PN and DON. The relative contribution of the various forms of P differed from N, with PP accounting for 65% of the increase, followed by DIP and DOP. Changes in dissolved silica export at the global scale calculated by the NEWS model were small.

[56] In the subsequent 30 years (2000–2030) trends among the various elements and nutrient forms continue to differ, and there are differences among the scenarios as well. No one policy or factor is responsible for the differences in river nutrient export among the nutrient elements/forms or scenarios. Rather it is the integrated result of all societal changes, changes in the energy system, agriculture, climate, and the feedback mechanisms, all of which vary regionally. A few examples illustrate these points. Under all four scenarios, global river export of DIP continues to increase in the future, although to different degrees. DIN increases under the two scenarios with a reactive approach to environmental management (Global Orchestration and Order from Strength) but decreases under the proactive environmental management scenarios (Technogarden and Adapting Mosaic). The trend in global river export of particulate forms reverses, from increasing in the previous 30 years to decreasing under all four future scenarios. The reasons for these different patterns among the nutrients are related to the relative importance of drivers of nutrient elements and forms. The decrease in particulate export is due in part to energy production, more explicitly to increased water retention in reservoirs associated with increased number of dams for hydropower. Sewage is a major source of anthropogenic DIP in rivers, and increases in sewage P in the scenarios are related to increases in population, connection to sewage systems and level of treatment which are related to per capita income, and use of phosphorus-free detergents. Agriculture is the primary anthropogenic source of DIN, and population, nitrogen use efficiency and nutrient balances are important in controlling the magnitude and direction of future DIN river export based on this scenario analysis.

[57] Underlying these global trends is substantial spatial variation among continents/regions. For example, world regions with primarily low to medium-income countries (e.g., Africa, South America) exhibit largest DIN increases in the past 30 years, and in subsequent 30 years under Global Orchestration scenario (2000–2030) (Figures 5 and 7). These increases are driven by fast growth in crop and livestock production moderated by improvements in agricultural nutrient efficiency (Figure 3). These factors increase less under the Adapting Mosaic scenario, leading to only small increases (South America) or even a decrease (Africa) by 2030 relative to 2000, in DIN river export. DIN from sewage, while still a relatively small source at the continental scale, increases, although for different reasons in Africa and South America; population growth is faster in Africa, while in South America the increase in the percentage of the population with a sewage connection is more rapid than in Africa because of higher per capita income. In contrast, differences between Europe and North America in future trends in DIN in sewage are due primarily to differences in population growth. While both already have a high proportion of inhabitants with a sewage connection (79% and 70%, respectively), and further increases in connection and treatment level are projected in all scenarios, in all scenarios only slight increases in sewage DIN are projected in Europe, because the population remains relatively steady (Figures 3 and 5d). In contrast, in the U.S.A. the sewage DIN source grows slightly because population increases somewhat.

[58] South Asia, a region in rapid economic transition and with a large and increasing population, dominates the global trends in nutrient export during all time periods and in all scenarios. For example, South Asia alone accounts for over half of the global increase (1970–2000 and Global Orchestration 2030) or decrease (Adapting Mosaic) in river DIN export. Large changes in the relative contribution of watershed N sources to DIN export occur, moving from a pattern in 1970 that was similar to lesser developed continents (South America and Africa) to a pattern by 2000 that is very similar to Europe and North America, as the contribution from fertilizer and manure increases markedly. The reversal in the trend in DIN export from a large increase in the Global Orchestration 2030 scenario, to a slight decrease in Adapting Mosaic, is due to a combination of many factors including a lower increase in, and better integration of, livestock and crop production, and higher nitrogen use efficiency. Sewage remains a relatively small contributor to river DIN export in all scenarios in South Asia, even though population growth is high.

[59] Scenarios have no uncertainty, since they are purely hypothetical sets of global assumptions. In reality, the world will be a mixture of countries and companies tending toward globalization and parts of the world with regional orientation. Within that there will be a range of reactive and proactive approaches to environmental threats, as well as a range of compliance and effectiveness of specific policies. The NEWS model results of the scenarios provide a range of potential outcomes under the specified suite of “model worlds.”

[60] Future research needs include (1) Additional measurements of river nutrient loadings for continued refinement of models such as NEWS. The available data set is limited, and biased toward rivers in industrialized countries. (2) Refinement of models such as NEWS to include seasonally varying export, extreme events, and time lags. (3) Downscaling of the NEWS model for particular regions to account for subbasin processes, providing more details on

regional trends and local conditions. (4) Development of quantitative relationships between nutrient loading (amount, form and ratios) and coastal ecosystem effects as well as on fisheries and tourism. (5) Exploration of alternative futures. (6) Improved understanding of the interacting social, economic and biogeochemical drivers of change.

[61] **Acknowledgments.** This study was performed as part of the Global NEWS project and cofunded by Intergovernmental Oceanographic Committee-UNESCO and a NASA IDS grant. Global NEWS is a workgroup of Intergovernmental Oceanographic Commission of UNESCO and an affiliated research activity of IGBP-LOICZ.

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