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Future trends in nutrient export to the coastal waters of South America: Implications for occurrence of eutrophication

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[1] We analyze future trends in nutrient export to the coastal waters of South America, with a special focus on the causes of nutrient export and their potential effects. Nutrient Export from Watersheds (NEWS) model results for South America are presented, including trends in human activities and the associated river export of nutrients for the period 1970–2050. For 25 areas in coastal waters of South America where eutrophication or hypoxia has been observed, we investigate how these relate to NEWS model output. For selected watersheds we discuss the causes of increased nutrient loadings of rivers and future trends as projected by the NEWS models.

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1. Introduction

[2] Coastal waters are experiencing eutrophication as a result of enriched nutrients, in particular nitrogen (N) and phosphorus (P). This may have severe implications for coastal systems. Initial responses of ecosystems to nutrient enrichment may be growth of phytoplankton, microalgae, and macroalgae. This may lead to reduced light penetration, potentially damaging sub aquatic vegetation. It may also affect benthic species diversity, and inhibit coral growth. Nutrient enrichment may benefit the growth of algal species, some of which are potentially harmful to aquatic life.

[3] Harmful algal blooms typically are formed by potentially toxic algal species and high-biomass producers that can cause hypoxia and anoxia, and as such cause mortalities of marine life after reaching dense concentrations [*Heisler et al.*, 2008]. Formation of harmful algal blooms is determined by a number of factors, but it is generally accepted that increased nutrient availability in coastal waters promotes the development of these algal blooms. It is also clear that there is no linear relationship between nutrient inputs to coastal waters and harmful algal blooms, and that several forms of N and P are involved. Rather, the ratios among different forms of N, P, carbon (C) and silica (Si), in combination with other environmental parameters are determining whether algal blooms will develop and persist [*Billen and Garnier*, 2007; *Heisler et al.*, 2008; *Kudela et al.*, 2008].

[4] The harmful algal species *Prorocentrum minimum* is generally considered an important indicator for serious effects of eutrophication. It is widely distributed around the globe, and *P. minimum* blooms can be harmful to other species. There is a relation between *P. minimum* blooms and coastal eutrophication [*Heil et al.*, 2005]. A comparison of modeled river export of N and P with the global distribution of *P. minimum*, indicates that this species benefits from increased riverine nutrient export [*Glibert et al.*, 2008]. Nevertheless, it is not easy to forecast high algal bloom events in eutrophic coastal seas, even though promising approaches exist [*Allen et al.*, 2008; *Wong et al.*, 2009].

[5] In addition to the global study on *P. minimum* [*Heil et al.*, 2005], two other assessments of the global distribution of eutrophication and hypoxia have been published. *Diaz and Rosenberg* [2008] and *Selman et al.* [2008] published global assessments of eutrophication and hypoxia in coastal areas. These studies indicate that dead zones in the coastal oceans spread exponentially, and started to approximately double every 10 years starting in the 1960s [*Diaz and Rosenberg*, 2008]. However, there are also systems in recovery [*Selman et al.*, 2008].

[6] In this paper, we focus on the causes of coastal eutrophication in South America. The three global assessments mentioned above give an indication of the occurrence of eutrophication in the coastal waters of South America. At least 25 locations in South American coastal seas have been reported as eutrophied, including episodic dead zones, hypoxic areas and so-called areas of concern [*Diaz and Rosenberg*, 2008; *Heil et al.*, 2005; *Selman et al.*, 2008]. None of these existing inventories claim to be complete. Rather, they report observed events of hypoxia. Since there is not yet a systematic monitoring of coastal eutrophication, the problem is likely larger than the available inventories indicate.

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[7] Rivers are the most important source of nutrients in coastal waters. Rivers transport nitrogen (N), phosphorus (P), carbon (C) and silica (Si) to the coastal seas. Diffuse sources (agriculture, natural ecosystems) and point sources (wastewater from households and industries) are among the most important factors determining the amount of nutrient inputs to coastal waters by rivers [*Howarth*, 2008; *Seitzinger et al.*, 2005; *Seitzinger et al.*, 2002]. Coastal eutrophication is, therefore, largely caused by human activities on the land that increase nutrient loading of rivers. Several diffuse sources add to the nutrient loading of rivers, including fertilizer use, manure production, biological N_2 fixation, and atmospheric deposition of nitrogen compounds in the watersheds. In addition to nutrient inputs from rivers, aquaculture is an important source of nutrients in coastal marine ecosystems. Since there is no inventory of nutrient inputs from finfish production and transformations by shellfish production, we focus on the impact of river export in this paper. We also do not account for atmospheric N deposition on water, since the models that we use here only account for N deposition on land as a source of riverine N after leaching. It should be noted, that in some regions, atmospheric N deposition may be an important nitrogen input to aquatic systems [*Duce et al.*, 2008]. However, close to river mouths, riverine inputs are most likely to be the dominant source of nutrients in coastal waters.

[8] The Global Nutrient Export from Watersheds (NEWS) models are global models, simulating spatially explicit nutrient export by rivers as affected by human activities on the land. NEWS models have been developed for different nutrients [*Seitzinger et al.*, 2010, 2005]. First, separate models were developed for dissolved inorganic N (DIN) and P (DIP) [*Dumont et al.*, 2005; *Harrison et al.*, 2005b], dissolved organic forms of N, P and C (DON, DOP, and DOC) [*Harrison et al.*, 2005a] and particulate forms (PN, PP, and PC) [*Beusen et al.*, 2005]. More recently a second generation of the NEWS models was used to explore future trends in nutrient export by rivers up to 2050 [*Mayorga et al.*, 2010; *Seitzinger et al.*, 2010]. The NEWS models now also includes a model for silica [*Beusen et al.*, 2009]. The analyses of future trends are consistent with the Millennium Ecosystem Assessment scenarios [*Alcamo et al.*, 2006]. Model input has been generated for the years 1970, 2000, 2030 and 2050 for four scenarios [*Bouwman et al.*, 2009; *Fekete et al.*, 2010; *Van Drecht et al.*, 2009]. The NEWS models have been used to calculate an Indicator for Coastal Eutrophication Potential (ICEP) [*Billen and Garnier*, 2007; *Garnier et al.*, 2010], which is based on the ratio of different nutrient inputs to coastal waters. ICEP is an interesting approach toward assessing the risk for eutrophication, in addition to information on nutrient concentration, bioessays and uptake kinetics.

[9] The NEWS models can be used to calculate the nutrient export by more than 5000 rivers worldwide, as a function of human activities in the watersheds. NEWS model results indicate that anthropogenic inputs of dissolved forms N and P are largely associated with agriculture, land use, sewage and to a lesser extent with fossil fuel combustion. Particulate forms of nutrients are primarily driven by hydrology and slope, and therefore by land use. We present here the first detailed assessment of NEWS model results for South America, focusing on the causes and effects of nutrient export by rivers.

[10] Only a few studies have attempted to link river loading of nutrients to observed coastal eutrophication. An interesting comparison was made of modeled river export of DIN, DON, DIP and DOP with the global distribution of *P. minimum* [*Glibert et al.*, 2008]. Their modeled DIN and DIP river export was model output of earlier versions of the NEWS models [*Dumont et al.*, 2005; *Harrison et al.*, 2005a, 2005b], and they used the 2005 assessment of *P. minimum* [*Heil et al.*, 2005]. This comparison of the global distribution of DIN and DIP river export with the known distribution of *P. minimum* indicates that this species proliferates where dissolved N and P river yields are high, and where these nutrient sources, whether in inorganic or organic form, have a substantial anthropogenic component.

[11] In this paper we analyze future trends in nutrient export to the coastal waters of South America, with a special focus on the causes of nutrient export, and their potential effects. We will first analyze the most recent NEWS model results for South America and present general trends in human activities and the associated river export of nutrients for the period 1970–2050 and for the whole continent. Next, we will focus on the 25 areas in coastal waters of South America where eutrophication or hypoxia has been observed [*Diaz and Rosenberg*, 2008; *Selman et al.*, 2008] and investigate how these relate to NEWS model output. For selected watersheds we will discuss the causes of increased nutrient loadings of rivers, and future trends as projected by the NEWS models.

2. Modeling Approach

2.1. NEWS Model Description

[12] The Global NEWS models calculate nutrient export by rivers to coastal waters, as a function of hydrology, basin characteristics and human activities on the land. The NEWS models that we use have been described in detail elsewhere [*Mayorga et al.*, 2010; *Seitzinger et al.*, 2010, 2005], and are largely in line with earlier versions of the NEWS models [*Beusen et al.*, 2005; *Dumont et al.*, 2005; *Harrison et al.*, 2005a, 2005b; *Seitzinger et al.*, 2005].

[13] The Global NEWS models are global, spatially explicit models. They include > 5000 river basins for which input data are lumped to be used as input to the Global NEWS models. The stream network and basin delineation is from the 0.5 x 0.5 degree STN30 global river network [*Vörösmarty et al.*, 2000a, 2000b] for which hydrology was provided for the years 1970, 2000, 2030 and 2050 [*Fekete et al.*, 2010]. Nutrient export by rivers is calculated for each river as a function of the export of N, P or C from the watershed to streams, and river retention of nutrients. The nutrient inputs to streams include point sources (sewage) and diffuse sources, both natural and anthropogenic. The model inputs to calculate point sources and diffuse sources include, among others, land use, population densities, gross domestic product, fertilizer use, animal manure excretion, biological N_2 fixation, crop export, and atmospheric deposition on the watershed [*Bouwman et al.*, 2009; *Van Drecht et al.*, 2009].

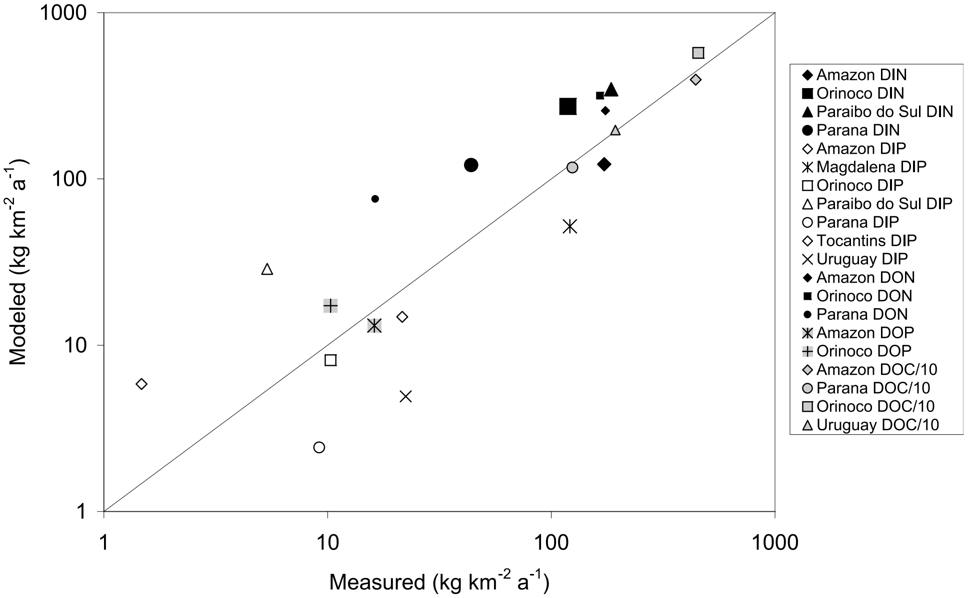

Figure 1. Measured versus modeled river yield of dissolved N and P. Data for measurements are from multiple sources as used in NEWS model development [*Dumont et al.*, 2005; *Harrison et al.*, 2005a, 2005b; *Mayorga et al.*, 2010]. Modeled yields are NEWS model results for the year 2000.

[14] The NEWS models typically explain 50–70% of the observed variation in nutrient export by rivers worldwide. Here, we compare the NEWS model calculated nutrient yields to observed values for South American rivers. We selected the South American rivers from the global data set that was used to calibrate and validate the NEWS models. This data subset includes rivers from different climatic zones [*Dumont et al.*, 2005; *Harrison et al.*, 2005a, 2005b; *Mayorga et al.*, 2010]. Figure 1 shows a comparison of NEWS model results for DIN, DIP, DON and DOC to measured data. Although the number of rivers in the data set is too limited for statistical analyses, we may draw some conclusions from this comparison. For some rivers (such as the Amazon), the model performs better than for others. In general, the model seems to do better for DIN, DON and DOC than for DIP, although for the Amazon also modeled DIP yields also compare well to measured values. The variations in yields among rivers are described well by the NEWS models: the highest DIN yield (Paraibo do Sul) is a factor of 3–4 higher than the lowest yield (Parana) in both measured and modeled data sets. For DIP the highest yield (Magdalena) is almost 2 orders of magnitude higher than the lowest yields (Parana and Tocantins). And for DOC this difference in yield is a factor 4–5, both for measurements and modeled values. There are also outliers, such as DIP yields for the Tocantins and Parana. Nevertheless, we may argue that the NEWS models in general perform reasonably well for South American rivers.

2.2. MEA Scenario Description

[15] The Global NEWS models calculate future trends in river export of N, P and C for the years 2030 and 2050. In addition, past trends are analyzed (for 1970 and 2000). The future trends are based on interpretations of the four Millennium Ecosystem Assessment (MEA) scenarios [*Alcamo et al.*, 2006]. Four MEA scenarios exist. These scenarios describe four plausible global futures in an internally consistent way. They differ in the way markets will develop (globalization or regionalization) and the attitude toward environmental issues and ecosystem management (proactive or reactive). Here we summarize some trends for South America.

[16] The Global Orchestration (GO) scenario describes a globalized world. It is characterized by global trade and economic liberalization, with a reactive attitude toward ecosystem management. The focus is on material wealth and economic growth. It also aims at reducing poverty and inequality and to invest in infrastructure and education.

[17] In the Order from Strength (OS) scenario a regional market is developed. This scenario thus describes a regionalized world. As in GO, the attitude toward ecosystem management is reactive. The OS world is characterized by regionalization and fragmentation, and concerns about security and protection.

[18] The Technogarden (TG) scenario is another globalized scenario, but with a proactive approach toward ecosystem management. It includes green technology development, ecoefficiency, and tradable ecological property rights. The scenario assumes a global reduction of tariff boundaries, relatively free movement of goods, capital and people, and global markets in ecological property. The environmental management is characterized by environmentally sound technologies. It focuses, however, not as much as the Adapting Mosaic (AM) scenario on local solutions.

[19] The AM scenario describes a regionalized world, with proactive ecosystem management. Regional watershed-scale ecosystems are the focus of economic and political devel-

Table 1. NEWS Model Inputs for South America[a]

	Actual Basin Discharge (km^3 yr^{-1})	Population (millions)	Urban Population (%)	Population Connected to Sewage (%)	GDP (billion 1995 U.S. \$ yr^{-1})	Fertilizer N Use (Gg yr^{-1})	Manure N Excretion (Gg yr^{-1})	Fertilizer P Use (Gg yr^{-1})	Manure P Excretion (Gg yr^{-1})
1970	10,689	174	57	25	778	522	7,232	281	1,646
2000	10,086	313	78	45	2,126	3,402	12,938	1,446	2,646
GO 2050	9,385	438	91	69	16,986	6,815	23,737	2,990	4,840
OS 2050	9,427	557	92	51	9,427	5,514	22,751	2,534	4,257
TG 2050	9,708	490	91	69	15,380	7,778	24,712	3,987	3,826
AM 2050	9,468	551	91	51	12,246	3,601	21,563	1,863	4,007
					Percent Change				
2000	−6	80	37	78	173	551	79	415	61
GO 2050	−7	40	16	53	699	100	83	107	83
OS 2050	−7	78	17	13	343	62	76	75	61
TG 2050	−4	56	16	53	623	129	91	176	45
AM 2050	−6	76	16	12	476	6	67	29	51

[a] *Bouwman et al.* [2009], *Fekete et al.* [2010], and *Van Drecht et al.* [2009]. Absolute values and % change over time since 1970 (for the year 2000) and since 2000 (for the year 2050). Exoreic basins only. GDP, gross domestic product; GO, Global Orchestration; OS, Order from Strength; TG, Techno-garden; AM, Adapting Mosaic.

opments. This is associated with strong local institutions and local ecosystem management strategies. The economic approach is focused on integration of local rules regulating trade, and local nonmarket rights.

[20] Table 1 summarizes some key characteristics of these four scenarios for South America that are drivers of the NEWS models. The scenarios were interpreted to prepare the input data that the Global NEWS models need [*Bouwman et al.*, 2009; *Fekete et al.*, 2010; *Van Drecht et al.*, 2009].

[21] The discharge of South American basins has been decreasing since 1970, and this reduction will continue in the future as a result of human water consumption and climate change [*Fekete et al.*, 2010]. The population almost doubled since 1970, and will continue to increase in all MEA scenarios. The population growth is larger in the regionalization scenarios (about 75%) than in the globalization scenarios (56% or less). In 1970 less than 60% of the population lived in urban areas. By 2050 more than 90% will live in cities. Currently, 45% of the people are connected to sewage systems. This percentage will increase in the future to almost 70% in the globalization scenarios. In the regionalization scenarios less people are connected to sewage systems. Gross domestic product (GDP) more than doubled between 1970 and 2000, and the increase will be even larger in the coming decades: GDP may increase by a factor of 5 to 7 between 2000 and 2050 with highest growth rates in the globalization scenarios. Also fertilizer use and manure excretion by livestock will continue to increase. However, there are differences among the scenarios: fertilizer N inputs increase only by 6% in the AM scenario, but by over 550% in the GO scenario. The Global NEWS models need, in addition to the selected inputs presented in Table 1, other inputs at the individual basin level. Based on these inputs, the model then calculates river export of nutrients for past and future years, as described below.

3. Nutrient Export to the Coastal Waters of South America

3.1. Continental Trends

[22] We first analyze continental trends in N and P export by rivers to the coastal waters of South America (Table 2 and Figures 2a–2c). Total river exports of N and P amounted

Table 2. NEWS Model Output for South America[a]

	DIN Load		DIP Load		DON Load		DOP Load		PN Load		PP Load		Total N Load		Total P Load	
	Tg yr^{-1}	Percent Change	Tg yr^{-1}	Percent Change	Tg yr^{-1}	Percent Change	Tg yr^{-1}	Percent Change	Tg yr^{-1}	Percent Change	Tg yr^{-1}	Percent Change	Tg yr^{-1}	Percent Change	Tg yr^{-1}	Percent Change
1970	2.28		0.17		3.06		0.16		2.92		1.28		8.26		1.62	
2000	2.66	17	0.25	47	2.96	−3	0.16	−2	2.79	−5	1.22	−5	8.41	2	1.64	1
GO 2030	3.35	26	0.37	47	2.96	0	0.16	0	2.65	−5	1.16	−5	8.96	7	1.70	4
GO 2050	3.61	36	0.37	45	2.91	−2	0.16	−1	2.55	−8	1.12	−8	9.07	8	1.65	1
OS 2030	3.08	16	0.34	36	2.93	−1	0.16	−1	2.66	−5	1.17	−4	8.67	3	1.67	2
OS 2050	3.21	21	0.38	51	2.89	−2	0.16	−1	2.58	−7	1.14	−7	8.68	3	1.68	3
TG 2030	3.11	17	0.37	46	2.99	1	0.16	1	2.66	−5	1.17	−4	8.75	4	1.70	4
TG 2050	3.05	15	0.43	69	2.99	1	0.17	4	2.64	−5	1.16	−5	8.68	3	1.76	7
AM 2030	2.88	8	0.33	29	2.93	−1	0.16	−2	2.65	−5	1.17	−5	8.46	1	1.65	1
AM 2050	2.88	8	0.36	42	2.90	−2	0.16	−3	2.58	−7	1.14	−7	8.36	−1	1.65	1

[a] Calculated nutrient loads and % change over time since 1970 (for the year 2000) and since 2000 (for the years 2030 and 2050). Exoreic basins only. DIN, dissolved inorganic N; DIP, dissolved inorganic P; DON, dissolved organic N; DOP, dissolved organic P; PN, particulate form of N; PP, particulate form of P.

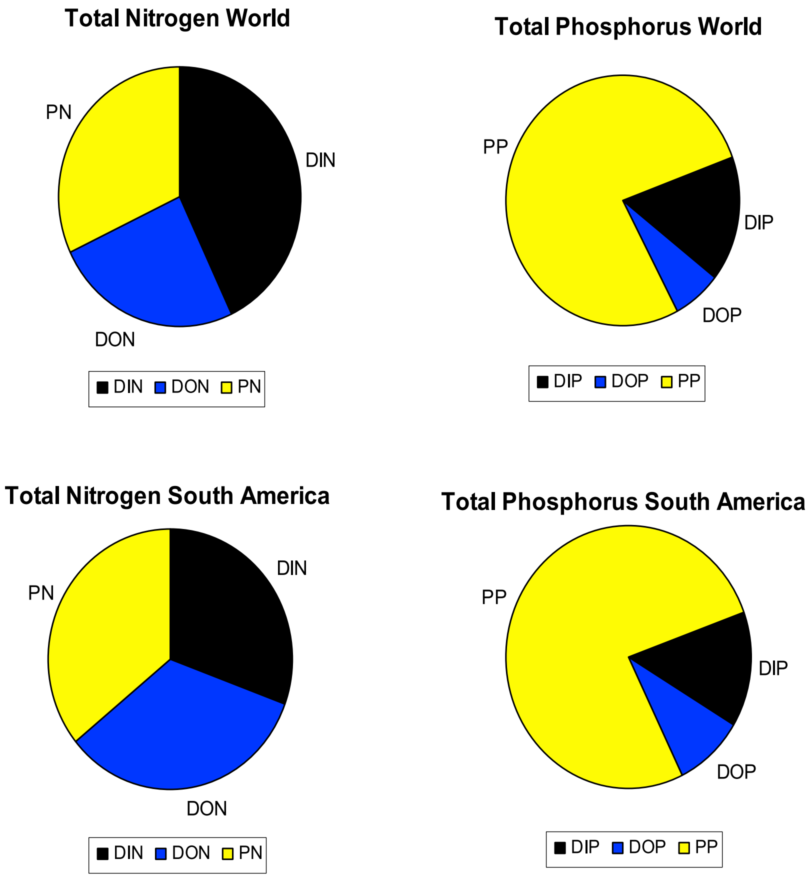

Figure 2a. Relative share of different forms of N and P in total N and P export by rivers to the coastal waters of the world and South America. NEWS model output.

to 8.4 Tg N and 1.6 Tg P in the year 2000 (Table 2). This is about 20% of the global total river export of N and P.

[23] Total N exported by South American rivers to coastal waters consists of about equal shares (30%) of DIN, DON and PN (Figure 2a). For South America the relative share of DIN is somewhat lower than for the global total. This can be explained by a relatively large share of diffuse sources from natural ecosystems (where DON is more important than in agriculture-dominated river basins) in river N export. The river export of P is largely in the form of particulate P, both in South America and globally.

[24] For the period 1970–2000, we calculate increasing trends for river export of DIN and DIP, but slightly decreasing trends for dissolved organic N and P, and for particulate N and P (Figures 2b and 2c). This is in contrast with global trends, for which an increase in all forms of N is calculated between 1970 and 2000 (Figure 2b). The increase in DIN and DIP export can be largely explained by increased human pressure on the system associated with population growth, agriculture and urbanization, and to some extent with industrialization and fossil fuel use. DIN and DIP in rivers are largely associated with anthropogenic sources, including leaching from agricultural fields and sewage, while for DON and DOP natural sources dominate (Figure 2c). The trends for DON, DOP, PN and PP are the net effect of changes in hydrology, land use and other human activities in the basins. Prior to 2000 several large dams were constructed in South America, increasing river retention of nutrients, as will be discussed below.

[25] Future trends differ among nutrient forms and scenarios (Figure 2b). We calculate increasing trends in all scenarios for dissolved inorganic N, and decreasing trends for the other forms (DON and PN) in South American rivers. This is in contrast with some of the global trends, in particulate for DIN: the NEWS models calculate decreasing future trends in worldwide export of DIN for the Adapting Mosaic scenario. For DON the differences between South American and global trends are in fact small, and close to a stabilization over time (Figure 2b). The differences between South American and global trends have different explanations. For DIN, the difference for the Adapting Mosaic scenario can be explained by future developments in sewage treatment. Globally, there is a tendency toward connecting more people to sewerage systems, and construction of sewage water treatment installations [*Van Drecht et al.*, 2009]. In many developing countries the effects of connecting more people to sewage systems outweigh the effects of improved sewage water treatment. It is interesting that for PN both past and future trends are decreasing. This is associated with changes in land use, river discharge and damming of rivers [*Fekete*

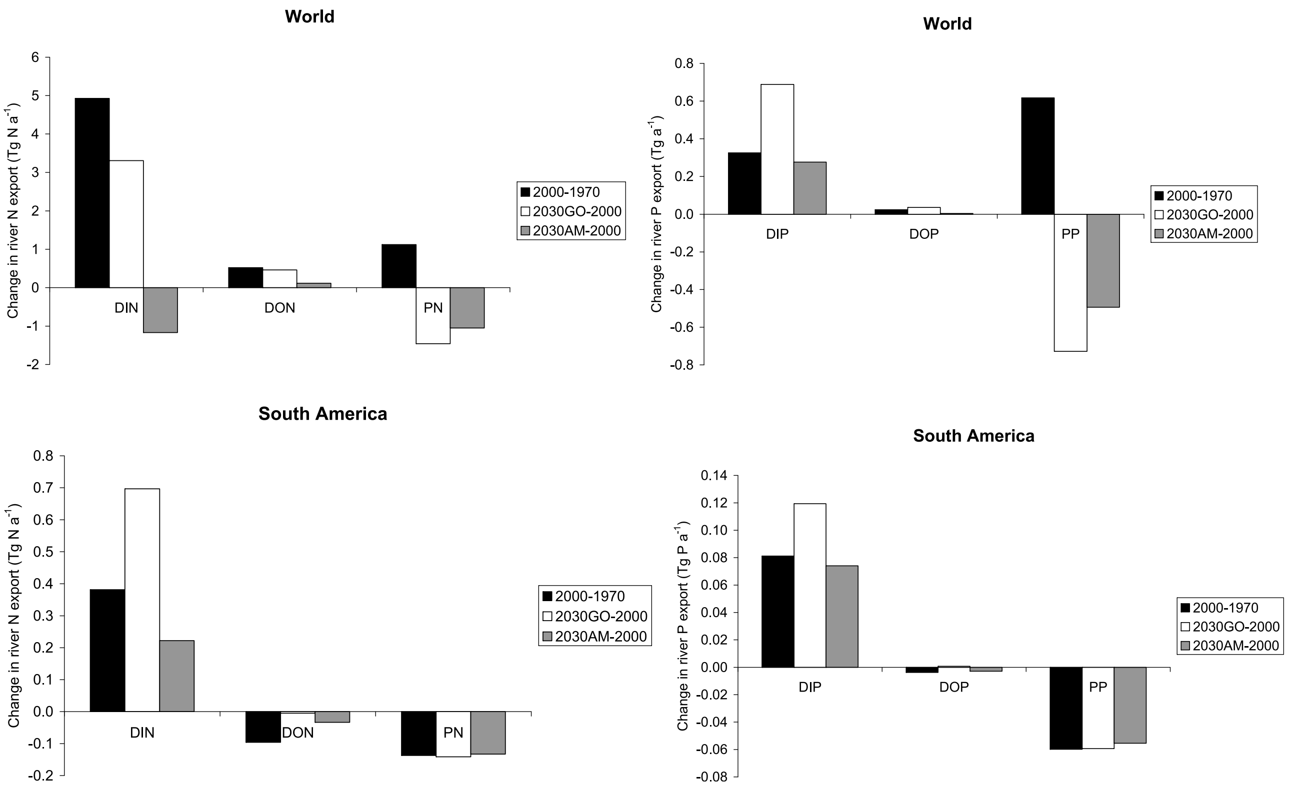

Figure 2b. NEWS Model output: Changes in N and P export by rivers to coastal waters of the world and of South America. Results for the period 1970–2000, and 2000–2030 for two scenarios: Global Orchestration (GO2030) and Adapting Mosaic (AM2030). Exoreic basins only.

et al., 2010]. The AM scenario is a special case, where there is a major effort to close nutrient cycles in agriculture by better incorporating animal manure in the production system to substitute N and P fertilizers, and by recycling human N and P. This leads to an overall reduction in river export of nutrients from agriculture.

[26] For future P export, the differences between global and South American trends are relatively small. River export of DIP is projected to increase in all scenarios (Figures 2a and 2c). The trends over time for DOP are small, as is the case for DON. For particulate forms of P the NEWS models calculate decreasing trends for South America, both for the past and the future. As for particulate N, we observe a difference with past global trends for particulate P. Trends in particulate P can, as for particulate N, be explained by trends in land use and hydrography.

3.2. Spatially Explicit Trends

3.2.1. Past Trends

[27] There is a large variation in the nutrient export among river basins in South America (Figures 3–7). Calculated total dissolved N and P yields for the year 2000 range from very low values (close to zero) to considerably more than 1000 kg N km^{-2} yr^{-1} and 100 kg P km^{-2} yr^{-1}. For dissolved inorganic N and P (DIN and DIP) the NEWS models calculate relatively high yields for a number of relatively small river basins. For the largest rivers (the Amazon and Orinoco, for instance) the yields of dissolved nutrients are typically less than 300 kg N km^{-2} yr^{-1} and less than 20 kg P km^{-2} yr^{-1}. For dissolved organic and particulate N and P (DON, DOP, PN and PP) the NEWS models also calculate relatively large yields for a number of large basins, including the Amazon. The N and P loads (in Mg per basin per year) also differ largely among basins (Figure 3). In general, total N and P loading of coastal seas by large rivers dominate.

[28] There is a large difference in past trends within the continent (Figure 4). The NEWS models calculate both increasing and decreasing trends for the period 1970–2000 for all nutrient forms. In most of the southern part of the continent (large parts of Argentina and Chile) we calculate lower nutrient export in 2000 than in 1970 (for some regions a reduction of at least 50%). Large increases are calculated for the eastern part of Brazil (Sao Francisco river and several adjacent smaller rivers draining into the Atlantic ocean). The largest increases between 1970 and 2000 are calculated for dissolved inorganic N and P (DIN and DIP). In particular river export of DIP has increased fast between 1970 and 2000: the NEWS models indicate a doubling or more for a number of rivers in the eastern part of South America, including the Parana river and the Sao Francisco river. This is associated with increased inputs from sewage systems between 1970 and 2000. During that period more people

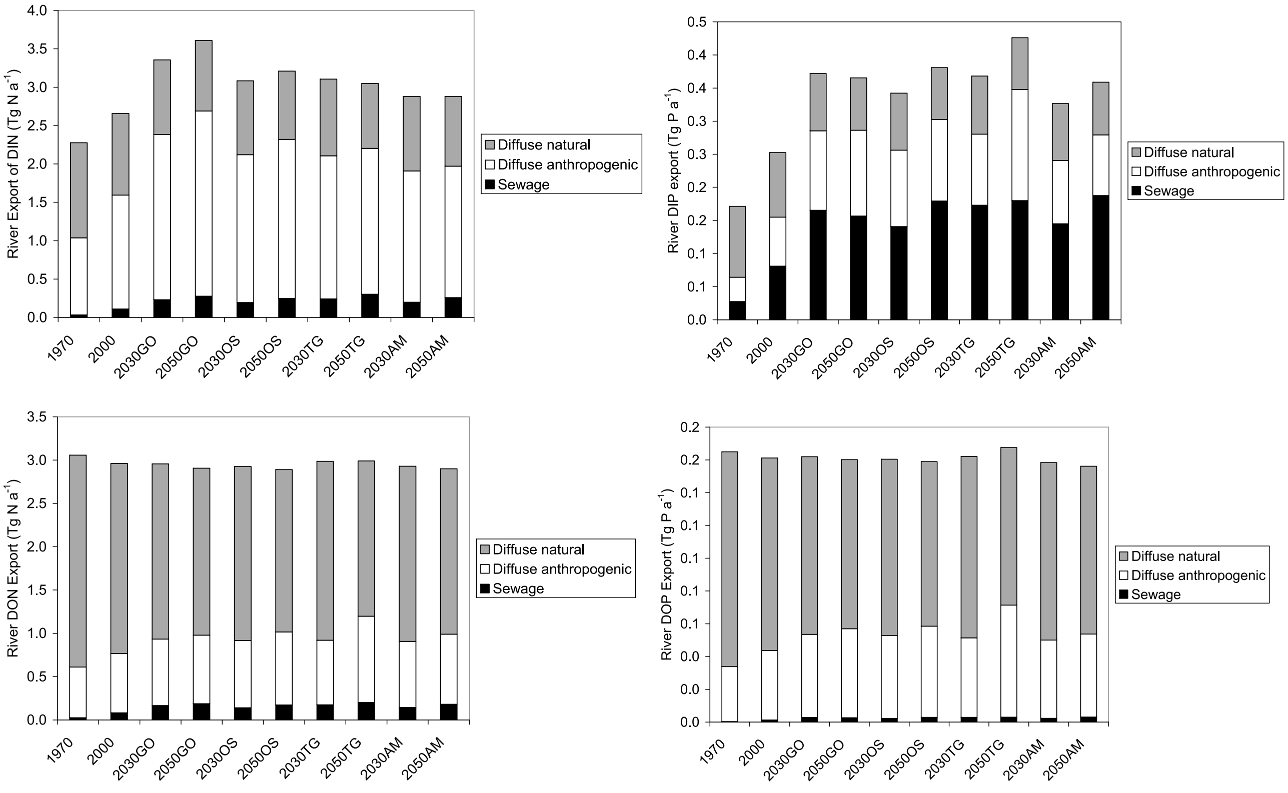

Figure 2c. NEWS Model output: dissolved inorganic N (DIN), dissolved organic N (DON), dissolved inorganic P (DIP) and dissolved organic P (DOP) export by rivers to coastal waters of South America. Results for 1970, 2000, and for 2030 and 2050 for four scenarios: Global Orchestration (GO), Order from Strength (OS), Technogarden (TG) and Adapting Mosaic (AM). Exoreic basins only.

were connected to sewerage systems, but not all systems were equipped with wastewater treatment yet, as a result of which sewage inputs of DIP to rivers increased [*Van Drecht et al.*, 2009]. Increases in river export of DIN are primarily associated with agriculture, and in particular with increased animal manure production [*Bouwman et al.*, 2009].

[29] For dissolved organic N and P (DON and DOP) the difference between export rates for the year 1970 and 2000 is less than 25% (lower or higher). These changes are smaller than for DIN and DIP. This can be explained by the fact that trends in dissolved organic fluxes are largely determined by trends in the hydrology and to some extent by land use [*Harrison et al.*, 2005a], which have not changed to a large extent over the period 1970–2000.

[30] For particulate nutrients the NEWS models calculate decreasing river export for most of the continent. The decreasing trends at the continental level are largely caused by reduced total suspended solids loads (TSS) in the Amazon, Deseado and Orinoco. These reductions in TSS loadings of rivers are associated with lower river discharge (in part caused by reduced precipitation and increased removal of water for human consumption), and land use changes. In addition, prior to 2000 a large number of dams have been built in South American rivers. Ambitious dam-building programs have more than doubled stable river flows over the last 40 years in South America [*Jones and Scarpati*, 2007]. For example, the Itaipu Dam in the Parana river is one of the largest dams worldwide, with a length of almost 8 km. Other examples of important dams are the Balbina dam in the Amazon and the Tucurui dam in the Tocantins. All three dams mentioned here are in rivers discharging into the Atlantic Ocean.

3.2.2. Future Trends

[31] Next, we analyzed spatially explicit future trends (2000–2030). We present future trends for the two most extreme scenarios: Global Orchestration and Adapting Mosaic. The calculated changes in river nutrients export for the coming decades (Figure 5 and 6) are generally smaller than the changes we have seen in past decades (Figure 4). Similar to the period 1970–2000, there is a large variation within South America: nutrient export rates may increase or decrease over time.

[32] In general, larger nutrient exports by rivers are calculated for the Global Orchestration Scenario than for Adapting Mosaic. This is a result of the proactive approach toward ecosystem management that is assumed in the Adapting Mosaic scenario. This is perhaps most clear for DIP export by rivers: for large parts of the continent the NEWS models calculate increasing trends for the period 2000–2030, in line with increased population growth and associated increases

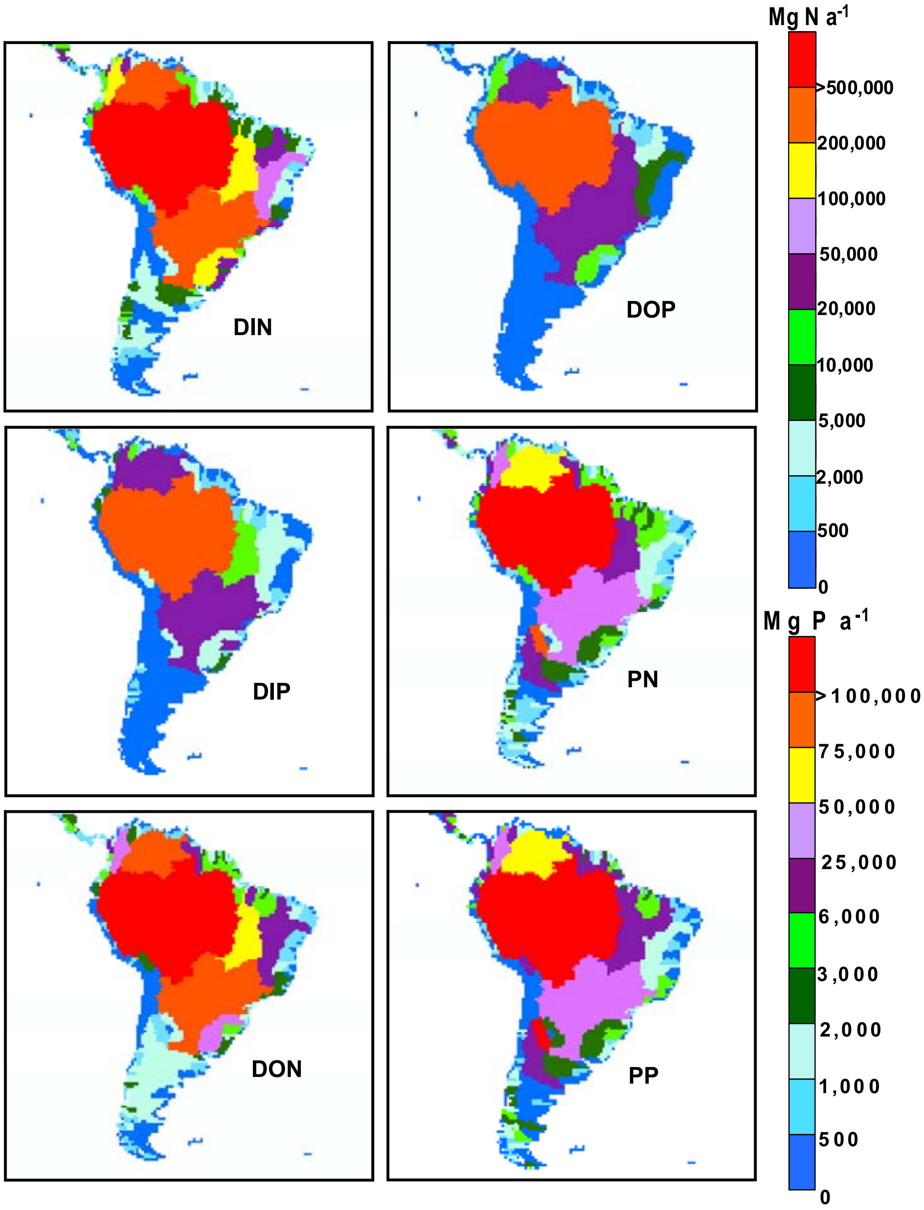

Figure 3. Nutrient export by South American rivers in 2000. NEWS Model output.

in sewage inputs of DIP in rivers. However, river export of DIP is largest for the Global Orchestration scenario. For instance, for the Parana river, draining into the Atlantic at the border of Uruguay and Argentina, we calculate large increases (more than a doubling) of DIP export in the Global Orchestration scenario (note that this implies a quadrupling since 1970), while in Adapting Mosaic the increase is less than 50%.

[33] The differences between the two scenarios are in general largely explained by the number of people connected to sewerage systems and changes in agriculture. The economic growth is lower in Adapting Mosaic than in Global Orchestration. In Adapting Mosaic the faction of the human population that is connected to sewerage systems is smaller than in Global Orchestration. In addition, the removal of N and P as a fraction of total influent to wastewater treatment is less in Adapting Mosaic than in Global Orchestration [*Van Drecht et al.*, 2009]. Finally, fertilizer N and P use is more efficient (as a result of integration of animal manure and use of human N and P) in Adapting Mosaic than in Global Orchestration [*Bouwman et al.*, 2009; *Van Drecht et al.*, 2009].

[34] The results of these changes differ among river basins. For DIN, determined primarily by agricultural sources, the export rates increase over time for most South American rivers, in line with increased food production for a growing population. In Adapting Mosaic, future fertilizer use is considerably less than in Global Orchestration, which explains

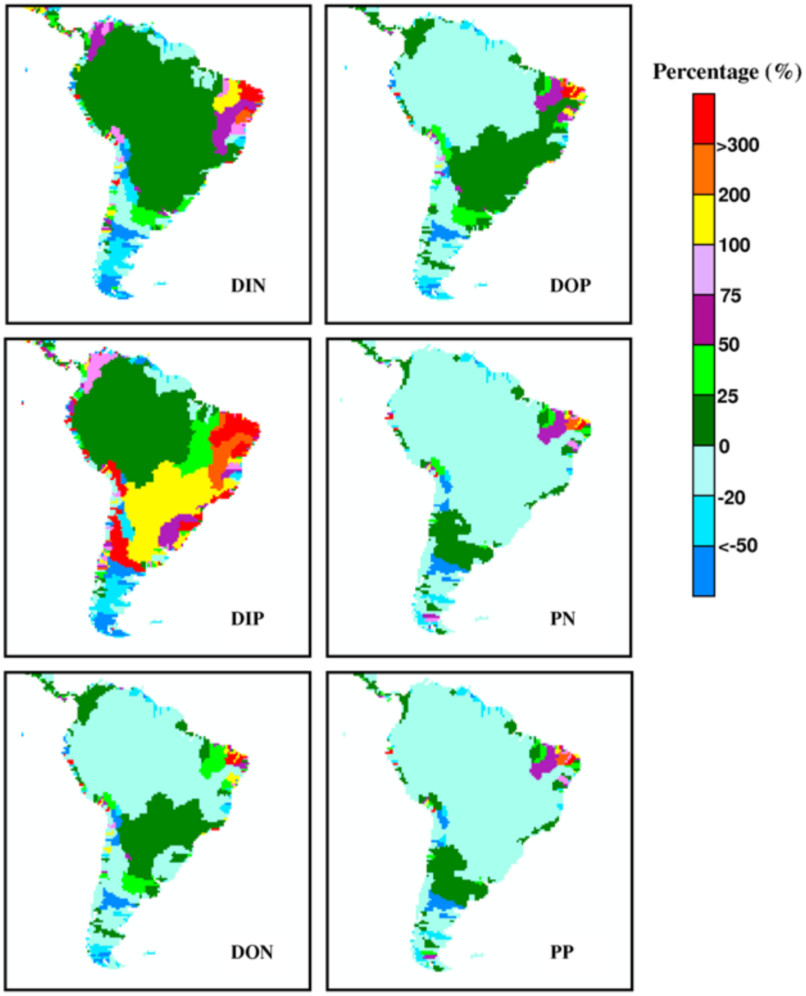

Figure 4. Changes in nutrient export by South American rivers between 1970 and 2000 (%). NEWS Model output.

the lower DIN export by rivers by 2030 (Figures 5 and 6). River exports of particulate forms of N and P (PN and PP) continue to decrease in the future, in line with changes in land use and hydrography [*Fekete et al.*, 2010].

4. Comparison of River Nutrient Export to Observed Eutrophication

[35] The next step is to compare the calculated river nutrient export rates generated by the NEWS models with observed coastal eutrophication in South America. Three global inventories of coastal eutrophication have been published [*Diaz and Rosenberg*, 2008; *Heil et al.*, 2005; *Selman et al.*, 2008]. *Heil et al.* [2005] report *P. minimum* in only two locations in South America. *Diaz and Rosenberg* [2008] include 10 observations of hypoxia in the coastal waters of South America in their inventory. *Selman et al.* [2008] indicate at least 25 locations in South American seas where eutrophication has been observed, including hypoxic areas and so-called areas of concern. The problem is likely larger than the available inventories indicate. Here, we use the assessment by *Selman et al.* [2008] as a basis for our comparison. Given the largest number of reported events of eutrophication in the *Selman et al.* [2008] inventory for South America, we consider this to be the most appropriate data set for our purpose.

[36] We compared the NEWS model outputs for the year 2000 to 25 locations identified by *Selman et al.* [2008] as eutrophied or hypoxic. We first identified rivers draining into these eutrophied locations by comparing the coordinates (degrees longitude and latitude) of the observed eutrophication zones with the location of the river mouths of the NEWS model basins. Next, we analyzed the N and P yields and loads of rivers draining into these coastal waters. We considered river nutrient export to be a potential factor explaining the observed coastal eutrophication, if N and P loads or N and P yields are relatively high. As indicator for high N load and yield we used 5 Gg N yr^{-1} and 400 kg N km^{-2} yr^{-1}, respectively. For P load and yield we used 0.5 Gg P yr^{-1} and 40 kg N km^{-2} yr^{-1}, respectively. These levels are about 40 times the average natural TDN and TDP yields and loads of rivers [*Meybeck*, 1982; *Seitzinger and Kroeze*,

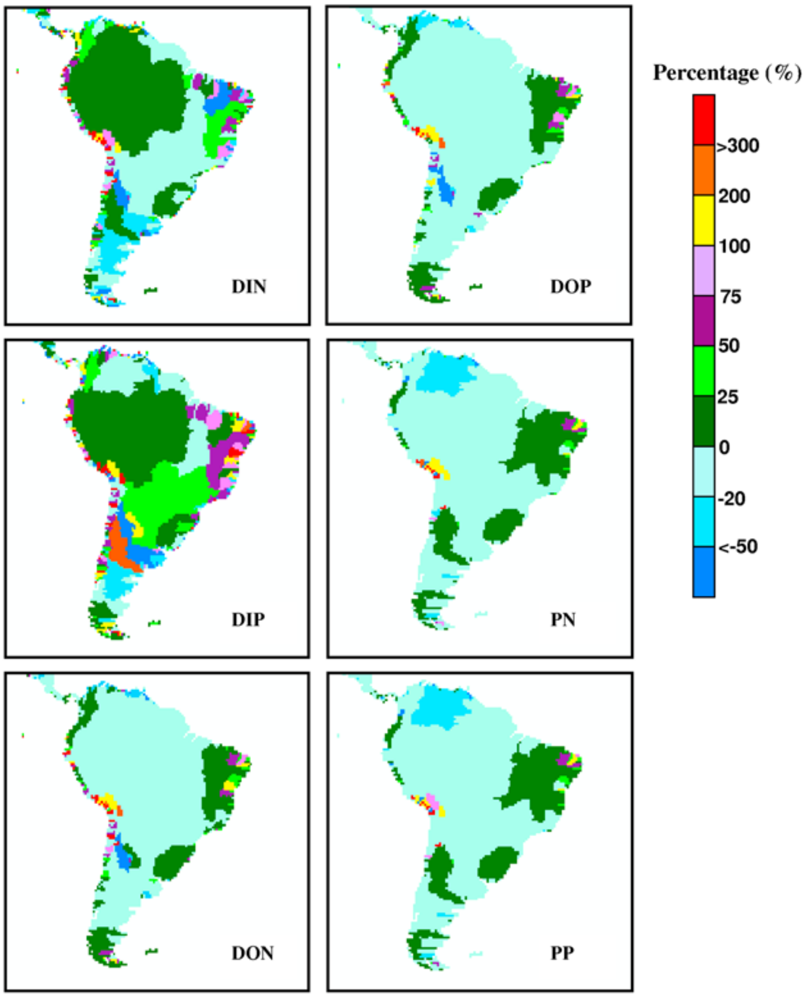

Figure 5. Changes in nutrient export by South American rivers between 2000 and 2050 for the Global Orchestration scenario (%). NEWS Model output.

1998]. The percentage of South American rivers exceeding these levels may be increasing in the future. For the Global Orchestration scenario, we calculate that the number of rivers with TDP yields exceeding 40 kg P km^{-2} yr^{-1} may double from 15% in 1970 to 30% in 2050 (Global Orchestration) (Figure 7). For total dissolved N we calculate an increase from 28% (1970) to 36% (2050 GO) of the rivers with TDN yields exceeding 400 kg N km^{-2} yr^{-1}. Rivers for which we calculate nutrient yields exceeding 40 kg P km^{-2} yr^{-1} or 400 kg N km^{-2} yr^{-1} have in many cases not yet been identified as eutrophied systems in the available inventories of coastal eutrophication. We consider this an indication that the risk for eutrophication in coastal waters of South America may increase in the future.

[37] On the basis of these criteria, there are 12 locations where river nutrient export may explain the observed eutrophication problems, out of the 25 locations from *Selman et al.* [2008] (Figure 8). Anthropogenic sources of N and P are dominant in the rivers draining into these 12 coastal zones, the most important sources of DIN, DON and DIP being animal manure and sewage. For DOP also leaching is identified as an important source. Among the 12 locations, there are four in which large rivers drain, i.e., Patos Lagoon, the Itata draining into the Concepcion Bay, the Chira draining into the Paita Bay, and the Orinico river draining into the Orinico Delta (Table 3). Among the other rivers several are relatively small (covering less than 5 grid cells, or ~12500 km^2). It should be noted that for small river basins the NEWS results need to be interpreted with caution because of scaling problems.

[38] We also explored future trends for the relatively large rivers (Table 3) to analyze in what direction potential eutrophication may change in the coming decades according to the MEA scenarios. The results for these systems differ considerably. For Patos Lagoon, we calculate increases in river export for all nutrient forms in all scenarios. For the Oronico, we calculate decreasing trends, except for DIN. For Concepcion Bay and Paita Bay the trends differ among nutrient forms. The rates of increase are highest for DIN and DIP inputs to Paita Bay (5–10 fold increase). We also identified the dominant sources of dissolved N and P. For Patos Lagoon and Concepcion Bay diffuse sources from agricul-

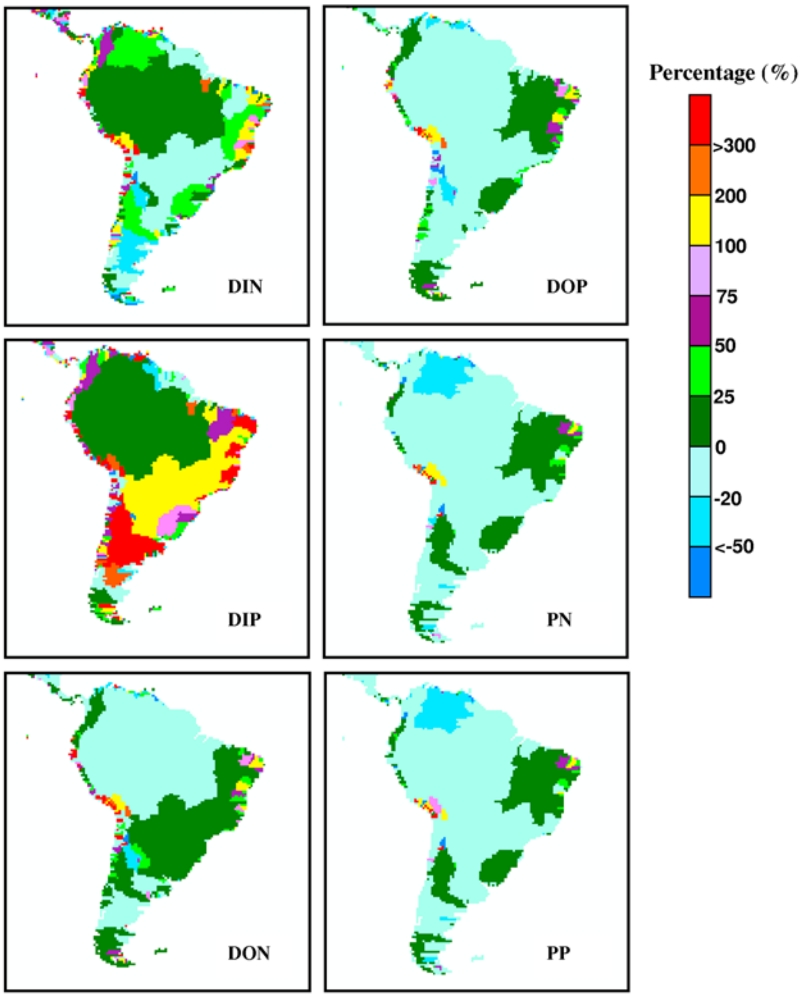

Figure 6. As Figure 5 but for the Adapting Mosaic scenario.

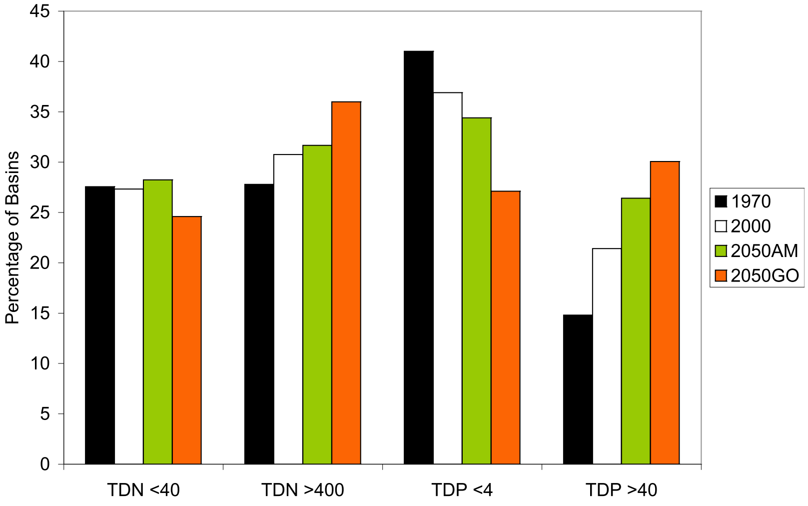

Figure 7. Percentage of river basins in South America with Total Dissolved N and P yields below 40 and 4 kg km^{-2} yr^{-1}, and above 400 and 40 kg km^{-2} yr^{-1}, respectively.

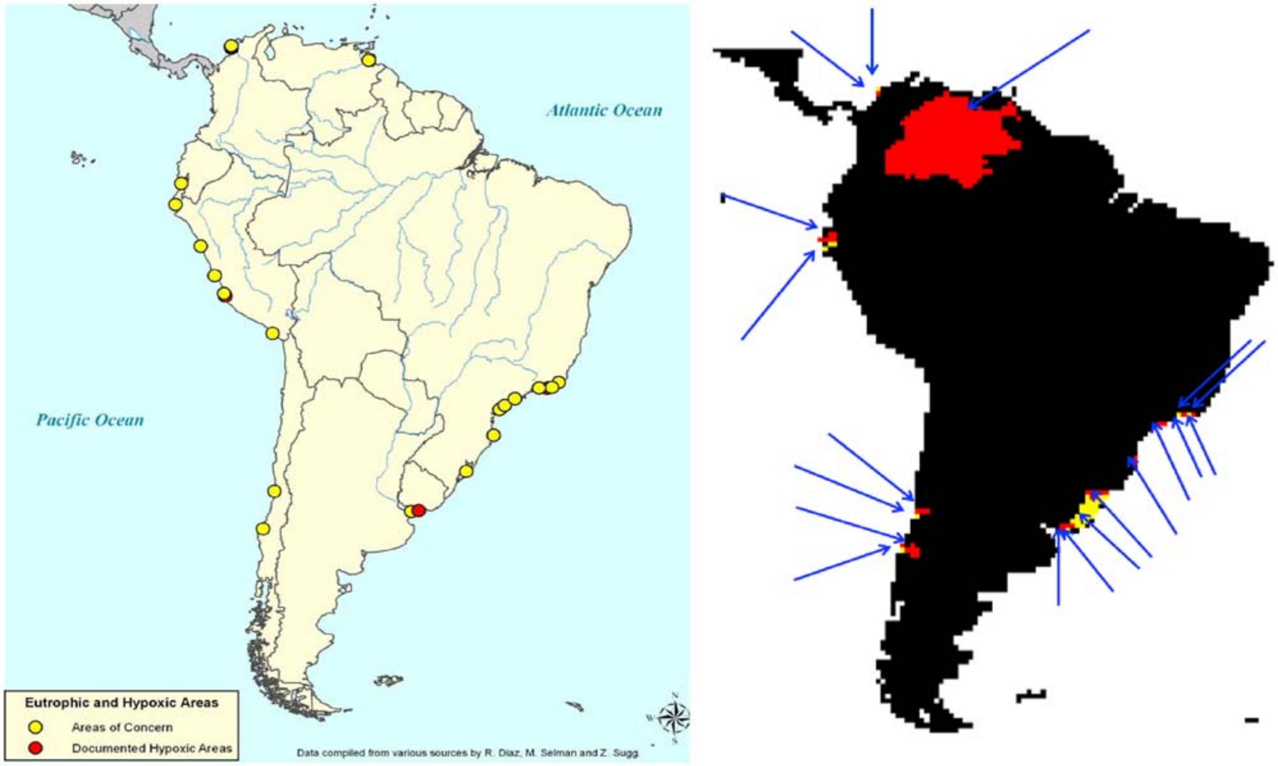

Figure 8. (left) Twenty-five locations where episodes of coastal eutrophication or hypoxia have been observed in South America [*Selman et al.*, 2008] and (right) nineteen Global NEWS river basins (indicated by arrows and colors) for which we consider the modeled nutrient export rates consistent with observed eutrophication in 12 locations.

Table 3. Changes in Calculated Nutrient Export by Rivers to Four Observed Eutrophic Sites[a]

	Change in Nutrient Export by Rivers 2000–2050 (Percent Relative to 2000)								Dominant Sources			
	DIN	DIP	DON	DOP	DOC	PN	PP	POC	DIN	DIP	DON	DOP
						Patos Lagoon						
GO	61	45	13	17	7	5	5	5	AntDif	AntDif	AntDif	AntDif
OS	21	21	8	4	5	5	5	5	AntDif	AntDif	AntDif	AntDif
TG	26	15	9	4	5	3	3	3	AntDif	AntDif	AntDif	AntDif
AM	18	19	9	4	6	5	5	5	AntDif	AntDif	AntDif	AntDif
						Concepcion Bay (*Itata River*)						
GO	111	77	−1	28	−20	−20	−18	−18	AntDif	AntDif	AntDif	AntDif
OS	107	116	3	32	−19	−17	−16	−16	AntDif	AntDif	AntDif	AntDif
TG	120	96	5	33	−14	−14	−13	−13	AntDif	AntDif	AntDif	AntDif
AM	60	86	3	12	−17	−16	−15	−15	AntDif	Sewage	AntDif	AntDif
						Paita Bay (*Chira River*)						
GO	1098	2200	651	461	214	−8	−7	−7	Sewage	Sewage	Sewage	Sewage
OS	513	892	371	240	56	−3	−3	−3	Sewage	Sewage	Sewage	Sewage
TG	1271	2853	764	548	233	−8	−7	−7	Sewage	Sewage	Sewage	Sewage
AM	1054	2420	727	490	175	−7	−6	−6	Sewage	Sewage	Sewage	Sewage
						Orinoco Delta						
GO	39	−20	−16	−13	−19	−43	−43	−43	AntDif	AntDif	NatDif	NatDif
OS	41	−21	−14	−11	−16	−41	−41	−41	AntDif	AntDif	NatDif	NatDif
TG	34	−10	−9	−7	−12	−29	−29	−29	AntDif	AntDif	NatDif	NatDif
AM	7	−35	−15	−15	−17	−40	−40	−40	AntDif	AntDif	NatDif	NatDif

[a] Also shown are the dominant sources of dissolved N and P: AntDif, Diffuse sources from agricultural land; NatDif, Diffuse sources from natural land; Sewage, point source inputs from sewage.

tural lands are dominating, while for Paita Bay sewage inputs are dominant. Nutrients in the Orinoco river are both from natural leaching and agricultural lands. These analyses may point toward policies to reduce the nutrient inputs to these coastal systems. Nutrient inputs to Paita Bay would be most effectively reduced by improved sewage treatment, while in Patos Lagoon and Concepcion Bay it is likely more effective to reduce N and P losses from agriculture.

[39] Our analyses also reveal interesting trends in sources over time. For instance, for the Chira river we identified for 1970 manure as dominant source of DIN in rivers, natural weathering as dominant source for DIP, and leaching as dominant source for DON and DOP. For 2050, sewage is dominant for all nutrients in the Chira river (Table 3). For DIP in the Itata river the results are opposite: while sewage was the dominant source of DIP in 1970, agricultural sources dominate in 2050. For the Orinoco, we see a shift in dominant sources for DIP from natural sources (weathering) in 1970, to anthropogenic sources (manure) in 2050. These trends reflect the regional differences in human activities in the MEA scenarios.

[40] It should be noted, that the NEWS models ignore a few sources of nutrients in coastal waters. Among these are direct atmospheric inputs of N to coastal waters, direct leaching of nutrients into coastal waters (not through rivers), and onwelling from the deep ocean. In addition, we did not account for aquaculture. In Brazil and other South American countries, aquaculture is important, and may contribute to coastal eutrophication, since fish ponds are in general sources of nutrients and sediments, while aquaculture in marine waters may enhance mineralization of organic N into mineral forms, thus contributing to eutrophication. To what extent aquaculture is a dominant source of nutrients in coastal seas remains to be investigated. It would be interesting to expand the NEWS models with aquaculture as a source of nutrients, to analyze this in more detail.

[41] Summarizing, comparison of observed eutrophication with NEWS model results is useful, but complicated by several factors. Coastal eutrophication is usually a local phenomenon, occurring only part of the year, while the Global NEWS models are developed to explore larger-scale annual trends. Nevertheless, we could link about 50% of the locations with observed coastal eutrophication to NEWS model basins with relatively high N and P export rates. This is an indication that the NEWS model results can be used as a basis for analyses of potential eutrophication, and help to identify policy options to reduce coastal eutrophication. It should be noted, that in such assessments not only N, P and C should be considered, but also Si [*Billen and Garnier*, 2007; *Garnier et al.*, 2010].

5. Conclusions

[42] We analyzed past and future trends in nutrient export by rivers to the coastal waters of South America. River exports of DIN and DIP increased between 1970 and 2000, while for dissolved organic N and P, and for particulate N and P decreasing trends are calculated. Future trends differ among nutrient forms and scenarios. We calculate increasing trends in all scenarios for dissolved inorganic N and P, and decreasing trends for the other forms (DON, DOP, PN and PP) in South America.

[43] We conclude that in the future, there may be more eutrophication in the coastal waters of South America than today. The number of rivers with high N and P yields may increase considerably between 1970 and 2050. For instance, the number of rivers with total dissolved P yields exceeding 40 kg P km^{-2} yr^{-1} may double between 1970 and 2050. If this is accompanied with increased N and C yields, and reduced Si yields, there is an increased risk for coastal eutrophication [*Billen and Garnier*, 2007; *Garnier et al.*, 2010].

[44] We also conclude that river exports of N and P vary among river basins. The calculated N and P yields for the year 2000 range from low values (close to zero) to more than 1000 kg N km^{-2} yr^{-1} and more than 100 kg P km^{-2} yr^{-1}. In general, increased nutrient exports by rivers are calculated for the Global Orchestration Scenario than for Adapting Mosaic, in line with the proactive approach toward ecosystem management that is assumed in the Adapting Mosaic scenario.

[45] The NEWS models not only calculate river export of nutrients, but also give insight in the sources of these nutrients. Combining this information with trends in human activities that are used as model inputs gives insight in why nutrient loadings in rivers are changing over time, and how to prioritize policies to reduce coastal eutrophication. We illustrate this for four eutrophied coastal systems. We show that for some systems improved sewage treatment may be the most effective policy to reduce emissions, while for others fertilizer efficiency improvement may be preferred.

[46] The strength of the NEWS approach is how trends in nutrient export are calculated as a function of human activities on the land, and watershed characteristics. Another strength is the global coverage. This makes it possible to analyze potential coastal eutrophication for regions that are poor in data and for which few local models exist, such as many tropical regions. Although the NEWS models were not developed for analyses of individual rivers, a number of successful local application of global nutrient export models exist [*Scheren et al.*, 2004; *Thieu et al.*, 2010; *Yan et al.*, 2010]. Our study adds to this by illustrating how the NEWS models can be useful in regional assessments of coastal eutrophication.

[47] **Acknowledgments.** This study was performed as part of the international Global Nutrient Export from Watershed(S) (NEWS) activity: http://marine.rutgers.edu/globalnews. Global NEWS has been cofunded by UNESCO-IOC and is a project under LOICZ.

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