



Nutrients export by rivers to the coastal waters of Africa: Past and future trends

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[1] We analyze past and future trends in nitrogen (N), phosphorus (P), and carbon (C) export by rivers to the coastal waters of Africa as calculated by the Global Nutrient Export to WaterShed (NEWS) models for the period 1970–2050. Between 1970 and 2000 the total nutrient export by African rivers increased by 10–80%. For future years (2000–2050) we calculate an increase in the total loads of dissolved forms of N and P, but decreasing trends for dissolved organic C and particulate forms of N and P. There are large regions that deviate from these pan-African trends. We explore the regional patterns and the underlying processes, in particular for the Nile, Zaire, Niger, and Zambezi. In the future, anthropogenic sources may, in large parts of Africa, become larger contributors to riverine nutrient loads than natural sources.

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1. Introduction

[2] More than one third of the global population lives in coastal areas constituting less than 10% of the global surface area [Vitousek *et al.*, 1997], while approximately 70% of the population resides within 60 km of the shore [Pernetta and Elder, 1992]. Consequently, many economic and industrial activities take place directly in coastal areas. The world's largest harbors, large cities and tourist resorts are built along the coast.

[3] Human activities on land affect the quality of coastal waters. Agricultural and industrial activities and combustion of fossil fuels have increased nutrients inputs to aquatic systems, including nitrogen (N), phosphorus (P) and carbon (C) species [Galloway and Cowling, 2002; Galloway *et al.*, 2004; Meybeck, 1982]. The resulting eutrophication of coastal waters has impacted aquatic ecosystems and societal use of coastal resources. Across the world, increased nutrient concentrations and shifts in N:P ratios that remove nutrient limitations have been linked to algal blooms and subsequent oxygen depletion or hypoxia, with often severe impacts on coastal ecosystems [Diaz and Rosenberg, 2008; Justic *et al.*, 1995; Turner and Rabalais, 1994; Vince and Valiela, 1973]. Worldwide, a few hundred observations of eutrophic and hypoxic coastal systems have been reported [Selman *et al.*,

2008], including hypoxia-induced “dead zones” [Diaz, 2001; Diaz and Rosenberg, 2008].

[4] As in other parts of the world, the coastal population in Africa has been increasing rapidly. This population increase is associated with increased human activities, potentially resulting in pollution of surface waters. Untreated sewage systems are an important source of nutrients in African surface waters. In addition, the demand for fuel wood and timber has increased in many regions. The resulting deforestation and erosion may lead to increased nutrient levels in surface waters. As in many other regions, an important driver for increased nutrient export by African rivers is increased and inefficient use of artificial fertilizers [Coughanowr and Linden, 1995; Galloway *et al.*, 2004; Vitousek *et al.*, 1997], although in many parts of Africa crop production without nutrient replenishment has led to substantial soil impoverishment and decreasing crop yields [Vitousek *et al.*, 2009]. As a result of these and other pressures coastal waters have deteriorated, and in some cases nutrient enrichment may have led to irreversible changes [Boesch, 1999; Kullenberg, 2001; Turner and Rabalais, 1994; Turner *et al.*, 2003]. In African coastal waters, approximately 20 occurrences of eutrophication have been reported [Selman *et al.*, 2008]. This must be considered a serious concern, given the fact that no systematic research has been performed on the frequency of eutrophic events in Africa.

[5] A typical example of severe coastal eutrophication in Africa is the Ebrié lagoon: a large coastal ecosystem off Ivory Coast in Western Africa, in the Gulf of Guinea [Droge and Kroeze, 2007; Scheren *et al.*, 2004; Ukwe *et al.*, 2006]. Along the coast of this Gulf, rapid population growth has been associated with industrial development and increased agricultural production, with negative consequences for the

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Figure 1. The four largest rivers of Africa.

environment [Scheren *et al.*, 2002]. Abidjan, a large city in Ivory Coast, is located close to the coast, and its wastewater is discharged almost directly into the Ebrié lagoon. Apart from this direct influence of Abidjan on coastal water quality, nutrient levels in the lagoon depend on the influx of nutrients from three major rivers: the Comoé, Mé, and Agnéby. The sources of N loads to the lagoon are estimated to be urban (45%), land runoff (43%), and atmospheric deposition (13%) [Scheren *et al.*, 2004]. Without pollution reduction measures, nutrient inputs to the lagoon may increase relatively fast in the coming decades [Scheren *et al.*, 2004].

[6] Studies on future trends in nutrient export by African rivers are scarce. Even though African rivers typically export less nutrients to coastal waters than many rivers in other regions [Caraco and Cole, 1999; Meybeck, 1982; Meybeck and Ragu, 1996], this may change rapidly in the future. The African population is projected to grow relatively fast. As a consequence, more sewage will be generated and drained to the coastal waters by rivers [Scheren *et al.*, 2004]. In addition, fuel, food consumption and fertilizer application will increase accordingly as the economy of the continent is anticipated to steadily grow in the decades to come.

[7] An early modeling study indicated that the export of dissolved inorganic N (DIN) by African rivers to the Atlantic Ocean may triple between 1990 and 2050, to 1.8 Tg N yr^{-1} [Kroeze and Seitzinger, 1998]. This increase is largely associated with an increasing population in the African watersheds draining into the North Atlantic Ocean, as a result of which fertilizer use may increase fivefold and atmospheric N deposition may double. These trends are in line with IPCC IS92 scenarios, published in the early nineties and the model used to calculate DIN export rates has been improved considerably since then [Dumont *et al.*, 2005].

[8] The more recently developed Nutrient Export to WaterShed (NEWS) models, developed by the Global NEWS group simulate nutrient export from land to sea for nitrogen, phosphorus and carbon species. NEWS models have been developed for dissolved and particulate forms of N, P and C [Beusen *et al.*, 2005; Dumont *et al.*, 2005; Harrison *et al.*, 2005a, 2005b; Mayorga *et al.*, 2010; Seitzinger *et al.*,

2005]. The NEWS models are spatially explicit, global nutrient export models, linking human activities on land and watershed characteristics to nutrient export by rivers to coastal waters. Recently, the NEWS models have been used to explore global trends in nutrient loading of coastal waters for the period 1970–2050 [Seitzinger *et al.*, 2010]. These scenarios are based on the Millennium Ecosystem Assessment Scenarios [Alcamo *et al.*, 2006], and describe possible futures without explicit policies to reduce pollution of coastal waters. The NEWS models include more than 500 African basins.

[9] The purpose of our study is to analyze the past and future trends of export of NEWS nutrients by rivers to the coastal waters of Africa. NEWS models calculate river export of dissolved inorganic N and P (DIN, DIP), dissolved organic N, P and C (DON, DOP, DOC), and particulate forms of N, P and C (POC, PN, PP) as well as total suspended solids (TSS). We will first analyze nutrient export rates by African rivers in 1970 and 2000. Next, we will explore future (up to 2050) trends for the four Millennium Ecosystem Assessment (MEA) scenarios. We will present nutrient yields and exports, and dominant nutrient sources. We will discuss past and future nutrient export rates by the four largest African rivers: the Nile, Zaire, Niger, and Zambezi, with a special focus on dissolved inorganic N (DIN). These four rivers covering about one third of the total surface area of Africa (Figure 1).

2. Models and Scenarios

2.1. NEWS Models

[10] The NEWS Expert Group developed a number of global, regionally explicit models of nutrient export from land to sea [Seitzinger *et al.*, 2010]. As mentioned above, we use the NEWS models to calculate past and future trends in river export of eight nutrient forms of N, P and C, and Total Suspended Solids (TSS) to coastal waters. River export of these compounds is calculated as a function of human activities on the land, river basin characteristics, and hydrology. The 2009 versions of NEWS models are combined in one interface to ensure consistency in input data and calculations [Mayorga *et al.*, 2010]. The models are updates of the 2005 NEWS models [Seitzinger *et al.*, 2005], in which every dissolved nutrient form had an independent model. These models were referred as NEWS-DIN, NEWS-DIP NEWS-DOC, NEWS-DON and NEWS-DOP [Dumont *et al.*, 2005; Harrison *et al.*, 2005a, 2005b]. For the particulate forms and TSS, a model called NEWS-PNU was developed [Beusen *et al.*, 2005]. The 2009 versions of NEWS models include the NEWS individual models in one interface, which makes it a very powerful multinutrient and multiform unified model with 0.5×0.5 degree global resolution. This interface allows us to run all the NEWS nutrient forms at the same time.

[11] The NEWS models have been used to calculate past trends in nutrient export by rivers (1970–2000) and future trends for the four Millennium Ecosystem Assessment scenarios for the years 2030 and 2050. The NEWS model inputs include information on diffuse sources of nutrients [Bouwman *et al.*, 2009], point sources [Van Drecht *et al.*,

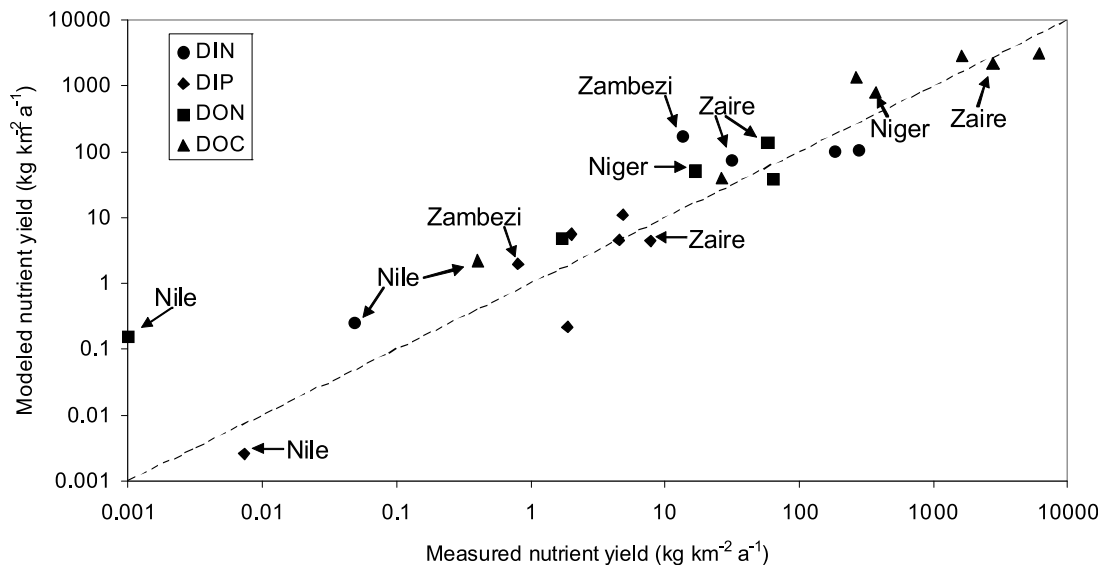


Figure 2. Modeled (year 2000) versus measured nutrient yield by African rivers (Nile, Gambia, Niger, Ogooue, Orange, Rufiji, Sanaga, Sebou, Tana, Tugela, Zaire, and Zambezi). Measured yields include DIN (Dissolved Inorganic Nitrogen), DON (Dissolved Organic Nitrogen), DIP (Dissolved Inorganic Phosphorus), and DOC (Dissolved Organic Carbon) and are from various sources including data sets used for NEWS model development and global validation [Dumont *et al.*, 2005; Hall *et al.*, 1977; Harrison *et al.*, 2005a, 2005b; Lesack *et al.*, 1984; Mayorga *et al.*, 2010; Meybeck and Ragu, 1996; Nixon, 2003; Smith, 2003; Van Bennekom *et al.*, 1978].

2009] and hydrology [Fekete *et al.*, 2010]. The models include more than 6000 rivers basins of the world, of which 524 in Africa, of which 11 do not drain into the oceans (endorheic basins). Input data for these basins are typically needed on a grid of 0.5×0.5 degree. The catchment sizes of river basins vary largely. Large basins, such as those of the Nile, Zaire, Niger and Zambezi, cover large parts of Africa, while there are also many small basins covering only a few grid cells in the NEWS models. We consider the NEWS models as fairly complete and comprehensive. For details on the NEWS models we refer to other papers describing the model and model inputs, as indicated above. We present results for exorheic basins (draining into coastal waters) unless mentioned otherwise.

[12] There are three reasons why we consider the Global NEWS model applicable to Africa, a continent for which measurements of nutrients in rivers are not widely available.

[13] First, and most importantly, the Global NEWS models have been calibrated and validated at the global level, using measurements of nutrient export by rivers in many different climatic regimes, including tropical rivers similar to African conditions. To this end, a carefully selected set of measurement data has been compiled, including a wide range of rivers from different continents and different climatic zones. Only observed values were included for rivers where measurements at the river mouth are available for a relatively large part of the year. The NEWS models typically explain 50–70% of the observed variation in nutrient export by rivers worldwide. The manuscripts describing the Global NEWS models present and discuss these validations [Beusen *et al.*, 2005; Dumont *et al.*, 2005;

Harrison *et al.*, 2010, 2005a; Mayorga *et al.*, 2010]. These global validations help to justify the use of Global NEWS models to Africa or any other world region.

[14] Second, Figure 2 shows that nutrient yields range from <0.01 to over $6000 \text{ kg km}^{-2} \text{ yr}^{-1}$. This ranges covers 5 orders of magnitude. The modeled range is generally in line with the observed range, indicating that the NEWS models generally calculate highest nutrient export rates for the most polluted rivers, and vice versa. For instance, for the Nile the measured yields ($<0.1 \text{ kg km}^{-2} \text{ yr}^{-1}$) [Nixon, 2003] are as low as the modeled yields ($<0.3 \text{ kg km}^{-2} \text{ yr}^{-1}$), while for the Zaire both measured and modeled yields are 2 to 3 orders of magnitude larger. The low yields for the Nile are associated with the damming of the river in the year 1965 by the Aswan High Dam. Before that year, DIN and DIP yields were a factor of 35–250 higher than today [Nixon, 2003]. The NEWS model do not calculate predam conditions, but are able to reflect the low postdam nutrient yields reasonably well. Also for the Ebrié Lagoon (Ivory Coast) past trends are resembled well: the calculated total N exported by rivers into for 1970 (almost 20 Gg N yr^{-1}) and 2000 (almost 30 Gg yr^{-1}) are in line with a detailed assessment of this lagoon [Scheren *et al.*, 2004]. Figure 2 includes, however, also outliers, such as DIN yield for the Zambezi. It is important to note that measurement data for African rivers are not widely available. Figure 2 includes annual yields of DIN, DIP, DON and DOC for only 12 African rivers. Only measurement data are included of experiments where nutrient concentrations at the mouth of the river were measured for a long enough period to estimate annual fluxes. The data set is too small for statistical analyses. We also need to note that

Table 1. Population, Gross Domestic Product, Population Connected to Sewage, N Surplus, and P Surplus for Africa in 1970, 2000, and in 2050 for the Four Millennium Ecosystem Assessment Scenarios^a

	Population (millions)	GDP (1995 US\$ person ⁻¹ yr ⁻¹)	Population Connected to Sewage (%)	Soil N Balance ^b (Tg N yr ⁻¹)	Soil P Balance ^b (Tg P yr ⁻¹)
1970	357	695	10	12.7	0.6
2000	796	746	14	18.2	1.2
2050 AM	1927	1905	16	25.6	3.2
2050 GO	1443	2993	36	42.4	6.1
2050 OS	2014	1488	17	36.8	4.7
2050 TG	1717	2659	36	37.0	5.1

^aScenarios: GO, OS, TG, AM; see text for scenario descriptions. Source: *Bouwman et al.* [2009] and *Van Drecht et al.* [2009]. Including endorheic basins. GDP, Gross Domestic Product.

^bSum of all inputs minus sum of N and P removal in crops, grass, and grazing and minus ammonia volatilization.

the results are presented at a logarithmic scale. For a number of rivers the model seems to overestimate nutrient yields. This is why we do not present model output for individual rivers in this study. However, because of the low number of rivers included in Figure 2, we cannot draw conclusions from this on the validity of the model for Africa. It rather illustrates the lack of experimental data for Africa.

[15] A third reason to apply Global NEWS to Africa is the fact that data are limited. An earlier version of the NEWS DIN model has been found useful for analyses of N export to coastal waters of Africa, in particular for data poor regions [*Scheren et al.*, 2004]. When coastal eutrophication is a problem to be solved, and experimental studies on the causes of the problem and trends over time are lacking, models can help to better understand the problem at stake. We believe it is the strength of the Global NEWS models that we can use them for large world regions where data is limited. Our reasoning is in line with a study demonstrating the use of global Earth System Science for water assessment in information-poor regions, such as Africa [*Vörösmarty et al.*, 2005].

2.2. Millennium Ecosystem Assessment Scenarios

[16] In this study, four Millennium Ecosystem Assessment (MEA) scenarios are analyzed to project future nutrient export by rivers: Global Orchestration (GO), Order From Strength (OS), Technogarden (TG) and Adapting Mosaic (AM). For each of these scenarios the input data needed for the NEWS models were prepared [*Bouwman et al.*, 2009; *Fekete et al.*, 2010; *Van Drecht et al.*, 2009]. The model input is required on a 0.5×0.5 degree longitude-latitude grid, or on a watershed basis. Important inputs include trends in hydrology, human population, agriculture (fertilizer use, animal manure excretion, land use) and point sources inputs (largely associated with sewage systems). A brief description is given below for each scenario. The descriptions are adapted from the Millennium Ecosystem Assessment [*Alcamo et al.*, 2006]. The 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). The GO scenario and TG scenario describe a globalized

world, while TG and AM are characterized by proactive ecosystem management.

[17] In the following we characterize the MEA scenarios shortly, and also describe some important assumptions made for Africa. In general, all scenarios assume that population and per capita GDP increase over time in Africa, as well as meat and milk consumption. On the other hand, the N efficiency of agriculture is assumed to increase as well in all scenarios. The net effect of these trends is that fertilizer use and animal production are increasing at a faster rate than population in all scenarios [*Bouwman et al.*, 2009]. Point sources of N and P in rivers are mainly associated with sewage, which in turn is driven by trends in population and sewage treatment.

2.3. Adapting Mosaic

[18] The Adapting Mosaic (AM) scenario describes a regionalized world, with proactive ecosystem management. Regional watershed-scale ecosystems are the focus of economic and political developments. 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. The population increase is comparable to the other regionalized scenario (OS), with the African population increasing to 1.9 billion by 2050 (Table 1). The per capita GDP increases by 140% between 2000 and 2050. The environmental management in AM includes local, simple and economically feasible options. This is in contrast with the TG scenario, which focuses on high-tech options. In the AM scenario, human N and P use follows the concept of ecological sanitation and closing N and P cycles locally. Only 16% of the African people are connected to sewage systems in this scenario in 2050.

2.4. Global Orchestration

[19] The Global Orchestration (GO) scenario describes a globalized world characterized by global trade and economic liberalization, with a reactive attitude toward ecosystem management. Rather, the focus is on material wealth and economic growth. It also aims at reducing poverty and inequality and to invest in infrastructure and education. Between 2000 and 2050, the Africa population increases by 80% to 1.4 billion in this scenario, which is lower than for

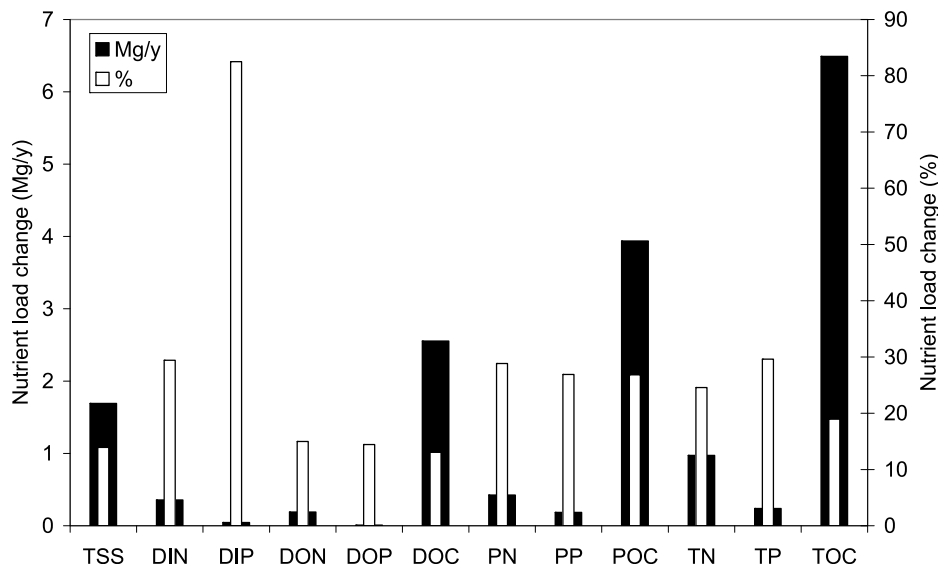


Figure 3. Change in nutrient loads to coastal waters from African watersheds between 1970 and 2000 as calculated by the NEWS models, for individual nutrient forms, total elemental loads, and suspended solids. TSS, Total Suspended Solids; DIN, Dissolved Inorganic Nitrogen; DIP, Dissolved Inorganic Phosphorus; DON, Dissolved Organic Nitrogen; DOP, Dissolved Organic Phosphorus; DOC, Dissolved Organic Carbon; PN, Particulate Nitrogen; PP, Particulate Phosphorus; POC, Particulate Organic Carbon; TN, Total Nitrogen; TP, Total Phosphorus; TOC, Total Organic Carbon (note that unit for TSS nutrient load change is in $\text{Mg yr}^{-1}/100$). Exorheic basins only.

the other three scenarios (Table 1). On the other hand, the increase in per capita GDP (300% between 2000 and 2050) is larger than in the other three scenarios and also meat and milk consumption is increasing at a relatively fast rate in the GO scenario. This all results in a relatively large N and P surplus in 2050. In the GO scenario 36% of the population is connected to sewage systems, which is more than in the other scenarios.

2.5. Order From Strength

[20] In the Order From Strength (OS) scenario a regional market is developed, as in the AM scenario. The OS world is characterized by regionalization and fragmentation, and concerns about security and protection. The approach toward ecosystem problems is reactive, as in the GO scenario. In Africa, the population increase is highest in the OS scenario, with a 150% increase between 2000 and 2050 to 2 billion, while per capita GDP is lowest. The percentage of people connected to sewage systems is 17%.

2.6. Technogarden

[21] The Technogarden (TG) scenario is another globalized scenario, but other than GO characterized by a proactive approach toward ecosystem management. It includes green technology development, ecoefficiency, and tradable ecological property rights. There is 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, and not so much, as in the AM scenario by local solutions. In 2050, 1.7 billion people live

in Africa, and the per capita GDP has increased 256% relative to 2000. Sanitation is as in the GO scenario. In the TG scenario, agriculture is more N efficient than in GO and OS.

3. Past and Future Trends: 1970–2050

3.1. Past Trends: 1970–2000

[22] We first analyze NEWS model results for the period 1970–2000 (Figures 3 and 4). Most African rivers drain into the Atlantic Ocean, exporting more than half of all DIN and DIP and about three quarters of the dissolved organic nutrients (DON, DOP and DOC) to this ocean. Almost two thirds of the past (1970–2000) DIN export by African rivers entered the coastal seas within the 0–35S latitude band encompassing the southern tropics and subtropics. Similar patterns can be found for DIP and other nutrient forms. This makes the coastal waters in the 0–35S latitude band important in studies on the potential effects of nutrient inputs to African coastal waters. As indicated above, there are no systematic analyses of eutrophication in coastal waters of Africa, and most reported occurrences of eutrophication are in fact not in the 0–35S latitude band [Diaz and Rosenberg, 2008; Selman *et al.*, 2008]. While modeled nutrient export by rivers cannot be used unambiguously as indicators for potential eutrophication because of the complexity of processes involved and uncertainties in the NEWS model calculations, this mismatch between observed eutrophication and calculated river nutrient export highlights the need for more widespread and systematic monitoring of nutrient export and eutrophication extent in this region.

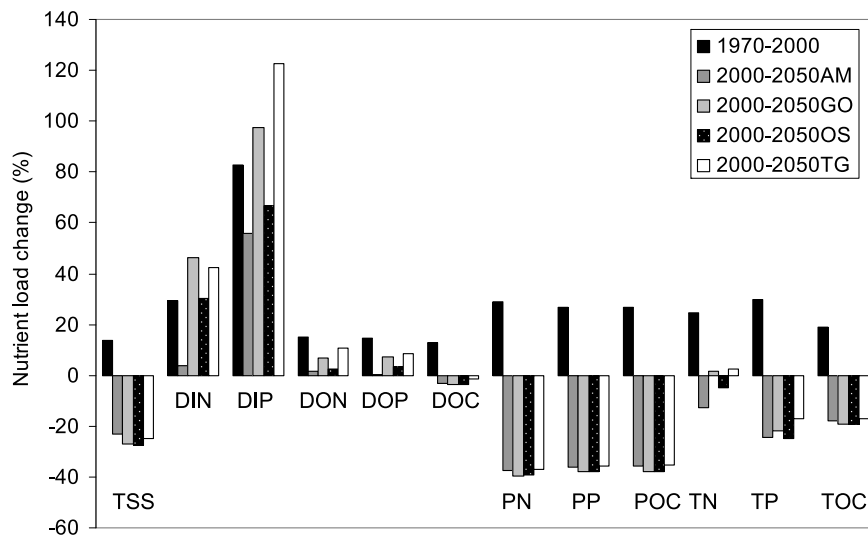


Figure 4. Changes in nutrient loads from African watersheds to the coastal waters between 1970 and 2000 and between 2000 and 2050, as calculated by the NEWS models for the four Millennium Ecosystem Assessment scenarios: GO, Global Orchestration. AM, Adapting Mosaic; OS, Order from Strength; TG, Technogarden. See Figure 3 for explanation of nutrient acronyms. Exorheic basins only.

[23] Large contrasts in DIN yields are observed among watersheds. The calculated DIN yields for 1970 and 2000 (in kg per km² of watershed) range between zero and several hundreds of kilograms per year (Figure 5). This large range in DIN yields reflects variability in environmental characteristics and human activities in the watersheds.

[24] Model results indicate that total river nutrient export to the coastal waters of Africa increased between 1970 and 2000 for all forms (Figures 3 and 4). The largest increase is calculated for DIP: total continental DIP export is calculated to have increased by 83% between 1970 and 2000 (Figure 3). The increase in river export for other nutrient forms ranges between 14% (for TSS) and 29% (for DIN).

[25] The increase in total continental exports for all forms obscures large regional contrasts in these trends (Figure 5). For instance, DIN yield is calculated to have increased in most of central Africa, while in the northern and southern parts of the continent DIN yield has decreased. To examine the reasons of these trends, we analyzed which sources contributed to nutrient export by rivers, and we identified the dominant sources, defined as the largest single source of nutrients in a river [Mayorga *et al.*, 2010; Seitzinger *et al.*, 2010]. The NEWS models distinguish between three major source types: diffuse sources from anthropogenic areas (largely associated with agriculture), anthropogenic point sources (largely associated with sewage) and diffuse sources from natural areas (largely associated with natural biogeochemical processes). In many African rivers, most nutrients originate from natural sources (Figure 6). This is in line with N budgets for West Africa, indicating that the N cycle is dominated by pools and fluxes in noncropped systems [Robertson and Rosswall, 1986]. For instance, for DIN diffuse sources from natural lands dominate in more than 80% of the African watersheds in 1970, with most of this nitrogen entering watersheds through biological N₂ fixation

(Figure 6). Nevertheless, there are also watersheds where DIN exports are dominated by anthropogenic sources, particularly in Western and Southern Africa.

3.2. Future Trends: 2000–2050

[26] We present the future trends in nutrient export by African rivers up to 2050 (Figures 4, 5, and 6). The NEWS models can also be used to analyze results for the year 2030 [Seitzinger *et al.*, 2010]. Here, however, we focus on the longer-term future.

[27] We calculate increasing trends for all dissolved N and P species (DIN, DIP, DON, DOP) up to more than a doubling for DIP (Figure 4). For the other nutrient species (DOC and the particulate forms) we calculate decreasing trends. River export of particulates (PN, PP and POC) are in 2050 calculated to be almost 40% lower than in 2000. This decline is the net effect of climate change and especially the construction of dams, which impact the hydrology, nutrient retention, and sediment trapping within river systems.

[28] The increase in river export of dissolved N and P is largely associated with an increasing African population combined with an increased per capita GDP and increased meat consumption. As a result, the projections for nitrogen and phosphorus inputs from manure and fertilizer application, and from sewage are for 2050 significantly higher than in 2000.

[29] The 2000–2050 increase in DIN export by African rivers is lowest for the AM scenario (4%). For the other three scenarios we calculate increases ranging between 30% (OS Scenario) and 47% (GO scenario) (Figure 4). This is in line with the differences among scenarios in N inputs from sewage, fertilizer and manure, that are highest in the globalized scenarios (GO and TG). The N surplus in the AM scenario is about one third lower than in the other three scenarios (Table 1). The NEWS models calculate a shift

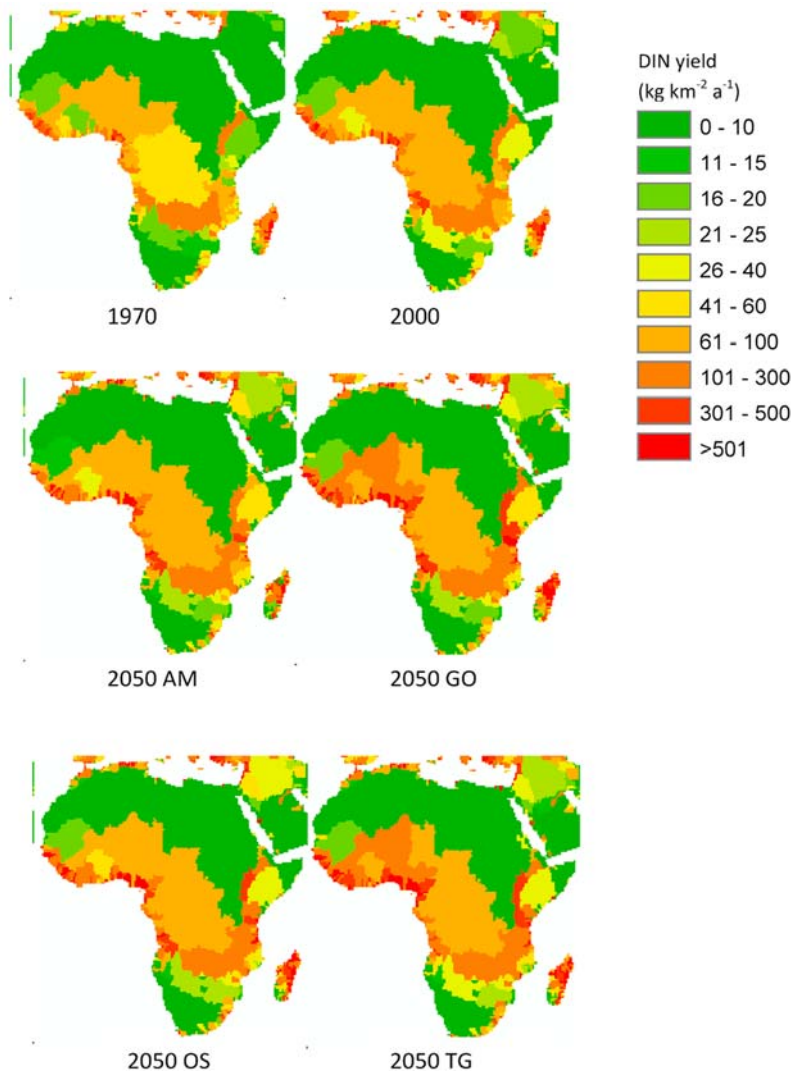


Figure 5. DIN yield as calculated by the NEWS models for 1970, 2000, and the 2050 Millennium Ecosystem Assessment scenarios. See Figure 4 for scenario codes.

from natural toward anthropogenic sources of DIN in rivers (Figure 6). In 1970, diffuse sources from natural areas were the dominant source of DIN in many African rivers. In 2050, agriculture (fertilizer and manure) has become the dominant source of DIN in many rivers. In fact, agriculture is not only the dominant future source of DIN in rivers, but also of several other nutrient forms. The 2000–2050 increase in DIN export (4–47%) is lower than the tripling estimated for the period 1990–2050 using an early version of the DIN model [Kroeze and Seitzinger, 1998]. This can be explained by many differences between the current NEWS-DIN model and this early DIN model: the current version of the NEWS models include more river basins (>6000 now compared to <200 in the early DIN model), and a better representation of N cycling. Another improvement is that the NEWS models include the construction of dams in rivers, and the effects of damming on nutrient retention. Finally, the inputs to the models have been updated.

[30] For DIP export we calculate in general larger increases than for DIN (Figure 4). Again, the AM scenario shows the smallest increase (56%) in DIP export by rivers between 2000 and 2050. The two globalized scenarios (GO and TG) result in the largest increases in DIP export. In the TG scenario, the DIP export more than doubles between 2000 and 2050. This shows that a proactive approach toward environmental management alone is no guarantee for lower phosphate inputs to coastal waters. The relatively high DIP export rates in the TG scenario are associated with relatively large inputs from sewage, which in turn follow from a relatively large African population, and, more importantly, a relatively large fraction of the population connected to sewage systems, draining into the rivers. In addition, P surplus is relatively high in the two globalized scenarios.

[31] For DON and DOP the patterns are comparable to those of DIN and DIP. We calculated increasing trends between 2000 and 2050 for all scenarios. The increase is

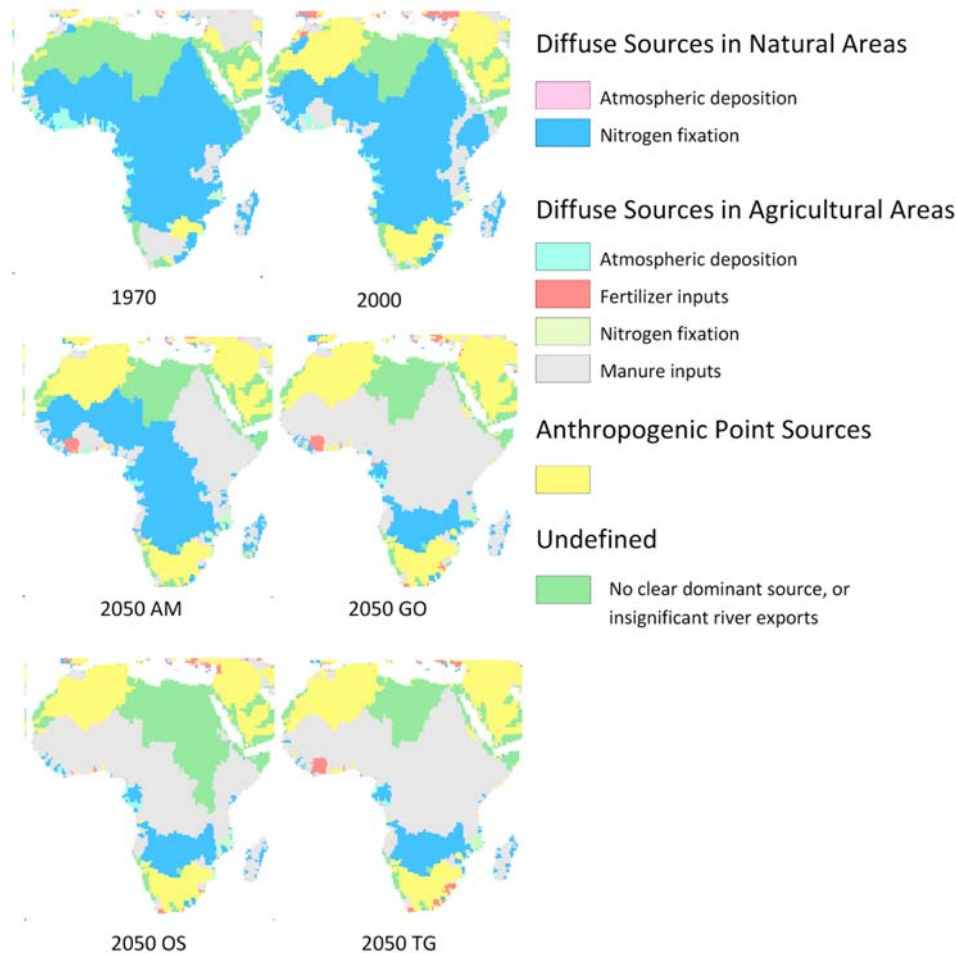


Figure 6. Dominant sources of DIN to rivers as calculated by the NEWS models for 1970, 2000, and the 2050 Millennium Ecosystem Assessment scenarios. See Figure 4 for scenario codes.

lowest for the Adapting Mosaic scenario (<2%), and highest for the two globalized scenarios (about 10%), for similar reasons as for DIN and DIP. DOC shows a different trend: we calculate for 2050 somewhat lower DOC export rates than in 2000 for all scenarios (1–3% decrease). Large decreases in river export are calculated for the particulate forms of N, P and C (PN, PP and POC) as well as for Total Suspended Solids (TSS). These decreases are largely associated with changes in hydrology, including damming of rivers, and increases in human water consumption. The differences among scenarios are small for export of TSS and particulates by rivers.

[32] The net effect of increasing trends in dissolved N and P, and decreasing trends in other nutrient forms are presented in Figure 4. The calculated 2050 total inputs of P and C to coastal waters are lower than in 2000 for all scenarios. Thus the decreasing trends in river export of particulate P outweigh the increases in river export of dissolved P. For N export by rivers there is a difference among scenarios: we calculate small increases in total N export in the GO and TG scenarios (<5%) and considerable reductions for the AM and OS scenarios.

[33] It is interesting to note the difference in past and future trends. For the period 1970–2000 we calculate 20–30% increases in total N, P and C inputs to coastal waters of Africa. For the coming decades, we calculate decreasing inputs of P and C (2050 levels are up to 25% lower than in 2000), while N export in 2050 may be a few percent higher than in 2000, or 13% lower, depending on the scenario. We may conclude that past trends (1970–2000) show larger differences than the calculated future trends up to 2050 for most nutrient species.

[34] Summarizing, our analyses of continental trends indicate that river export of dissolved N, P and C may increase considerably in the future, although not in all basins and scenarios. In contrast, river export of particulate N, P and C may decrease in the future in almost all basins and scenarios. As a result, future trends in total N, P and C inputs to coastal waters may increase or decrease. What the net effect of these trends will be on the risk for eutrophication in the coastal waters of Africa depends not only on the inputs of biologically available nutrients, but also on the C: N: P: Si (Silica) ratios in river export. Trends in these ratios in NEWS model output indicate that the risk for eutrophication in the coastal

Table 2. Selected NEWS Model Inputs for the Four Largest Rivers of Africa (Nile, Zaire, Niger, and Zambezi) for the Years 1970, 2000, and 2050 for the Four Millennium Ecosystem Assessment Scenarios^a

River	Area (1000 km ²) ^a	Draining Into ^b	Actual Basin Discharge (km ³ yr ⁻¹)	GDP (1995 US\$ person ⁻¹ yr ⁻¹)	Population Density (persons km ⁻²)	Urban Population Density (persons km ⁻²)	Population Connected to Sewage (persons km ⁻²)	Agriculture (% of land)	Total Fertilizer + Manure Inputs (kg km ⁻² yr ⁻¹)	
									N	P
<i>1970</i>										
Nile	3822	Mediterranean	447	250	19	4	2	39	489	76
Zaire	3694	Atlantic	1551	462	7	1	0	10	42	7
Niger	2237	Atlantic	344	389	14	1	0	41	476	82
Zambezi	1362	Indian	352	660	9	2	1	51	216	38
<i>2000</i>										
Nile	-	-	485	407	41	13	5	42	1318	212
Zaire	-	-	1783	243	16	4	0	15	85	15
Niger	-	-	369	393	33	8	0	40	883	153
Zambezi	-	-	389	492	23	6	2	53	318	59
<i>2050 Adapting Mosaic</i>										
Nile	-	-	496	1486	107	58	14	43	1786	328
Zaire	-	-	1817	1150	50	26	2	25	249	48
Niger	-	-	354	1356	97	50	5	45	1827	351
Zambezi	-	-	252	2808	43	23	5	59	837	167
<i>2050 Global Orchestration</i>										
Nile	-	-	502	2397	81	41	24	43	3173	598
Zaire	-	-	1820	2054	38	17	9	25	477	94
Niger	-	-	351	2188	73	34	20	44	3485	638
Zambezi	-	-	237	5138	32	16	9	61	1490	307
<i>2050 Order from Strength</i>										
Nile	-	-	489	1144	111	63	15	45	2757	505
Zaire	-	-	1802	953	53	28	2	29	434	82
Niger	-	-	352	1067	101	59	6	46	2746	497
Zambezi	-	-	258	2315	45	25	6	60	1334	267
<i>2050 Technogarden</i>										
Nile	-	-	500	2137	95	48	28	47	2710	509
Zaire	-	-	1836	1744	45	21	11	28	444	89
Niger	-	-	363	1939	87	40	24	48	3076	547
Zambezi	-	-	287	4329	38	19	11	63	1286	258

^aSource: Bouwman et al. [2009] and Van Drecht et al. [2009].

^bDash indicates no change relative to 1970.

waters of Africa may increase in the future, despite the potential decreases in total N, P and C inputs over time [Garnier et al., 2010].

3.3. Nile, Zaire, Niger, and Zambezi

[35] We analyzed the NEWS model results for the four largest rivers of Africa (Nile, Zaire, Niger, and Zambezi) (Figure 1). They drain into different oceans. The Zaire and Niger drain into the Atlantic Ocean, the Nile into the Mediterranean Sea and the Zambezi into the Indian Ocean (Table 2). The Nile has the largest basin, but the basin discharge is largest for the Zaire (3–5 times the discharge of the other three rivers). It should be noted that the NEWS models were not developed for the analysis of individual rivers. However, these four rivers are among the largest included in the NEWS models, covering about one third of the African continent. The NEWS model results for these rivers are in reasonable agreement with measurements, as far as available, with some exceptions (Figure 2). We further-

more argue that the uncertainties in the nutrient inputs [Bouwman et al., 2009; Van Drecht et al., 2009] are generally smaller than those in the calculated river export of nutrients. Therefore, we will in the following discuss the trends in model inputs for the four individual rivers, and the nutrient yields at an aggregated level. Before we present NEWS model results, we will characterize each basin shortly.

3.4. Basin Characteristics and Future Trends in Human Activities

[36] The Nile is a large African river (basin area 3.8 million km²), and one of the largest rivers in the world. It is draining into the Mediterranean Sea. Population density in the basin is considerably higher than that of the Zaire and the Zambezi (Table 2). Given the size of the basin, the annual discharge is relatively low compared to the other four rivers. The two most important tributaries to the Nile are the White Nile (from lake Victoria) and the Blue Nile (from

Table 3. Trends in Modeled Nutrient Export Rates for the Periods 1970–2000 and 2000–2050 for the Four Largest Rivers of Africa (Nile, Zaire, Niger, and Zambezi) and for Africa as a Whole and the Relative Contribution of the Four Rivers to Total African Nutrient Exports^a

	DIN	DIP	DON	DOP	DOC	PN	PP	POC
<i>1970–2000</i>								
Four large rivers	23	47	12	13	12	18	17	17
Total Africa ^b	29	83	15	14	13	29	27	27
Share of four rivers ^c	47	26	52	53	55	20	18	18
<i>2000–2050 AM</i>								
Four large rivers	–20	–66	–3	–4	–4	–76	–76	–76
Total Africa ^b	4	56	2	0	–3	–38	–36	–36
Share of four rivers ^c	34	5	49	50	53	7	6	6
<i>2000–2050 GO</i>								
Four large rivers	3	–22	2	1	–5	–77	–77	–77
Total Africa ^b	47	97	7	7	–3	–39	–38	–38
Share of four rivers ^c	31	8	49	49	53	7	6	6
<i>2000–2050 OS</i>								
Four large rivers	–5	–58	–3	–2	–5	–77	–77	–77
Total Africa ^b	30	67	2	3	–4	–39	–38	–38
Share of four rivers ^c	32	5	49	49	53	7	6	6
<i>2000–2050 TG</i>								
Four large rivers	4	–15	5	4	–2	–67	–66	–66
Total Africa ^b	42	123	11	8	–1	–37	–35	–35
Share of four rivers ^c	33	8	49	49	54	10	9	9

^aUnit: % change relative to 1970 for past trends and relative to 2000 for future trends.

^bExorheic basins only.

^cShare of four large rivers in total export to coastal waters in 1970 or in 2050.

Ethiopian highlands), joining in Khartoum, Sudan. The Northern part of the Nile flows through deserts of Egypt. In 1902 the Nile was dammed at Aswan (in Egypt) to store water for human consumption. In 1965, the Aswan High Dam was built in the Nile in Egypt. After completion of this dam, nutrient export by the Nile has decreased dramatically [Aleem, 1972; Nixon, 2003]. About 40% of the basin area is currently used for agriculture (Table 2).

[37] The Zaire (or Congo) River is another large African river (basin area 3.7 million km²). It straddles the equator, and flows through large rain forest extents before draining into the Atlantic Ocean. Population density in the basin is relatively low compared to the other three large African rivers (Table 2). Its annual discharge is much larger than that of the other three rivers (1.5–1.8 thousand km³ yr^{–1}), and also large compared to other world rivers [Coyne et al., 2005]. The river is an important navigation system in Africa: people and freight are transported over the river. As many other African rivers, it is generally considered a relatively unpolluted river when compared to other large rivers in the world such as the Rhine, Mississippi and Seine [Caraco and Cole, 1999; Justic et al., 1995]. However, the nutrient yields are relatively high compared to other tropical rivers [Coyne et al., 2005]. N and P inputs from agriculture are low compared to the other three large African rivers (Table 2).

[38] The Niger flows in Western Africa through semiarid areas in Mali, Niger and Nigeria mainly. These countries depend for their water resources on the Niger river. The basin area is 2.2 million km², and it drains into the Atlantic Ocean. There are several dams in the river, used for hydro-power and irrigation. Although nutrient and sediment export rates by the Niger are low compared to many other major world rivers [Caraco and Cole, 1999; Meybeck and Ragu, 1996; Picouet et al., 2001] there are indications of nutrient pollution within the watershed [Girard and Hillaire-Marcel, 1997]. About 40% of the basin area is currently used for agriculture, and N and P inputs from agriculture are relatively high compared to those in the Zambezi and the Zaire (Table 2).

[39] The Zambezi is the smallest of the four rivers with a basin area (1.4 million km²) less than half of that of the Nile and draining into the Indian Ocean. It flows through Zambia, Angola, Zimbabwe, Mozambique, Malawi and other countries, and encompasses the well known Victoria Falls. The river includes a few important dams and is an important source of fresh water [Bond et al., 1978; Hall et al., 1977; Shela, 2000]. About half of the basin area is currently agricultural land, which is a larger percentage than for the other four rivers (Table 2). Nevertheless, N and P inputs from agriculture are about half that of inputs in the Nile and Niger basins, indicating that extensive forms of agriculture prevail.

[40] Comparing future trends in the four river basins, reveals that population densities range between 7 persons km^{–2} for the Zaire in 1970 to 111 persons km^{–2} for the Nile in 2050 in the OS Scenario (Table 2). In all river basins population densities increase over time. Between 1970 and 2000 the populations more or less doubled in all four basins. The projected population densities in 2050 are 1.5–3 times the 2000 level. We also see an increasing urbanization. In 1970 less than 5% of the population was urban. In 2000 the urban population was 4% (Zaire) to 13% (Nile) of the total. And in 2050 the urban population ranges from 16 to 25% of the total population for the Zambezi, to 41–63% for the Nile. In general, the population, both urban and rural, increases at a faster rate in the regionalized scenarios (AM and AS) than in the globalized scenarios (GO and TG). In 2050, the GDP is considerably higher than in 2000. Per capita GDP increases faster than the population: the 2050 per capita GDP is 3–10 times that in 2000. GDP is lowest in the OS scenario, and highest in the GO scenario (Table 2).

[41] The increase in population and GDP is associated with changes in the human diet (more meat consumption) but also with agricultural changes that result in a more efficient use of fertilizers. The net effect of these trends are that by 2050 the N and P inputs to the basins from fertilizer and manure are 1.5–6 times the 2000 level. These agricultural N and P inputs are relatively high in the Nile and Niger basins (up to 3173 kg N km^{–2} yr^{–1} and 598 kg P km^{–2} yr^{–1}) and lowest for the Zaire (up to 477 kg N km^{–2} yr^{–1} and 94 kg P km^{–2} yr^{–1}). The N and P inputs differ considerably among scenarios: the scenarios focusing on sustainability (AM and TG) have considerably lower inputs. The AM levels are almost 50% lower than the GO levels (Table 2).

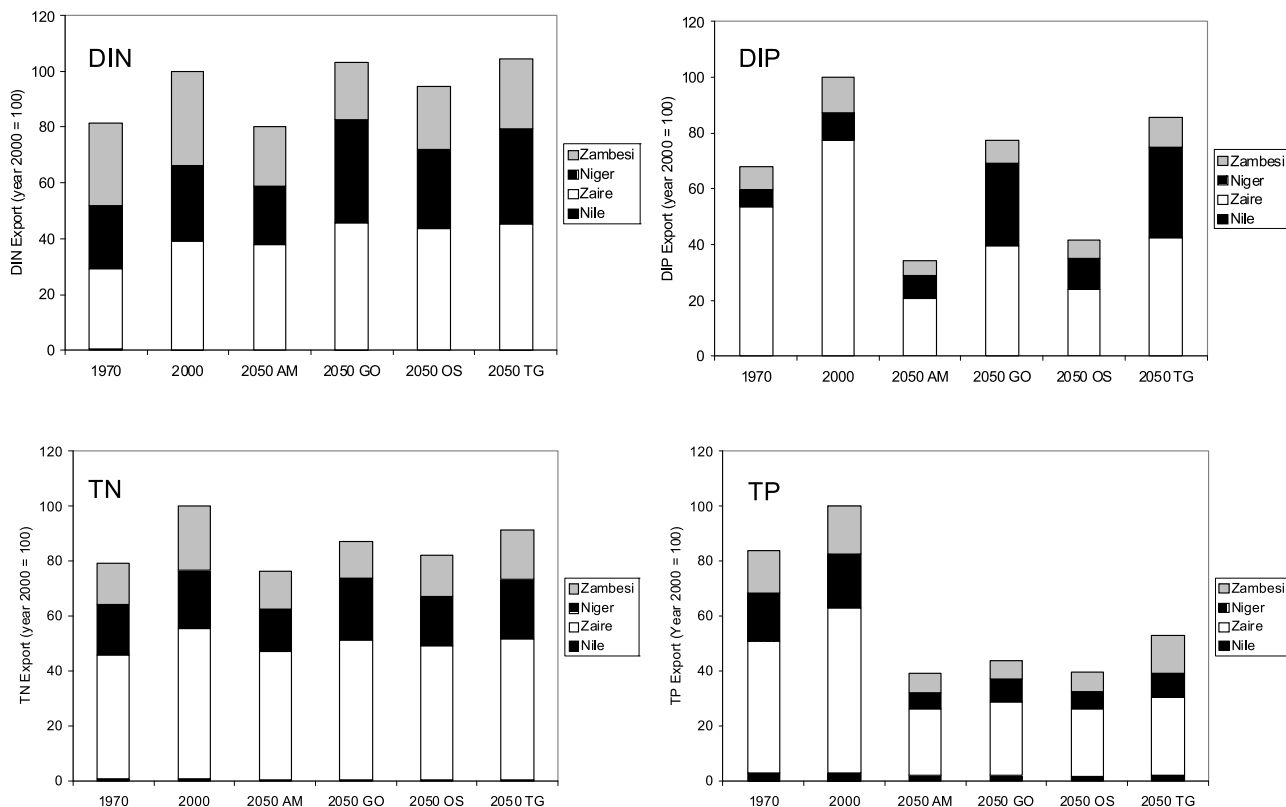


Figure 7. River export of dissolved inorganic N and P (DIN and DIP) and total N and P (TN and TP) as calculated by the NEWS models for the Nile, Zaire, Niger, and Zambezi. Results are shown for 1970, 2000, and the 2050 Millennium Ecosystem Assessment scenarios (relative to the year 2000, which is set at 100). See Figure 4 for scenario codes.

3.5. River Export of Nutrients

[42] We analyzed past and future trends in nutrient export to coastal waters by these four large African rivers (Table 3 and Figure 7). Between 1970 and 2000, nutrient export of all forms of N, P and C increased, albeit not as fast as continental trends (Table 3). For the four large rivers these past increases range between 12% (for DON) to 47% (for DIP). In particular for DIP this is considerably lower than what we calculate for total Africa (an 83% increase between 1970 and 2000). This can be explained by the fact that the African population increased relatively fast in areas close to the coast. This in turn, caused relatively large increases in DIP inputs from sewage in river basins near the coast. In large basins, such as the four analyzed here, these coastal developments are less dominant. Many relatively small river basins in southern and western Africa have higher calculated nutrient yields (nutrient export per km² of basin) than many large rivers (Figure 5).

[43] In the future, nutrient export by these four rivers may be lower than today (Table 2), except for dissolved organic forms of N, P and C, for which the 2050 levels are close to the 2000 levels. We calculate considerable reductions for DIN (in 2050 up to 20% lower than in 2000), DIP (up to 66% lower) and particulate nutrient forms (up to 77% lower). This may seem surprising, given the projected in-

creases in population and agricultural activities in all four basins (Table 2). There are several reasons for the projected reduction in nutrient export by the four rivers. Part of the reason is changing hydrology. Actual discharge of the Niger and Zambezi is in 2050 lower than in 2000 (Table 2), as a result of climate change and human water consumption. This has a direct effect on the nutrient yields of these rivers. Another reason is increased damming of rivers, as a result of which nutrient retention in rivers may increase. In addition, sewage treatment and assumptions on fertilizer efficiency and land use may in the scenarios assuming proactive environmental management (AM and TG) explain part of the calculated reductions in nutrient loadings of rivers.

[44] Figure 7 reveals that trends vary among the four rivers. Total nutrient export by the four large rivers is dominated by the Zaire, which is as expected, given the size of the basin and the relatively high nutrient concentrations compared to other tropical rivers [Van Bennekom *et al.*, 1978] (see also Figure 2). Nutrient export by the Nile is negligibly low. This is in line with low observed nutrient concentrations in the Nile (Figure 2) and in part explained by hydrology (i.e., the relatively low discharge of the Nile considering the basin area, and the High Aswan dam in the Nile [Nixon, 2003]) and by human activities in the basin.

[45] For 2050 we calculate lower DIN export rates for the Niger (in AM and TG) and the Zambezi (all scenarios) than

in 2000 (Figure 7). This can largely be explained by lower river discharge in 2050 (Table 2). For the Zaire, we calculate stabilizing or slightly increasing DIN export (Figure 7). The increasing N and P inputs to the Zaire (Table 2) are increasing faster than river export of nutrients, in line with assumptions on N and P use efficiency and trends in hydrology [Bouwman *et al.*, 2009; Van Drecht *et al.*, 2009]. For DIP the 2050 export rates are considerably lower than in 2000. This is largely explained by reduced DIP export by the Zaire, where population increase is on the one hand resulting in land conversion (reducing natural P weathering) while the number of people connected to sewage systems remains low (as a result of which DIP inputs from sewage are low) [Van Drecht *et al.*, 2009]. For the Niger, we calculate increasing river export of DIP in the globalized scenarios (GO and TG), because in these scenarios a relatively large percentage of the population is connected to sewage, and because P inputs to agriculture are relatively high (Table 2). Total N and P export are in 2050 lower than in 2000 in all scenarios (Figure 7). This is the net effect of trends in dissolved N and P (increasing or decreasing) and particulates (decreasing, as in continental trends; see Figure 4). As expected, the lowest 2050 N and P export rates are calculated for the AM scenario, assuming a regionalized world and a proactive attitude toward ecosystem management.

[46] The four large rivers export almost half of the total amount of dissolved organic nutrients (DON, DOP and DOC) and DIN to the coastal waters of Africa (Table 3). However, they export relatively small amounts of particulate nutrients and DIP. In 1970, they accounted for a considerable part of the total African river export of DIN (47%), DIP (26%), and dissolved organic nutrients (DON, DOP and DOC) (52–55%). Considerably lower contributions are calculated for particulate nutrients (PP, PN and POC) (18–20%). By 2050, the relative share of these four rivers is lower than in the past years: by 2050 they export 31–33% of total DIN, 5–8% of total DIP, 49–53% of total dissolved organic nutrients (DON, DOP and DOC), and 6–10% of particulate nutrients (PP, PN and POC) to the coastal waters of Africa.

[47] We also analyzed the most important sources of dissolved inorganic N in the rivers (Figure 6). We first of all observe that between 1970 and 2050 there is a shift from natural sources of DIN toward anthropogenic sources. In fact, this holds for most nutrients in most African basins. In 2050, different sources are dominant in the different basins and scenarios. For instance, for the Zaire we calculate that manure is the dominant source of DIN in all scenarios, except for the AM scenario in which natural sources dominate (Figure 6). This can be explained by the relatively low N inputs from manure in the AM scenario compared to the other three scenarios. Manure N inputs are also the dominant source of DIN in most scenarios for the Nile and the Niger in 2050. The Zambezi is dominated by natural sources of DIN in all scenarios for 2050, in line with relatively low population densities, and low N inputs per hectare of agricultural land. By 2050, the Zambezi basin is more agricultural than the other basins, illustrated by the relatively low urban population in this basin (Table 2). Anthropogenic point sources, mainly from sewage, are projected to become

a major source of DIP in rivers. It is interesting to note that small and medium-sized basins located near the coasts are projected to export relatively large amounts of DIP, in some cases even more than the four largest rivers of Africa. This could be associated with large cities close to the coast, such as Abidjan (Ivory Coast) [Scheren *et al.*, 2004].

[48] These analyses could help to identify effective policies to reduce nutrient inputs to coastal waters. DIN inputs from natural sources such as N₂ fixation and leaching from natural areas may be difficult to control. However, DIN from anthropogenic sources could possibly be reduced relative to the projected trends. For instance, more efficient use of fertilizers may reduce N inputs to watersheds and, as a result, DIN inputs to rivers. Also nutrient export from basins with high runoff coefficients, such as the Zaire basin (with pristine average annual runoff of 490 mm yr⁻¹), could be reduced relative to the trends by implementing sustainable land use and forest management and efficient farming (tilling) practices.

4. Conclusions

[49] We analyzed past and future trends in export of nutrients by rivers to the coastal waters of Africa, for various scenarios. Inputs and outputs of global NEWS models of nutrient export from watersheds to seas were analyzed for total suspended solids (TSS) and eight nutrient forms (DIN, DIP, DON, DOP, DOC, PN, PP and POC). First, results for the years 1970 and 2000 have been analyzed to study past trends in nutrient export by rivers. For future trends, four Millennium Ecosystem Assessment (MEA) scenarios were explored for the year 2050.

[50] We conclude that between 1970 and 2000, nutrient export by African rivers increased considerably. River export of DIP increased faster (83% between 1970 and 2000) than that of other nutrients (up to 30% between 1970 and 2000). Most important reasons for increased nutrient export by rivers are population increase associated with agricultural activities and increasing numbers of people connected to sewage systems.

[51] In the coming decades river export of nutrients may continue to increase, but not all nutrient forms, and not in all African basins. Between 2000 and 2050, the total river export may increase considerably in the case of DIN (4–47%), DIP (at least doubling), DON and DOP (2–10%). On the other hand, export of DOC, particulates (PN, PP and POC) and TSS may decrease in the decades to come. Regional differences are large, and exceed differences among scenarios, as well as trends over time. Temporal trends follow future trends in nutrient inputs to African watersheds from sewage, fertilizer and manure, and changes in hydrology.

[52] In the future, anthropogenic sources of nutrients in rivers will become more important than natural sources in large parts of Africa. Prior to 2000, nutrients originated largely from natural sources. From 2000, however, agricultural sources, in particular manure, are becoming increasingly important. This also holds for point sources, i.e., human sewage from urban centers.

[53] Of the four MEA scenarios, the two globalized scenarios (GO and TG) are calculated to have higher nutrient

inputs and outputs than the regionalized (AM and OS). Overall, the Adapting Mosaic (AM) scenario shows lowest nutrient export rates from African watersheds. This scenario reflects a regionalized world, a proactive approach toward ecosystem management, and a preference for local solutions to environmental problems.

[54] African rivers transport more nutrients to the Atlantic Ocean than to the Indian Ocean, the Mediterranean Sea and the Red Sea. We analyzed export rates for the four largest rivers of Africa draining into these oceans: Nile, Zaire, Niger, and Zambezi. These four export approximately half of the total DIN and dissolved organic nutrients (DON, DOP and DOC) export by African rivers in 2000 and 2050. They have a relatively low share in the total export of particulate nutrients (PN, PC, and POC) to the coastal waters of Africa in 2000 and 2050. Nutrient export by these large rivers does not increase as fast as for many other, smaller rivers.

[55] Our analysis can serve as a basis for a better understanding of the causes of coastal water pollution. Despite the uncertainties in the models and scenarios, and despite the lack of water quality data in Africa, the NEWS model can give indications of future trends, and identify likely causes of increased river export of nutrients. These could help us to not only prioritize future research, but also to focus environmental management toward the likely causes of coastal eutrophication.

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