Environmental Development 17 (2016) 220–229

Contents lists available at ScienceDirect

Environmental Development

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

Land-based nutrient loading to LMEs: A global watershed perspective on magnitudes and sources

Rosalynn Y. Lee [1], Sybil Seitzinger *, Emilio Mayorga [2]

Rutgers University, Rutgers/NOAA CMER Program, 71 Dudley Rd, New Brunswick, NJ 08901 USA

ARTICLE INFO

Article history:
Received 4 June 2015
Received in revised form
14 September 2015
Accepted 15 September 2015

Keywords:
Dissolved inorganic nitrogen
Large marine ecosystems
Watershed
River export
Point sources
Diffuse sources

ABSTRACT

Coastal resource management initiatives in recent years have moved towards ecosystem approaches such as embodied by Large Marine Ecosystems (LMEs). In this study, land-based dissolved inorganic nitrogen (DIN) loading to LMEs was evaluated using a spatially-explicit river export model (Global NEWS 2) for the year 2000 conditions and for a current trends analysis for the year 2050. Watershed export was aggregated by LME to estimate total DIN load and attribution to diffuse and point sources including natural biological fixation, agricultural biological fixation, fertilizer, manure, atmospheric deposition and sewage. Biological fixation in natural landscapes was the primary source of DIN to many LMEs, but in most (73%) LMEs, over half of the total DIN load was related to anthropogenic sources. Most of the anthropogenic DIN load across LMEs was related to agricultural sources especially fertilizer and manure. Fertilizer was the primary source of DIN to LMEs in most of Europe and Asia, while manure was the primary source in most of Central and South America. Agricultural biological fixation, sewage and atmospheric deposition in general supported a minor fraction of the DIN exported to LMEs although each was a dominant source to a few LMEs. If current trends continue, DIN export to coastal systems by 2050 relative to 2000 is predicted to increase by approximately 40–45% from Africa, South America, South Asia and Oceania. Almost half of the total global increase in DIN is from South Asia. Relatively smaller increases are predicted for North America, with slight decreases in Australia and Europe.

© 2015 Elsevier Ltd All rights reserved.

1. Introduction

To meet the growing population's food and energy demands, anthropogenic activities have greatly increased nutrient inputs to the landscape, at global factors of more than twice for nitrogen and triple for phosphorus over natural values (Galloway et al., 2004, 2008; Bennett et al., 2001). As these increasing nutrient loads reach coastal waters, effects of eutrophication may occur, including increased rates of phytoplankton production, increased frequency of harmful algal blooms, changes in algal and vascular plant community composition and fish and shellfish populations, loss of sea grass and coral reef habitat, and decreases in dissolved oxygen (National Research Council, 2000; Howarth and Marino, 2006; Granéli

---

* Corresponding author. Present address: International Geosphere-Biosphere Programme, Royal Swedish Academy of Sciences, Stockholm, SE.
E-mail addresses: Rosalyyl@usc.edu (R.Y. Lee), Sybil.Seitzinger@IGBP.kva.se (S. Seitzinger), mayorga@apl.washington.edu (E. Mayorga).

[1] Present address: Center for Dark Energy Biosphere Investigations, University of Southern California, 3616 Trousdale Pkwy, Los Angeles, CA 90089-0371, USA

[2] Present address: Applied Physics Laboratory, University of Washington, 1013 NE 40th St, Seattle, WA 98105-6698, USA

http://dx.doi.org/10.1016/j.envdev.2015.09.006
2211-4645/© 2015 Elsevier Ltd All rights reserved.

and Turner, 2006; Heisler et al., 2008; Rabalais et al., 2009; Glibert et al., 2010). Over 400 eutrophic and hypoxic coastal systems have been documented globally (Selman et al., 2008). There is a critical need to understand the quantitative links between anthropogenic activities in watersheds, nutrient inputs to coastal systems, and coastal ecosystem effects to better mitigate eutrophication and protect the ecosystem services of the coastal zone.

Globally, the coastal ocean can be subdivided into large marine ecosystems (LMEs) distinguished by specific physical environments and biological functioning (Sherman and Duda, 1999; Sherman et al., 2009). The LME approach for ecosystem-based management is based around the 5-modules of productivity, fish and fisheries, pollution and ecosystem health, socioeconomics, and governance. Within all LMEs, over 80% of the world's marine capture fisheries occur (Sherman, 1994; Sherman et al., 2009) which emphasizes the importance of cross political-boundary management of these international marine ecosystem units.

The current study seeks to provide input for the LME modules: pollution and ecosystem health, and productivity through an analysis of the magnitudes and sources of nutrients from land-based sources to the 63 LMEs. Nitrogen is the nutrient generally most limiting to biomass production in coastal waters and the form of N most rapidly used is dissolved inorganic N (DIN–ammonia plus nitrate). DIN is also the form of N that increases the most in rivers, and therefore delivered to LMEs, with increase in human activity (Seitzinger et al., 2010). Therefore in this paper we focus on the river DIN load and sources.

Dissolved inorganic (DIN) loading from watersheds to LMEs globally under both contemporary conditions and a future scenario for 2050 are analyzed. DIN loading to each LME was attributed to diffuse and point sources. The relationship between N loading rates and net phytoplankton production is examined to evaluate the role of land-based N loading on phytoplankton production in LMEs.

2. Methods

To address the links between land-based activities in watersheds and nutrient inputs to LMEs around the world, we use the global watershed model (Nutrient Export from WaterSheds; NEWS 2) (Seitzinger et al., 2005, 2010; Mayorga et al., 2010). NEWS 2 relates human activities and natural processes in watersheds to nutrient inputs to coastal systems throughout the world (Beusen et al., 2005; Dumont et al., 2005; J. Harrison et al., 2005a, J.A. Harrison et al., 2005b; Seitzinger et al., 2005). The NEWS model is a multi-element, multi-form, spatially explicit global model of nutrient (N, P, C and Si) export from watersheds by rivers. The model output is the annual export at the mouth of the river (essentially zero salinity). The NEWS 2 model has been validated with measured export near the river mouth from rivers representing a broad range of basins sizes, climates, and land-uses (Mayorga et al., 2010; Qu and Kroeze, 2010; Seitzinger et al., 2010; Van der Struijk and Kroeze, 2010; Yan et al., 2010; Yasin et al., 2010; Qu and Kroeze, 2012; Sattar et al., 2014). Over 5000

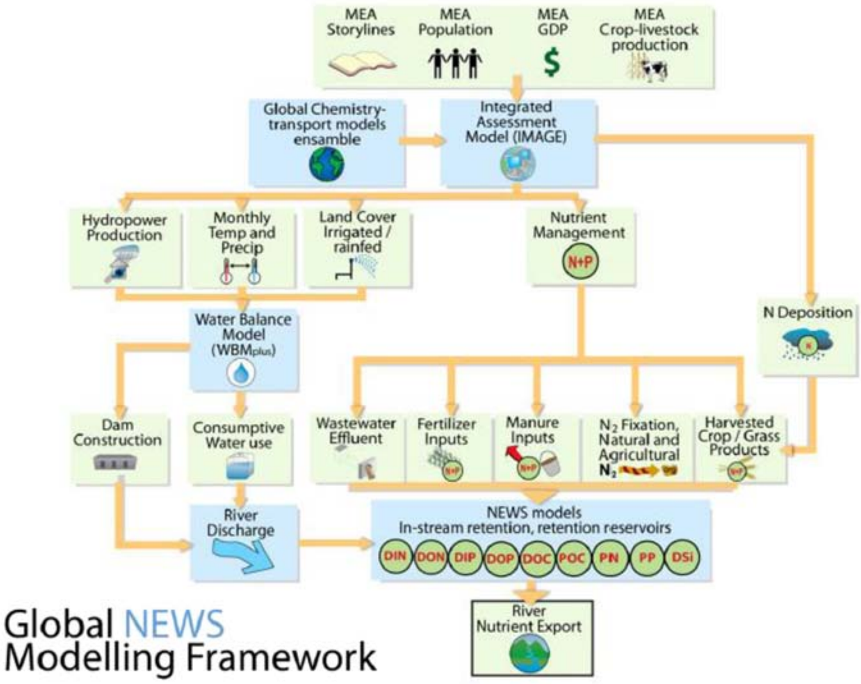

Fig. 1. Conceptual diagram of the Global NEWS model construction, submodels and parameters (from Glibert et al., 2010 modified from Seitzinger et al., 2010).

watersheds are included in the model with the river network and water discharge defined by STN-30 (Fekete et al., 2000; Vörösmarty et al., 2000a,b). Most input databases are at the scale of 0.5° latitude by 0.5° longitude.

The NEWS 2 model predicts riverine nutrient export (by form) as a function of point and non-point nutrient sources in the watershed, hydrological and physical factors, and removal within the river system (Fig. 1) (Beusen et al., 2005; Dumont

Table 1
LME numbering and naming system (Duda and Sherman, 2002).

LME#	LME name
1	EastBeringSea
2	GulfOfAlaska
3	CaliforniaCurrent
4	GulfOfCalifornia
5	GulfOfMexico
6	SoutheastUSContinentalShelf
7	NortheastUSContinentalShelf
8	ScotianShelf
9	NewfoundlandLabradorShelf
10	InsularPacificHawaiian
11	PacificCentralAmericanCoastal
12	CaribbeanSea
13	HumboldtCurrent
14	PatagonianShelf
15	SouthBrazilShelf
16	EastBrazilShelf
17	NorthBrazilShelf
18	WestGreenlandShelf
19	EastGreenlandShelf
20	BarentsSea
21	NorwegianShelf
22	NorthSea
23	BalticSea
24	CelticBiscayShelf
25	IberianCoastal
26	MediterraneanSea
27	CanaryCurrent
28	GuineaCurrent
29	BenguelaCurrent
30	AgulhasCurrent
31	SomaliCoastalCurrent
32	ArabianSea
33	RedSea
34	BayOfBengal
35	GulfOfThailand
36	SouthChinaSea
37	SuluCelebesSea
38	IndonesianSea
39	NorthAustralianShelf
40	NortheastAustralianShelfGreatBarrierReef
41	EastCentralAustralianShelf
42	SoutheastAustralianShelf
43	SouthwestAustralianShelf
44	WestCentralAustralianShelf
45	NorthwestAustralianShelf
46	NewZealandShelf
47	EastChinaSea
48	YellowSea
49	KuroshioCurrent
50	SeaOfJapan
51	OyashioCurrent
52	OkhotskSea
53	WestBeringSea
54	ChukchiSea
55	BeaufortSea
56	EastSiberianSea
57	LaptevSea
58	KaraSea
59	IcelandShelf
60	FaroePlateau
62	BlackSea
63	HudsonBay
64	ArcticOcean

et al., 2005; J. Harrison et al., 2005a, J.A. Harrison et al., 2005b; Seitzinger et al., 2005; Mayorga et al., 2010). A further feature of the model is that it can be used to estimate the relative contribution of each watershed source to export at the river mouth.

Calculation of DIN export (yield, $\text{kg N km}^{-2}\,\text{y}^{-1}$) by the NEWS 2 model applies watershed and river hydrology and removal processes to point source and diffuse source inputs (Dumont et al., 2005):

$$DIN\ export = FE_{riv}\cdot[DIN_{sew} + (FE_{ws}\cdot TN_{diff})] \tag{1}$$

where FE_{riv} is the fraction of DIN inputs to the river that is exported, DIN_{sew} is the DIN from sewage point sources, FE_{ws} is the fraction of total nitrogen from diffuse sources in the watershed that leaches to rivers as DIN, and TN_{diff} is the total nitrogen from diffuse sources mobilized from watershed soils and sediments.

Each of the terms in the DIN model (Eq. (1)) was calculated at the watershed scale using spatially-explicit input databases and relationships (as in Dumont et al., 2005; Mayorga et al., 2010). Briefly, watersheds were delineated by a $0.5° \times 0.5°$ resolution global river network, STN-30, of 6267 river basins (Vörösmarty et al., 2000a,b). Inputs of total nitrogen from diffuse sources to the landscape (TN_{diff}) include total nitrogen from fertilizer addition, animal manure addition, biological N_2 fixation, and atmospheric NO_y deposition, which are subject to removal by crop harvesting and grazing on agricultural land. Fertilizer inputs across various crop types, manure inputs across various animal types and crop harvesting and grazing were calculated at a $0.5° \times 0.5°$ global resolution (Bouwman et al., 2005a). Manure inputs were also distinguished by the proportion applied and the proportion excreted (Bouwman et al., 2005a). Total biological N_2 fixation includes natural and agricultural biological fixation and was estimated at a 0.5° x 0.5° global resolution (Green et al., 2004; Bouwman et al., 2005a). Atmospheric NO_y-N deposition was modeled at a $5° \times 3.75°$ global resolution (Dentener et al., 2006). Atmospheric deposition of NH_x volatilized from manure is included in the manure input term to avoid double counting. A $0.5° \times 0.5°$ global resolution of runoff (Fekete et al., 2000) was used to estimate the fraction of total nitrogen from diffuse sources that is transported from watersheds to rivers as DIN (FE_{ws}). Direct deposition of nitrogen to coastal waters and nutrient inputs with submarine groundwater are not included, although they may be important sources of N to coastal waters in some regions (Paerl et al., 2002; Burnett et al., 2003; Slomp and Van Cappellen, 2004).

DIN input from sewage point sources (DIN_{sew}) was modeled as a function of population, per capita human nitrogen emission, the fraction of the population connected to sewer systems and the fraction of nitrogen not removed by wastewater treatment as described by Bouwman et al. (2005b). Population density was calculated on a $0.5° \times 0.5°$ global resolution (Klein Goldewijk, 2001) and applied to country-level wastewater treatment, sewerage connectivity, and human nitrogen emission estimates (Bouwman et al., 2005b). Both diffuse and point source inputs are subject to aquatic retention ($1-FE_{riv}$) in reservoirs and the STN-30 basin river network that includes loss by denitrification, retention in dams and reservoirs, and water consumption (i.e. irrigation). Predicted DIN load per watershed basin (T y^{-1}) was estimated by the product of DIN yield and watershed area (km^2; Vörösmarty 2000a,b).

Watershed DIN export to rivers predicted by the NEWS 2 model was compiled for each of the 64 Large Marine Ecosystems (Table 1) except for the Antarctic (LME 61) where database information was limited. Total DIN load to each LME was aggregated from all watersheds with coastlines along that LME for point sources and only those watersheds with discharge to that LME for diffuse sources. DIN export attributed to each point and nonpoint source (i.e. sewage, fertilizer, manure, agricultural biological fixation, natural biological fixation, and atmospheric deposition) was estimated (Dumont et al., 2005; Mayorga et al., 2010). DIN export was also categorized by natural (i.e. biological fixation on natural landscapes) vs. anthropogenic sources (i.e. agricultural biological fixation, fertilizer, manure, atmospheric deposition and sewage), and aggregated for each LME to identify the primary and secondary land-based sources of DIN to LMEs.

The future scenario is a quantitative interpretation of the Global Orchestration scenario of the Millennium Ecosystem Assessment (MEA) (Alcamo et al., 2006). Input datasets for the 2050 Global Orchestration (GO) scenario analysis were developed for Global NEWS 2 (Seitzinger et al., 2010) and are summarized here. Inputs for population, Gross Domestic Product (GDP) and crop-livestock production were taken from the MEA directly. Additional input data sets were developed by interpreting the original MEA scenario. For example agricultural areas used net surface N balances as input. These surface balances were based on N inputs from fertilizer use, animal manure application, N_2-fixation by crops, atmospheric N deposition, and sewage N, minus N removal from crop harvest and animal grazing (Bouwman et al., 2009). The surface nutrient balances form the basis of the scenario assumptions for nutrient management in agriculture. Quantitative nutrient management scenarios used an updated version (2.4) of the Integrated Model for the Assessment of the Global Environment (IMAGE) (Bouwman et al., 2006). Regional scenarios for N fertilizer use were based on efficiency of N uptake in crop production (Bouwman et al., 2009). Manure production was computed from livestock production, animal numbers and excretion rates, and distributed over different animal manure managements systems (Bouwman et al., 2009). Livestock production was related to a number of factors including human population and diet. Atmospheric N deposition from natural and anthropogenic sources to all watersheds was from Bouwman et al. (2009). Natural ecosystem inputs include biological N_2-fixation and atmospheric nitrogen deposition.

N flows in urban wastewater for 2050 were calculated from influents to wastewater treatment systems computed from projected per capita incomes used to generate differing degrees of access to improved sanitation, connection to sewage systems, and nutrient removal in wastewater treatment systems (Van Drecht et al., 2009).

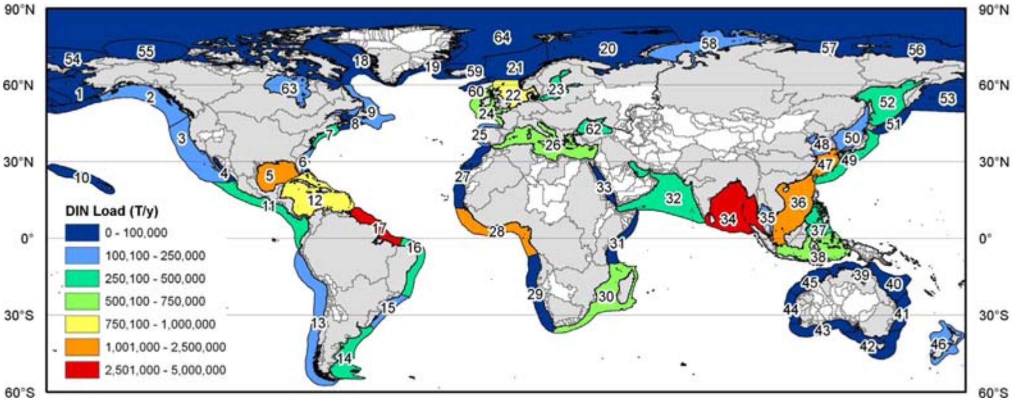

Fig. 2. DIN load to LMEs. Watersheds discharging to LMEs are grey; watersheds with zero coastal discharge are white.

For hydropower production, the $\mathrm{WBM_{plus}}$ hydrological model was driven with scenario estimates of monthly temperature and precipitation, land use, and irrigated and rainfed crop production areas from the IMAGE model to develop projections for construction of reservoirs (dams) and consumptive water use and irrigation (Fekete et al., 2010). The published global scenario application of Global NEWS 2 was based on modeled climate drivers ("Modeled Hydrology") for both contemporary (year 2000) and future conditions (Seitzinger et al., 2010). To adjust modeled results for future conditions to the "Realistic Hydrology" baseline for contemporary conditions used here, we scaled published future nutrient exports ("X") as follows:

$$X_{year} = (X_{2000\ \mathit{Realistic\ Hydrology}}/X_{2000\ \mathit{Modeled\ Hydrology}})^{*}X_{year\ \mathit{Modeled\ Hydrology}} \tag{2}$$

where "year" is the scenario year (2050) and ($X_{2000\ \mathit{Realistic\ Hydrology}}/X_{2000\ \mathit{Modeled\ Hydrology}}$) is the scaling factor.

3. Results and discussion

3.1. DIN export to LMEs

DIN export from watersheds to LMEs varies globally across a large range of magnitudes (Fig. 2). The smallest loads are exported to many polar and Australian LMEs, while the largest loads are exported to northern tropical and subtropical LMEs. The LMEs receiving the largest loads of land-based DIN are the North Brazil Shelf, Bay of Bengal, Guinea Current, South China Sea, East China Sea and Gulf of Mexico LMEs.

Land-based sources of DIN include biological fixation in natural landscapes and anthropogenic sources including fossil fuel combustion, agriculture (crop and livestock production) and sewage, which account for over half of the total DIN load in 73% of LMEs (Fig. 3). These LMEs are distributed across most continents, except sub-Saharan Africa and most polar regions. Some of the highest proportions ($>90\%$) of anthropogenic DIN loads are to European LMEs, such as the North Sea and Mediterranean LMEs, and East Asian LMEs, such as the Yellow Sea and East China Sea LMEs. In addition to N inputs to watersheds, river water discharge is a significant factor in the export of DIN as indicated by the high DIN load but low anthropogenic activities in the North Brazil Shelf (Amazon River) and Guinea Current LMEs which are dominated by flows from the Amazon and Congo Rivers, respectively.

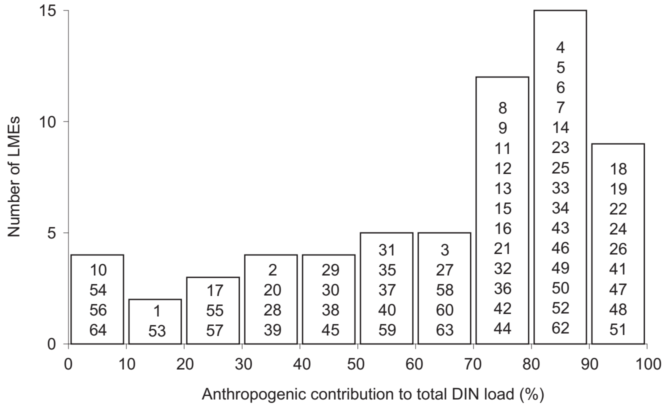

Fig. 3. Histogram of anthropogenic contribution to total DIN load to LMEs. LME numbers (Table 1) are shown in each bar.

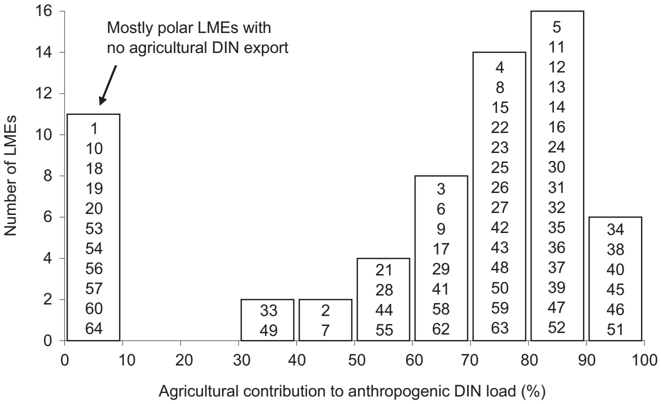

Fig. 4. Histogram of agricultural contribution to anthropogenic DIN load to LMEs. LME numbers (Table 1) are shown in each bar.

Agriculture is a major source of the anthropogenic DIN export to LMEs (Fig. 4). There is no agricultural export to most polar LMEs, but in 91% of the LMEs with agriculture occurring in their related watersheds, over half their anthropogenic export is due to agricultural sources which includes chemical fertilizer, manure and agricultural biological fixation. Attribution of agricultural DIN export to these three sources reveals the predominance of fertilizer and manure over biological fixation (Fig. 5). For example, LMEs with the largest agricultural loads (black symbols in Fig. 5) have less than 20% of the total DIN load due to biological fixation and over 50% due to either fertilizer (e.g., Bay of Bengal, East China Sea and South China Sea LMEs), to manure (e.g., Caribbean and North Brazil Shelf LMEs) or to a combination of both (e.g., North Sea and Celtic-Biscay Shelf LMEs) due to local agricultural practices.

Across the 63 LMEs, natural biological fixation, fertilizer, and manure are the dominant primary and secondary sources of DIN (Fig. 6). The primary source of land-based DIN export to most polar, sub-Saharan African, and northern Australian LMEs is natural biological fixation, while fertilizer is the primary source to many northern temperate and Southeast Asian LMEs. Manure from livestock production is an important source of nitrogen to many rivers globally (Galloway et al., 2010). Manure is the dominant source to most Central and South American LMEs, and is important as a primary or secondary source to a variety of LMEs globally. Atmospheric deposition is important in regions where there are few other land-based inputs (e.g. in polar regions such as the West and East Greenland Shelf LMEs), where fossil fuel combustion from development is extreme (e.g. in the North- and Southeast U.S. Continental Shelf LMEs), or where extensive landscape burning occurs (e.g. the Guinea Current LME which is fed by savannah fires in Western Central African watersheds; Barbosa et al., 1999). Sewage is an

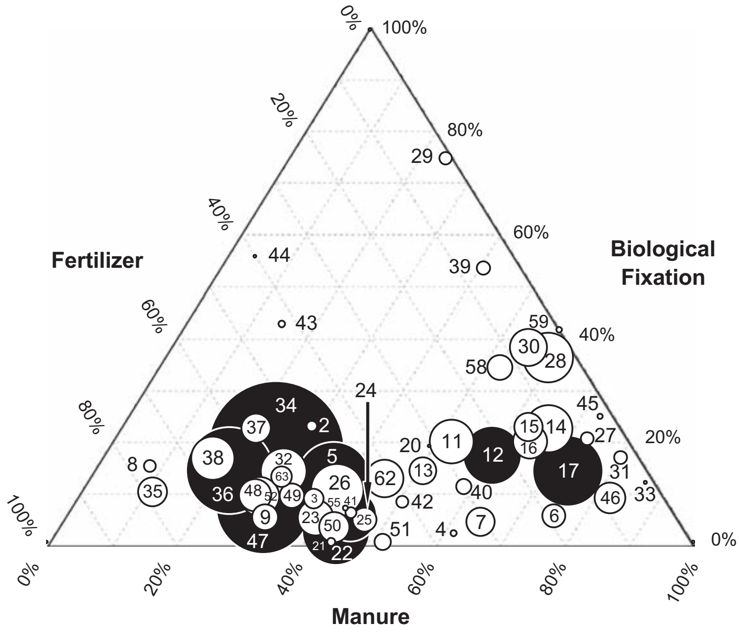

Fig. 5. Contribution of agricultural DIN export to LMEs by source: fertilizer, biological fixation and manure. Symbol sizes are proportional to agricultural DIN load to LMEs; black symbols indicate LMEs receiving the largest agricultural loads.

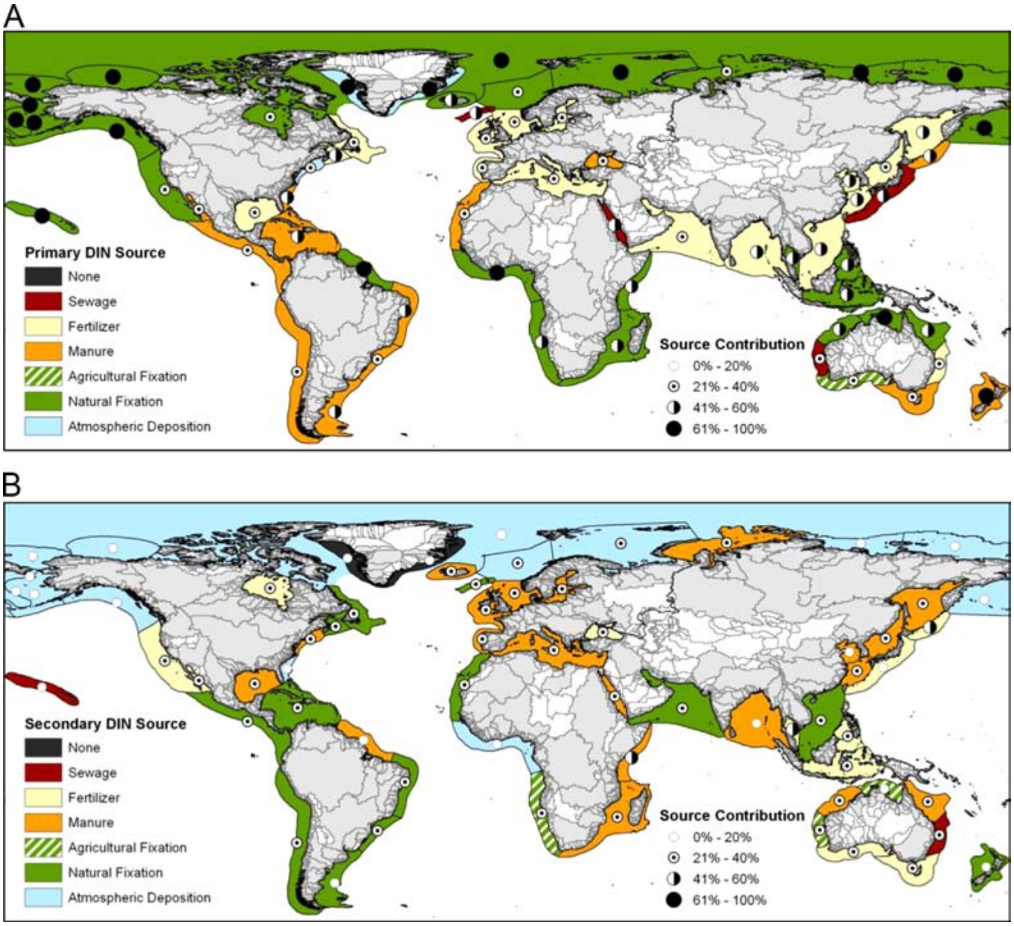

Fig. 6. Primary (A) and secondary (B) sources of DIN exported to LMEs. Sewage, fertilizer, manure, agricultural and natural fixation, and atmospheric deposition sources identified by color; contribution of the primary or secondary source from 0% to 100% identified by circle symbols.

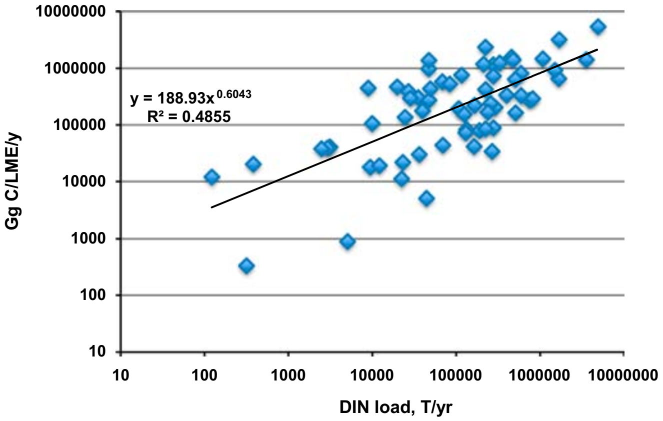

Fig. 7. Relationship between net phytoplankton production in LMEs (Sea Around Us, 2007; modeled estimates from SeaWiFS data) and land-based DIN load to LMEs (this study).

important source of DIN to only a few LMEs (as a primary source to the Kuroshio Current, Red Sea, West-Central Australian Shelf, and Faroe Plateau LMEs), while agricultural fixation plays an even lesser role as a primary source to only the Southwest Australian Shelf LME and a secondary source to the Benguela Current, North Australian Shelf, and West-Central Australian Shelf LMEs.

3.2. Coastal ecosystem effects

River nutrient loads to LMEs likely most directly affect the near coastal regions (estuaries, bays), or coastal river plumes such as those of the Mississippi and Hudson Rivers (e.g., Nixon, 1995; Paerl, 1997; Paerl et al., 2002; Cloern, 2001; Kemp et al., 2005; Rabalais et al., 2014). These effects can include increased phytoplankton production and frequency of harmful algal blooms, changes in algal and vascular plant community composition, loss of sea grass and coral reef habitat, changes in fish and shellfish populations and decreases in dissolved oxygen, among others (National Research Council, 2000; Howarth and Marino, 2006; Granéli and Turner, 2006; Heisler et al., 2008; Rabalais et al., 2009; Glibert et al., 2010). Relating the specific effects in individual near coastal regions, river plumes and open waters of LMEs due to the river nutrient loads presented here is beyond the scope of the current project, and warrants further data and analysis. However, even at the scale of the whole LME there appears to be a relationship between river DIN loading and phytoplankton production (Fig. 7), although, generally less than 2% (0.71% +/− 0.01; mean +/− SD) of the net primary production N requirements could be met directly by the river DIN load (using C:N ratio by wt of 5.7). Previous analyses have shown that primary production appears to constrain fisheries catches at the LME scale (Chassot et al., 2010). By extrapolation this infers that river DIN loading also, to some extent, indirectly affects fisheries catches at the LME scale. Other forms of river N (organic and particulate), vertical and horizontal advection, plus N from direct atmospheric deposition and in some cases submarine groundwater can also supply nutrients supporting phytoplankton production.

3.3. Future N loading from LME watersheds

As discussed above, human activities in watersheds have increased anthropogenic DIN loading to many LME coastal zones. At the global scale, river DIN export from all sources to coastal systems in 2000 relative to 1970 is estimated to have increased by 35% (Seitzinger et al., 2010). Over the next 50 years the human population is predicted to increase markedly in certain world regions, notably Southern and Eastern Asia, South America, and Africa (United Nations Department of Economic and Social Affairs, 2013). Growing food to feed the expanding world population will require increased use of nitrogen and phosphorus fertilizers (Bouwman et al., 2009). Increased industrialization, with the associated combustion of fossil fuels and NOx production, is predicted to increase atmospheric deposition of N (Dentener et al., 2006; IPCC, 2013).

If current trends continue, DIN export to coastal systems by 2050 relative to 2000 (based on the Global Orchestration scenario; Seitzinger et al., 2010), is predicted to increase by approximately 40–45% from Africa, South America, South Asia and Oceania (Fig. 8). Relatively smaller percent increases are predicted for North America, with slight decreases in Australia and Europe. Almost half of the predicted total global increase in DIN is from South Asia. Unless substantial technological innovations and management changes are implemented, increasing food production and industrialization in many regions will undoubtedly lead to increased export of N to coastal ecosystems with resultant water quality degradation and ecosystem changes. Understanding the effects of increased nutrient loading on coastal ecosystems in future decades will also need take into consideration increased water temperatures and changes in the hydrological cycle, among other effects, associated with climate change.

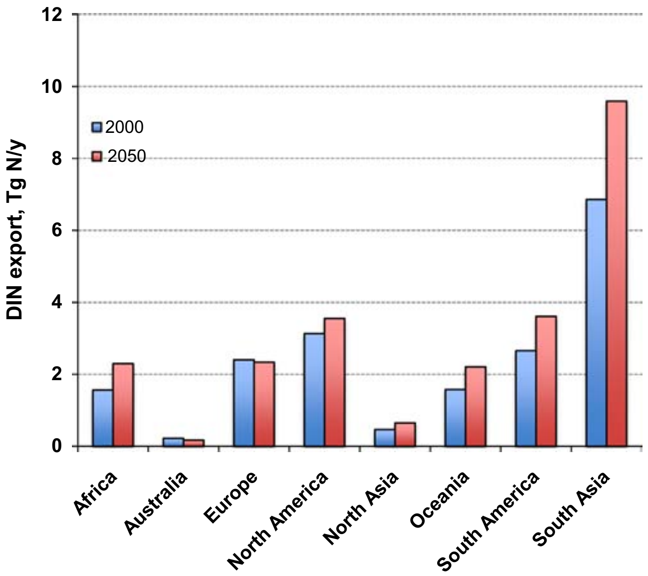

Fig. 8. River DIN export at continental/regional scale in 2000 and for the Global Orchestration scenario in 2050 (calculated from Seitzinger et al., 2010).

Acknowledgments

We thank the Global NEWS working group (http://marine.rutgers.edu/globalnews/) for development and implementation of the NEWS 2 model. This work was supported by funding from the UNESCO-Intergovernmental Oceanographic Commission, NASA ROSES Interdisciplinary Research in Earth Science (IDS) program, and the Global Environment Facility (GEF).

References

Alcamo, J., Van Vuuren, D., Cramer, W., 2006. Changes in ecosystem services and their drivers across the scenarios, in Ecosystems and Human Well-Being. In: Carpenter, S.R., et al. (Eds.), Scenarios, Island Press, Washington, D. C, pp. 279–354.

Barbosa, P.M., Stroppiana, D., Gregoire, J.-M., Pereira, J.M.C., 1999. An assessment of vegetation fire in Africa (1981–1991): burned areas, burned biomass, and atmospheric emissions. Glob. Biogeochem. Cycles 13, 933–950.

Bennett, E.M., Carpenter, S.R., Caraco, N.F., 2001. Phosphorus and eutrophication: a global perspective. Bioscience 51, 227–234.

Beusen, A.H.W., Dekkers, A.L.M., Bouwman, A.F., Ludwig, W., Harrison, J., 2005. Estimation of global river transport of sediments and associated particulate C,N, and P. Glob. Biogeochem. Cycles 19, GB4S05, http://dx.doi.org/10.1029/2005GB002453.

Bouwman, A.F., Van Drecht, G., Van der Hoek, K.W., 2005a. Global and regional surface nitrogen balances in intensive agricultural production systems for the period 1970–2030. Pedosphere 15, 137–155.

Bouwman, A.F., Van Drecht, G., Knoop, J.M., Beusen, A.H.W., Meinardi, C.R., 2005b. Exploring changes in river nitrogen export to the world's oceans. Glob. Biogeochem. Cycles 19, GB1002, http://dx.doi.org/10.1029/2004GB002314.

Bouwman, A.F., Kram, T., Klein Goldewijk, K., 2006. Integrated modelling of global environmental change. An overview of IMAGE 2.4, Neth. Environ. Assess. Agency, Bilthoven, 228pp.

Bouwman, A.F., Beusen, A.H.W., Billen, G., 2009. Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050. Glob. Biogeochem. Cycles 23, GB0A04, http://dx.doi.org/10.1029/ 2009GB003576.

Burnett, W.C., Bokuniewicz, H., Huettel, M., Moore, W.S., Taniguchi, M., 2003. Groundwater and pore water inputs to the coastal zone. Biogeochemistry 66 (1–2), 3–33.

Chassot, E., Bonhommeau, S., Dulvy, N.K., Mélin, F., Watson, R., Gascuel, D., Pape, O.L., 2010. Global marine primary production constrains fisheries catches. Ecol. Lett. 13, 495–505.

Cloern, J.E., 2001. Our evolving conceptual model of the coastal eutrophication problem. Mar. Ecol. Prog. Ser. 210, 223–253.

Dentener, F., Drevet, J., Lamarque, J.F., Bey, I., Eickhout, B., Fiore, A.M., Hauglustaine, D., Horowitz, L.W., Krol, M., Kulshrestha, U.C., Lawrence, M., Galy-Lacaux, C., Rast, S., Shindell, D., Stevenson, D., Van Noije, T., Atherton, C., Bell, N., Bergman, D., Butler, T., Cofala, J., Collins, B., Doherty, R., Ellingsen, K., Galloway, J., Gauss, M., Montanaro, V., Müller, J.F., Pitari, G., Rodriguez, J., Sanderson, M., Solmon, F., Strahan, S., Schultz, M., Sudo, K., Szopa, S., Wild, O., 2006. Nitrogen and sulfur deposition on regional and global scales: a multimodel evaluation. Glob. Biogeochem. Cycles 20, GB4003, http://dx.doi.org/10.1029/2005GB002672.

Duda, A.M., Sherman, K., 2002. A new imperative for improving management of large marine ecosystems. Ocean Coast. Manag. 45, 797–833.

Dumont, E., Harrison, J.A., Kroeze, C., Bakker, E.J., Seitzinger, S.P., 2005. Global distribution and sources of dissolved inorganic nitrogen export to the coastal zone: results from a spatially explicit, global model. Glob. Biogeochem. Cycles 19, GB4S02, http://dx.doi.org/10.1029/2005GB002488.

Fekete, B.M., Vorosmarty, C.J., Grabs, W., 2000. Global, composite runoff fields based on observed river discharge and simulated water balances, Report 22. World Meteorological Organization-Global Runoff Data Center Koblenz, Germany.

Fekete, B.M., Wisser, D., Kroeze, C., Mayorga, E., Bouwman, A.F., Wollheim, W.M., 2010. Millennium Ecosystem Assessment Scenario drivers (1970–2050): climate and hydrological alterations. Glob. Biogeochem. Cycles http://dx.doi.org/10.1029/2009GB003593.

Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P., Cleveland, C.C., Green, P.A., Holland, E.A., Karl, D.M., Michaels, A.F., Porter, J.H., Townsend, A.R., Vörösmarty, C.J., 2004. Nitrogen cycles: past, present and future. Biogeochemistry 70, 153–226.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., Sutton, M.A., 2008. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. Science 320, 889–892.

Galloway, J., Dentener, F., Burke, M., Dumont, E., Bouwman, L., Kohn, R., Mooney, H., Seitzinger, S., Kroeze, C., 2010. The impact of animal production systems on the nitrogen cycle. Chpt. 6. In: Steinfeld, H., Mooney, H.A., Schneider, F., Neville, L.E. (Eds.), Livestock in a Changing Landscape: Vol. 1. Drivers, Consequences, and Responses., Island Press, Washington DC.

Glibert, P.M., Allen, J.I., Bouwman, A.F., Brown, C.W., Flynn, K.J., Lewitus, A.J., Madden, C.J., 2010. Modeling of HABs and eutrophication: Status, advances, challenges. J. Mar. Syst. 83, 262–275.

Granéli, E., Turner, J.T. (Eds.), 2006. Ecology of Harmful Algae, Springer.

Green, P.A., Vorosmarty, C.J., Meybeck, M., Galloway, J.N., Peterson, B.J., Boyer, E.W., 2004. Pre-industrial and contemporary fluxes of nitrogen through rivers: a global assessment based on topology. Biogeochemistry 68, 71–105.

Harrison, J., Seitzinger, S., Bouwman, A.F., Caraco, N., Beusen, A., Vörösmarty, C., 2005a. Dissolved inorganic phosphorus export to the coastal zone: results from a spatially explicit, global model (NEWS-DIP). Glob. Biogeochem. Cycles 19, GB4S03, http://dx.doi.org/10.1029/2004GB002357.

Harrison, J.A., Caraco, N., Seitzinger, S.P., 2005b. Global patterns and sources of dissolved organic matter export to the coastal zone: results from a spatially explicit, global model. Glob. Biogeochem. Cycles 19, GB4S04, http://dx.doi.org/10.1029/2005GB002480.

Heisler, J., Glibert, P.M., Burkholder, J.M., Anderson, D.M., Cochlan, W., Dennison, W.C., Suddleson, M., 2008. Eutrophication and harmful algal blooms: a scientific consensus. Harmful Algae 8 (1), 3–13.

Howarth, R.W., Marino, R., 2006. Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: evolving views over three decades. Limnol. Oceanogr. 51, 364–376.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1535. doi:10.1017/CBO9781107415324.

Kemp, W.M., Boynton, W.R., Adolf, J.E., Boesch, D.F., Boicourt, W.C., Brush, G., Cornwell, J.C., et al., 2005. Eutrophication of Chesapeake Bay: historical trends and ecological interactions. Mar. Ecol. Prog. Ser. 303 (21), 1–29.

Klein Goldewijk, K., 2001. Estimating historical land use changes over the past 300 years: The HYDE database. Glob. Biogeochem. Cycles 15, 417–434.

Mayorga, E., Seitzinger, S.P., Harrison, J.A., Dumont, E., Beusen, A.H.W., Bouwman, A.F., Fekete, B.M., Kroeze, C., van Drecht, G., 2010. Global Nutrient Export from WaterSheds 2 (NEWS 2): model development and implementation. Environ. Model. Softw. 25, 837–853.

National Research Council, 2000. Clean Coastal Waters: Understanding and Reducing The Effects of Nutrient Pollution. National Academy Press.

Nixon, S.W., 1995. Coastal marine eutrophication: a definition, social causes, and future concerns. Ophelia 41, 199–219.

Paerl, H.W., 1997. Coastal eutrophication and harmful algal blooms: Importance of atmospheric deposition and groundwater as “new” nitrogen and other nutrient sources. Limnol. Oceanogr. 42, 1154–1165.

Paerl, H.W., Dennis, R.L., Whitall, D.R., 2002. Atmospheric deposition of nitrogen: Implications for nutrient over-enrichment of coastal waters. Estuaries 25, 677–693.

Qu, H.J., Kroeze, C., 2010. Past and future trends in nutrients export by rivers to the coastal waters of China. Sci. Total Environ. 408, 2075–2086.

Qu, H.J., Kroeze, C., 2012. Nutrient export by rivers to the coastal waters of China: management strategies and future trends. Reg. Environ. Change 12, 153–167.

Rabalais, N.N., Turner, R.E., Dı´az, R.J., Justic, D., 2009. Global change and eutrophication of coastal waters. ICES J. Mar. Sci. 66, 1528–1537.

Rabalais, N.N., Cai, W.-J., Carstensen, J., Conley, D.J., Fry, B., Hu, X., Quiñones-Rivera, Z., Rosenberg, R., Slomp, C.P., Turner, R.E., Voss, M., Wissel, B., Zhang, J., 2014. Eutrophication-driven deoxygenation in the coastal ocean. Oceanography 27 (1), 172–183, http://dx.doi.org/10.5670/oceanog.2014.21.

Sattar, M.A., Kroeze, C., Strokal, M., 2014. The increasing impact of food production on nutrient export by rivers to the Bay of Bengal 1970–2050. Mar. Pollut. Bull. 8, 168–178.

Sea Around Us, 2007. A global database on marine fisheries and ecosystems. World Wide Web site 〈www.seaaroundus.org〉. Fisheries Centre, University British Columbia, Vancouver, British Columbia, Canada. (accessed 15.05.07).

Seitzinger, S.P., Harrison, J.A., Dumont, E., Beusen, A.H.W., Bouwman, A.F., 2005. Sources and delivery of carbon, nitrogen, and phos- phorus to the coastal zone: an overview of Global Nutrient Export from Watersheds (NEWS) models and their application. Glob. Biogeochem. Cycles 19, GB4S01, http://dx.doi.org/10.1029/2005GB002606.

Seitzinger, S.P., et al., 2010. Global river nutrient export: a scenario analysis of past and future trends. Global Biogeochem. Cycles 24, GB0A08, http://dx.doi.org/10.1029/2009GB003587.

Selman, M., Greenhalgh, S., Diaz, R., Sugg, Z., 2008. Eutrophication and Hypoxia in Coastal Areas: A Global Assessment of the State of Knowledge. World Resources Institute, Washington, D.C.

Sherman, K., 1994. Sustainability, biomass yields, and health of coastal ecosystems: an ecological perspective. Mar. Ecol. Prog. Ser. 112, 277–301.

Sherman, K., Duda, A.M., 1999. An ecosystem approach to global assessment and management of coastal waters. Mar. Ecol. Prog. Ser. 190, 271–287.

Sherman, K., Aquarone, M.C., Adams, S., (Eds.), 2009. Sustaining the World's Large Marine Ecosystems. Gland, Switzerland: IUCN, viii + 140p.

Slomp, C.P., Van Cappellen, P., 2004. Nutrient inputs to the coastal ocean through submarine groundwater discharge: controls and potential impact. J. Hydrol. 295 (1), 64–86.

United Nations Department of Economic and Social Affairs, 2013. World population prospects the 2012 revision. ST/ESA/SER.A/336 United Nations, New York.

Van der Struijk, F., Kroeze, C., 2010. Future trends in nutrient export to the coastal waters of South America: implications for occurrence of eutrophication. Glob. Biogeochem. Cycles http://dx.doi.org/10.1029/2009GB003572.

Van Drecht, G., Bouwman, A.F., Harrison, J., Knoop, J.M., 2009. Global nitrogen and phosphate in urban wastewater between 1970 and 2050. Glob. Biogeochem. Cycles 23, GB0A03, http://dx.doi.org/10.1029/ 2009GB003458.

Vörösmarty, C.J., Fekete, B.M., Meybeck, M., Lammers, R., 2000a. Geomorphometric attributes of the global system of rivers at 30-min spatial resolution. J. Hydrol. 237, 17–39.

Vörösmarty, C.J., Fekete, B.M., Meybeck, M., Lammers, R., 2000b. A simulated topological network representing the global system of rivers at 30-min spatial resolution (STN-30). Glob. Biogeochem. Cycles 14, 599–621.

Yan, W., Mayorga, E., Li, X., Seitzinger, S.P., Bouwman, A.F., 2010. Increasing anthropogenic nitrogen inputs and riverine DIN exports from the Changjiang River basin under changing human pressures. Glob. Biogeochem. Cycles 24, GB0A06.

Yasin, J.A., Kroeze, C., Mayorga, E., 2010. Nutrients export by rivers to the coastal waters of Africa: past and future trends. Glob. Biogeochem. Cycles 24, GB0A07.