Land-based Nutrient Loading to LMEs: A Global Watershed Perspective on Magnitudes and Sources

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Abstract

Land-based nutrient (nitrogen and phosphorus) inputs to coastal systems around the world have markedly increased due primarily to the production of food and energy to support the growing population of over 6 billion people. The resulting nutrient enrichment has contributed to coastal eutrophication, degradation of water quality and coastal habitats, and increases in hypoxic waters, among other effects. There is a critical need to understand the quantitative links between anthropogenic activities in watersheds, nutrient inputs to coastal systems, and coastal ecosystem effects. As a first step in the process to gain a global perspective on the problem, a spatially explicit global watershed model (NEWS) was used to relate human activities and natural processes in watersheds to nutrient inputs to LMEs, with a focus on nitrogen.

Many LMEs are currently hotspots of nitrogen loading in both developed and developing countries. A clear understanding of the relative contribution of different nutrient sources within an LME is needed to support development of effective policies. In 73% of LMEs, anthropogenic sources account for over half of the dissolved inorganic nitrogen (DIN) exported by rivers to the coast. In most of these, agricultural activities (fertilizer use and wastes from livestock) are the dominant source of DIN loading, although atmospheric deposition and, in a few LMEs, sewage can also be important.

Over the next 50 years, human population, agricultural production, and energy production are predicted to increase especially rapidly in many developing regions of the world. Regions of particular note are in southern and eastern Asia, western Africa, and Latin America. Unless substantial technological innovations and management changes are implemented, this will lead to further increases in nutrient inputs to LME coastal waters with associated water quality and ecosystem degradation. An approach is needed such as that being developed in GEF-sponsored LMEs programs where all stakeholders – including scientists, policy makers and private sector leaders – work together to develop a better understanding of the issues and to identify and implement workable solutions.

Introduction of the Problem

Human activities related to food and energy production have greatly increased the amount of nutrient pollution entering the coastal environment from land-based sources (Howarth et al. 1996; Seitzinger and Kroeze 1998; Galloway et al. 2004; Green et al. 2004). Small amounts of nutrient enrichment can have beneficial impacts to some coastal waters and marine ecosystems by increasing primary production which can have potentially positive impacts on higher trophic levels. However, a high degree of nitrogen and phosphorus enrichment, causing eutrophication of coastal and even inland waters, tends towards detrimental effects including degradation of fisheries habitats. The negative effects of eutrophication begin with nutrient uptake by primary producers that can result in blooms of phytoplankton, macroalgae, and nuisance/toxic algae. When phytoplankton blooms die and sink, decomposition of the biomass consumes and may deplete dissolved oxygen in the bottom water resulting in hypoxic or “dead zones.” There are many other effects of nutrient over-enrichment including increased water turbidity, loss of habitat (e.g., seagrasses), decreases in coastal biodiversity and distribution of species, increase in frequency and severity of harmful and nuisance algal blooms, and coral reef degradation, among others (National Research Council 2000; Diaz et al. 2001; Rabalais 2002).

Nutrient over-enrichment and associated coastal ecosystem effects are occurring in many areas throughout the world and a number of recent assessments have begun to document their regional and global distribution. The European Outlook reported that in 2000, more than 55% of ecosystems were endangered by eutrophication. This includes the notable hypoxic/anoxic zones in the Baltic Sea, Black Sea and Adriatic Sea, among many others. In the USA, a recent assessment of over 140 coastal systems by the National Oceanic and Atmospheric Administration found that in 2004 50% of the assessed estuaries had a high chlorophyll a (phytoplankton) rating and 65% of the assessed estuaries were moderately to highly eutrophic (Bricker et al. 2007). In a recent literature review by the World Resources Institute (Selman et al. 2008), 375 eutrophic and hypoxic coastal systems were identified around the world, including many areas in developing countries.

The need to address nutrient over-enrichment as a priority threat to coastal waters and Large Marine Ecosystems (LMEs) has been recognized at national and global levels. The Global Plan of Action for the Protection of the Marine Environment from Land-based Activities (GPA), which was adopted by 108 Governments and the European Commission in 1995, recognized the need for global, regional and national action to address nutrients impacting the coastal and marine environment. Continued widespread government support to address nutrients has been noted in both the Montreal and Beijing Declarations. In 2002, the World Summit on Sustainable Development convened in Johannesburg identified substantial reductions in land-based sources of pollution by 2006 as one of their 4 marine targets. Over 60 countries have developed national policies or national action plans to address coastal nutrient-enrichment within the context of sustainable development of coastal areas and their associated watersheds.

Over the next 50 years, human population, agricultural production, and energy production are predicted to increase especially rapidly in many developing regions of the world (Hassan et al. 2005). Unless substantial technological innovations and management changes are implemented, this will lead to further increases in nutrient (nitrogen and phosphorus) inputs to the coastal zone with associated water quality and ecosystem degradation. In order to optimize use of land for food and energy production while at the same time minimizing degradation of coastal habitats, there is a critical need to understand the quantitative links between land-based activities in watersheds, nutrient inputs to coastal systems, and coastal ecosystem effects.

In this chapter we primarily address the links between land-based activities in watersheds and nutrient inputs to coastal systems around the world. Here we use a global watershed model (NEWS) to examine the patterns of nutrient loading and source attribution at global and regional scales and then apply the model at the scale of large marine ecosystems (LMEs) (Sherman & Duda 1999). Within all LMEs, 80% of the world's marine capture fisheries occur (Sherman 2008) which emphasizes the importance of cross political-boundary management of these international marine ecosystem units, as in the Global International Waters Assessment (GIWA; UNEP 2006). Various aspects including ecosystem productivity, fish and fisheries, pollution and ecosystem health, socioeconomic conditions, and governance, have been examined for many individual LMEs, but limited assessments across all LMEs have been made with a primarily fisheries emphasis (e.g., Sea Around Us Project 2007). In individual LMEs, few estimates of nutrient loading have been made, and only in the Baltic Sea LME has source apportionment been investigated (HELCOM 2004, 2002). At the end of the chapter we return to coastal ecosystem effects.

A Watershed Perspective

Rivers are a central link in the chain of nutrient transfer from watersheds to coastal.systems. Nutrient inputs to watersheds include natural (biological N_2-fixation, weathering of rock releasing phosphate) as well as many anthropogenic sources. At the global scale, anthropogenic nitrogen inputs to watersheds are now greater than natural inputs (Galloway et al. 2004). Anthropogenic nutrient inputs are primarily related to food and energy production to support the over 6 billion people on Earth with major sources including fertilizer, livestock production, sewage, and atmospheric nitrate deposition resulting from NOx emissions from fossil fuel combustion.

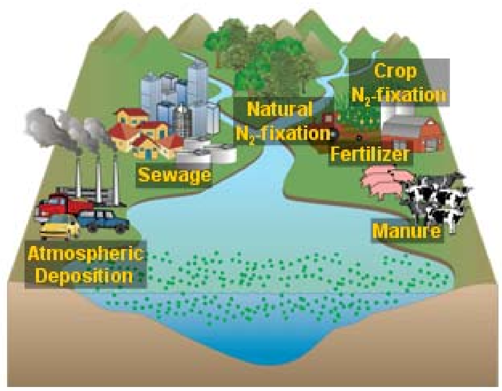

Figure 1. Watershed schematic of nitrogen inputs and transport to coastal systems. Symbols for diagram courtesy of the Integration and Application Network (ian.umces.edu/symbols), University of Maryland Center for Environmental Science.

Uneven spatial distribution of human population, agriculture, and energy production leads to spatial differences in the anthropogenic alterations of nutrient inputs to coastal ecosystems (Howarth et al. 1996; Seitzinger and Kroeze 1998; Green et al. 2004; Seitzinger et al. 2005). While many site-specific studies have documented river transport of nutrients (nitrogen (N), phosphorus (P), carbon (C) and silica (Si)) to coastal systems, there are many more rivers for which there are no measurements; sustained monitoring of temporal changes in exports is rarer still. A mechanism is needed to develop a comprehensive and quantitative global view of nutrient sources, controlling factors and nutrient loading to coastal systems around the world under current conditions, as well as to be able to look at past conditions and plausible future scenarios.

A Global Watershed Nutrient Export Model (NEWS)

In order to provide regional and global perspectives on changing nutrient transport to coastal systems throughout the world, an international workgroup (Global NEWS – Nutrient Export from WaterSheds; http://www.marine.rutgers.edu/globalnews) has developed a spatially explicit global watershed model that 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; Harrison et al. 2005a and b; Seitzinger et al. 2005). Global NEWS is an interdisciplinary workgroup of UNESCO's Intergovernmental Oceanographic Commission (IOC) focused on understanding the relationship between human activity and coastal nutrient enrichment.

In addition to current predictions, the NEWS model is also being used to hindcast and forecast changes in nutrient, carbon and water inputs to coastal systems under a range of scenarios. In this chapter we briefly describe the NEWS model and then present results for mid-1990's conditions at both global scales and as specifically applied to LME regions.

NEWS Model Basics. The NEWS model is a multi-element, multi-form, spatially explicit global model of nutrient (N, P, and C) export from watersheds by rivers (Table 1). The model output is the annual export at the mouth of the river (essentially zero salinity). The NEWS model was calibrated and validated with measured export near the river mouth from rivers representing a broad range of basins sizes, climates, and land-uses. Over 5000 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 and b). The input databases are at the scale of 0.5^o latitude by 0.5^o longitude.

Table 1. **Nutrient forms modeled in Global NEWS. DIC and DSi sub-models (in italics) are currently in development.**

	Dissolved		Particulate
	Inorganic	Organic	
N	DIN	DON	PN
P	DIP	DOP	PP
C	*DIC*	DOC	POC
Si	*DSi*		

Whereas previous efforts have generally been limited to a single element or form, the Global NEWS model is unique in that it can be used to predict magnitudes and sources of multiple bio-active elements (C, N, and P) and forms (dissolved/particulate, organic/inorganic). It is important to know coastal nutrient loading of multiple elements because different elements and elemental ratios can have different ecosystem effects. The various forms of the nutrients (dissolved inorganic and organic and particulate forms) also have different bioreactivities. For example, the dissolved inorganic nitrogen (DIN) pool is generally considered to be bio-available, while only a portion of river transported dissolved organic nitrogen (DON) is readily available for uptake by micro-organisms, including bacteria and some phytoplankton (Bronk, 2002; Seitzinger et al., 2002a). However, DON can be an important N source and it is implicated in the formation of some coastal harmful algal blooms (Paerl, 1988; Berg et al., 1997 and 2003; Granéli et al., 1999; Glibert et al., 2005a and b). Particulate and dissolved species can also have very different impacts on receiving ecosystems.

The NEWS 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 (Figure 2) (Beusen et al. 2005; Dumont et al. 2005; Harrison et al. 2005a and b; Seitzinger et al. 2005). 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. The NEWS model builds on an earlier model of dissolved inorganic N (DIN) export (Seitzinger and Kroeze 1998).

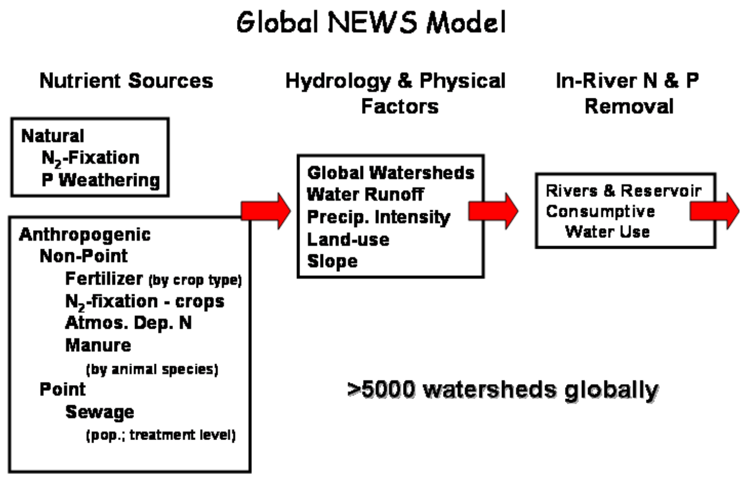

Figure 2. Schematic of some of the major inputs and controlling factors in the Global NEWS watershed river export model.

There is considerable detail in the input databases and model parameterizations that reflect food and energy production and climate (Figure 2). For example, crop type is important in determining fertilizer use, the amount of manure produced is a function of animal type (e.g., cows, camels, chickens, goats, etc.), nutrient loading from sewage depends not only on the number of people in a watershed but also on their connectivity to a sewage system and level of sewage treatment, atmospheric nitrate deposition is related to fossil fuel combustion. A number of hydrological and physical factors are important in transferring nutrients from soils to the river, with water runoff being important for all elements and forms. Once in the river, N and P can be removed by biological and physical processes during river transport within the river channels, in reservoirs, and through water removal for irrigation (consumptive water use).

NEWS Model Output: The NEWS model has provided the first spatially distributed global view of N, P and C export by world rivers to coastal systems. At the global scale rivers currently deliver about 65 Tg N and 11 Tg P per year according to NEWS model predictions (Tg = tera gram = 10^{12} g) (Figure 3). For nitrogen, DIN and particulate N (PN) each account for approximately 40% of the total N input, with DON comprising about 20%. This contrasts with P, where particulate P (PP) accounts for almost 90% of total P inputs. However, while DIP and dissolved organic P (DOP) each contribute only about 10% of total P, both of these forms are very bioreactive and thus may have a disproportionate impact relative to PP on coastal systems.

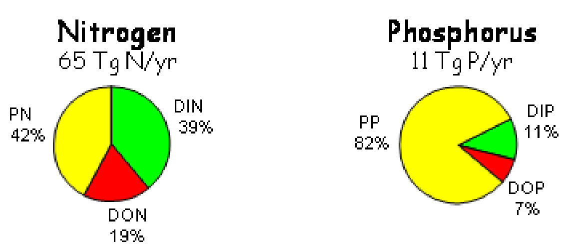

Figure 3. Global N and P river export to coastal systems by nutrient form based on the NEWS model (Dumont et al. 2005; Harrison et al. 2005a).

There is large spatial variation around the world in river nutrient export, including different patterns for the different nutrient forms (DIN, DON and PN) (Figure 4). Using N yield (kg N per km² watershed per year that is exported to the river mouth), DIN yield shows considerable variation at regional and continental scales, as well as among adjacent watersheds. As might be expected based on past measurements of river nutrient export, the NEWS model predicts relatively high watershed yields in the eastern USA, the Mississippi basin, and much of western Europe. Of particular note, however, are also the high DIN yields from developing regions including much of southern and eastern Asia, Central America and small coastal watersheds in western Africa.

The large spatial variation in N yield reflects the variable magnitudes of the different nutrient sources and controlling factors among watersheds. This underscores the importance of the need for a clear understanding of the nutrient sources and controls within LMEs at many scales in order to develop effective policies and implementation strategies to control coastal nutrient loading.

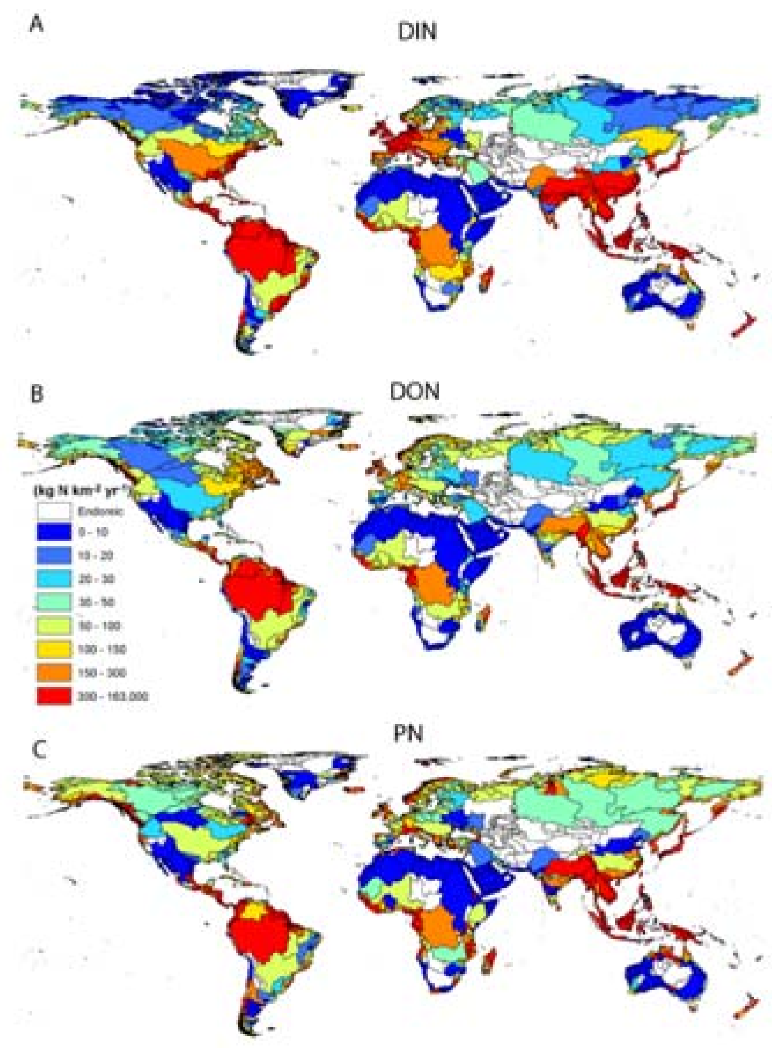

Figure 4. NEWS-model-predicted A) DIN, B) DON, and C) PN yield (kg N km-2 yr-1) to coastal systems from basins globally. Model output replotted from Harrison et al., 2005b, Dumont et al 2005, and Beusen et al. 2005.

N and P differ markedly in the relative contribution of different nutrient sources to river nutrient export (Seitzinger et al. 2005). At the global scale, natural sources account for about 40% of DIN and DIP river export (biological N_2-fixation and rock weathering, respectively) (Figure 5). Anthropogenic sources for DIN export are dominated by agriculture (fertilizer and manure) in contrast to DIP where sewage accounts for ~60% of river export. This difference in major sources, illustrates the need for different strategies to reduce nitrogen or phosphorus loading to coastal systems.

Of course there is considerable variation in the relative contribution of nutrient sources at continental, regional and watersheds scales, and this must be known and taken into consideration when developing nutrient reduction strategies. At the continental scale, for example, in South America livestock production (manure) is by far the largest anthropogenic N source contributing to river DIN loading to coastal systems (Figure 6). This contrasts with Asia where fertilizer use is about twice as great as livestock production in contributing to river DIN loading.

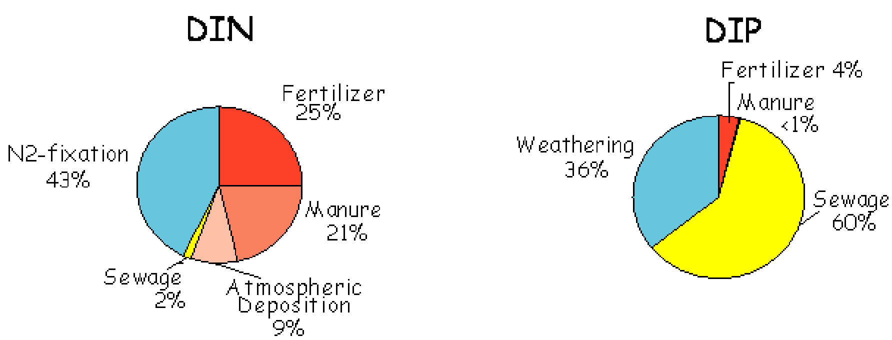

Figure 5. Contribution of different sources to DIN and DIP river export globally.

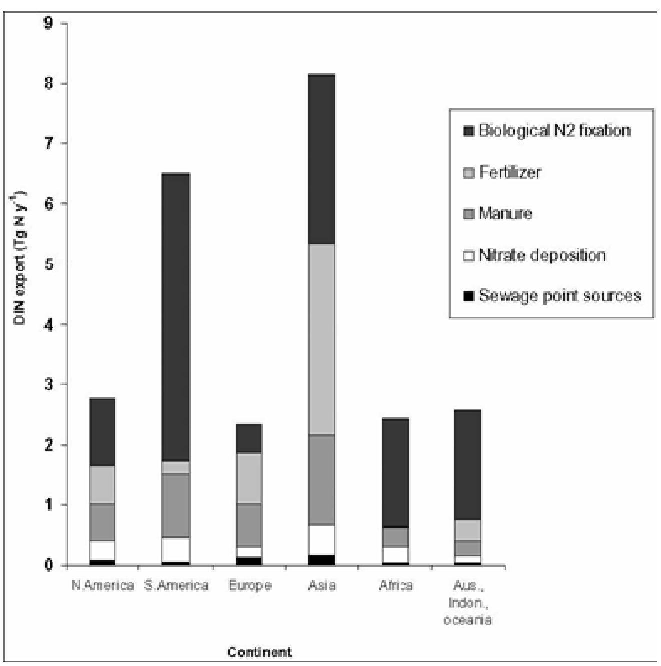

Figure 6. Contribution of N sources in watersheds to model predicted DIN river export to the coastal zone of each continent. (Figure from Dumont et al. 2005)

NEWS Model Application to LMEs

Land-based pollution of coastal waters in LMEs can have sources in multiple countries often located upstream at a considerable distance from the coastal zone. The release of nutrients into rivers can cross national borders and create environmental, social and economic impacts along the way - until reaching the coastal zone, which may be in a different country. Thus an LME transboundary approach is essential for identifying watershed nutrient sources and coastal nutrient loading to support policy development and implementation in LMEs that will reduce current and future coastal eutrophication.

Few estimates of nutrient loading have been made in individual LMEs, and only in the Baltic Sea LME has source apportionment been investigated (HELCOM 2004, 2002). As a first step in bridging the gap between land-based activities and LME waters, we examined the relative magnitudes and distribution of DIN loading from watersheds to LMEs globally. We focused on N because it is often the most limiting nutrient in coastal waters and thus important in controlling coastal eutrophication. DIN is often the most abundant and bioavilable form of nitrogen, and therefore contributes significantly to coastal eutrophication.

Watershed DIN export to rivers predicted by the NEWS model described above was compiled for each of the 64 LMEs (2002 delineation; Duda & Sherman 2002) 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. This work was part of the GEF Medium-Sized Project: Promoting Ecosystem-based Approaches to Fisheries Conservation and LMEs (Component 3: Seitzinger and Lee 2007).

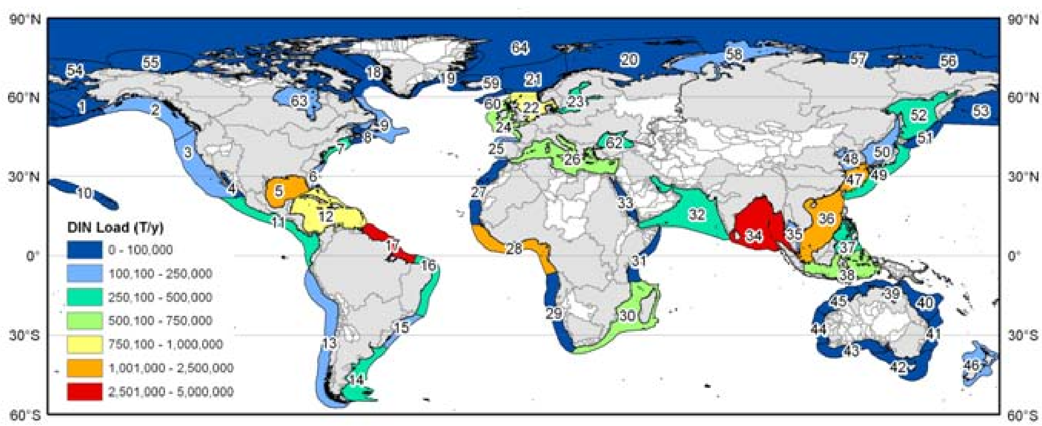

Figure 7. DIN inputs to LMEs from land-based sources predicted by the NEWS DIN model. Watersheds discharging to LMEs are grey; watersheds with zero coastal discharge are white. Units: Tons N/y. See Table 2 for LME identification. (Figure from Lee and Seitzinger submitted).

Table 2. LMEs identified by name and number (see Fig. 7 and 8)

LME #	LME name	LME #	LME name
1	East Bering Sea	33	Red Sea
2	Gulf of Alaska	34	Bay of Bengal
3	California Current	35	Gulf of Thailand
4	Gulf of California	36	South China Sea
5	Gulf of Mexico	37	Sulu-Celebes Sea
6	Southeast U.S. Continental Shelf	38	Indonesian Sea
7	Northeast U.S. Continental Shelf	39	North Australian Shelf
8	Scotian Shelf	40	Northeast Australian Shelf-Great Barrier Reef
9	Newfoundland-Labrador Shelf	41	East-Central Australian Shelf
10	Insular Pacific-Hawaiian	42	Southeast Australian Shelf
11	Pacific Central-American Coastal	43	Southwest Australian Shelf
12	Caribbean Sea	44	West-Central Australian Shelf
13	Humboldt Current	45	Northwest Australian Shelf
14	Patagonian Shelf	46	New Zealand Shelf
15	South Brazil Shelf	47	East China Sea
16	East Brazil Shelf	48	Yellow Sea
17	North Brazil Shelf	49	Kuroshio Current
18	West Greenland Shelf	50	Sea of Japan
19	East Greenland Shelf	51	Oyashio Current
20	Barents Sea	52	Okhotsk Sea
21	Norwegian Sea	53	West Bering Sea
22	North Sea	54	Chukchi Sea
23	Baltic Sea	55	Beaufort Sea
24	Celtic-Biscay Shelf	56	East Siberian Sea
25	Iberian Coastal	57	Laptev Sea
26	Mediterranean Sea	58	Kara Sea
27	Canary Current	59	Iceland Shelf
28	Guinea Current	60	Faroe Plateau
29	Benguela Current	61	Antarctic (not included in this analysis)
30	Agulhas Current	62	Black Sea
31	Somali Coastal Current	63	Hudson Bay
32	Arabian Sea	64	Arctic Ocean

DIN export from watersheds to LMEs varies globally across a large range of magnitudes (Figure 7). The smallest loads are exported to many polar and Australian LMEs, while the largest loads are exported to northern tropical and subtropical LMEs. Of particular note are the large loads exported to the Gulf of Mexico, South China Sea, East China Sea, and North Sea LMEs in which high anthropogenic activity occurs in their watersheds. The Carribean Sea, Mediterranean Sea and Indonesian Sea LMEs, among others, also receive substantial DIN loads.

The NEWS model also predicts substantial DIN export from the North Brazil Shelf LME which has relatively low anthropogenic activity in its watersheds. Further investigation is underway to evaluate the NEWS model for these large and relatively pristine tropical river basins. The high DIN load may reflect a number of factors including the large role that high water runoff from tropical rivers plays in the export of DIN, high biological N_2-fixation, low denitrification, and model uncertainty.

Identification of Land-based Nutrient Sources to LMEs. DIN loading to each LME was attributed to diffuse and point sources including natural biological N_2-fixation, agricultural biological N_2-fixation, fertilizer, manure, atmospheric deposition and sewage. Dominant sources of DIN to LMEs were also identified which may be useful for the management of land-based nutrient loading to LMEs.

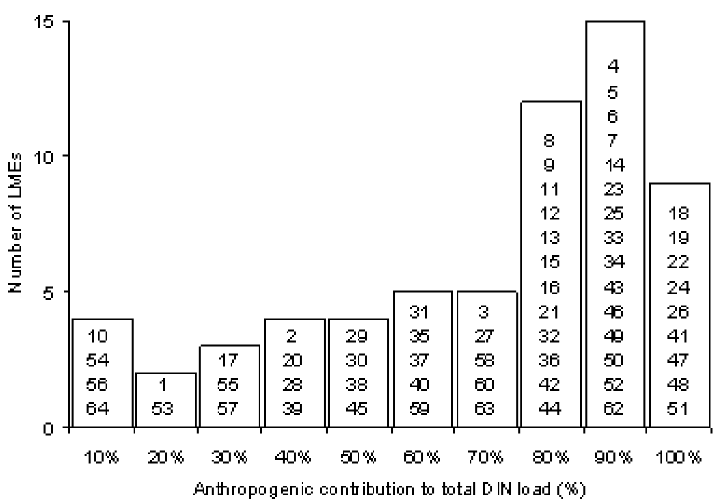

Figure 8. Histogram of anthropogenic contribution to total DIN load to LMEs. LME numbers are shown in each bar. See Table 2 for LME identification.

Land-based sources of DIN include natural sources (biological N_2-fixation in natural landscapes) and anthropogenic activities. In watersheds draining to LMEs, anthropogenic activities contribute to over half of the total DIN load in 73% of LMEs (Figure 8). These anthropogenic DIN dominant 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.

Agriculture is a major source of the anthropogenic DIN export to LMEs (Lee and Seitzinger submitted). In 91% of the LMEs with agriculture occurring in their related watersheds, over half their anthropogenic export is due to agricultural sources such as agricultural biological fixation, manure, and fertilizer. Attribution of agricultural DIN export to these three sources reveals the predominance of fertilizer and manure over agricultural biological fixation. For example, LMEs with the largest agricultural loads have less than 20% of the total DIN load due to biological fixation and over 50% due to either fertilizer (e.g., in many northern temperate and Southeast Asian LMEs such as the Bay of Bengal, East China Sea and South China Sea LMEs), to manure (e.g., in most Central and South American LMEs such as the Caribbean and North Brazil Shelf LMEs) or to a combination of both (e.g., in the North Sea and Celtic-Biscay Shelf LMEs) due to local agricultural practices. There is no agricultural export to most polar LMEs.

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., in the Guinea Current LME which is fed by savannah fires in Western Central African watersheds; Barbosa et al. 1999). Sewage is an 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.

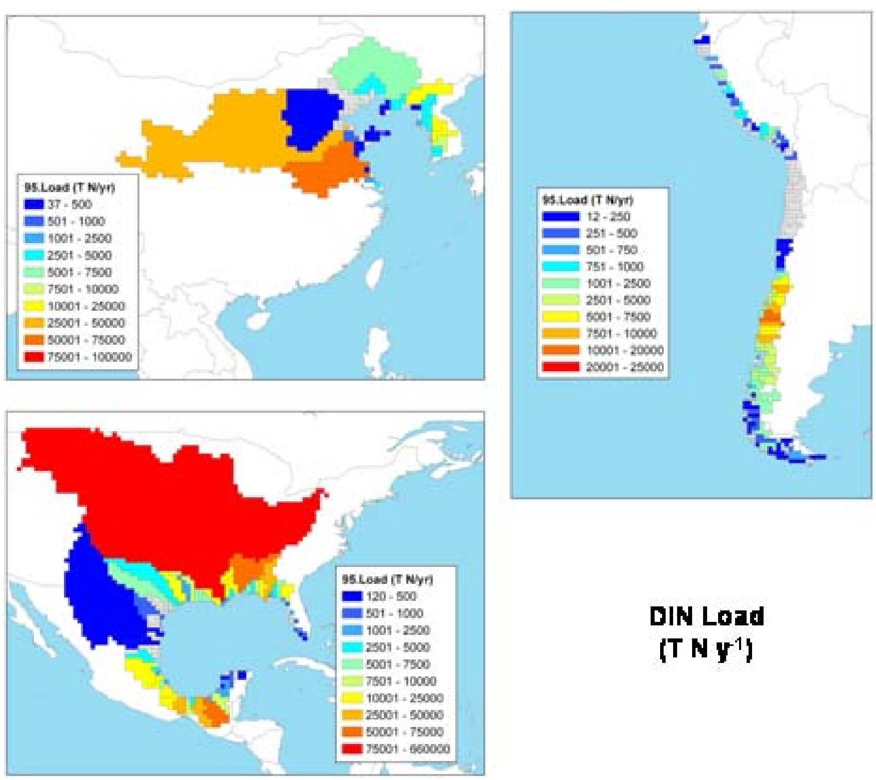

Figure 9. DIN export predicted by the NEWS DIN model from watersheds within the Yellow Sea, Humboldt Current and Gulf of Mexico LMEs. Units: Tons N/yr.

The variability in watershed DIN export and source attribution within individual LMEs exhibits comparably large differences as with across LMEs. Examples from different world regions including Asia, South America and the US-Latin America are presented below. Among the Yellow Sea, Humboldt Current and Gulf of Mexico LMEs, the DIN load from individual watersheds ranges over several orders of magnitude across both small and large watersheds (Figure 9). For example, similarly sized watersheds in both the Yellow Sea and Humboldt Current LMEs exhibit both the largest and smallest magnitudes of watershed DIN export. In contrast, the Mississippi watershed is the largest watershed contributing to the Gulf of Mexico LME and also exports the largest load of DIN to the Gulf of Mexico.

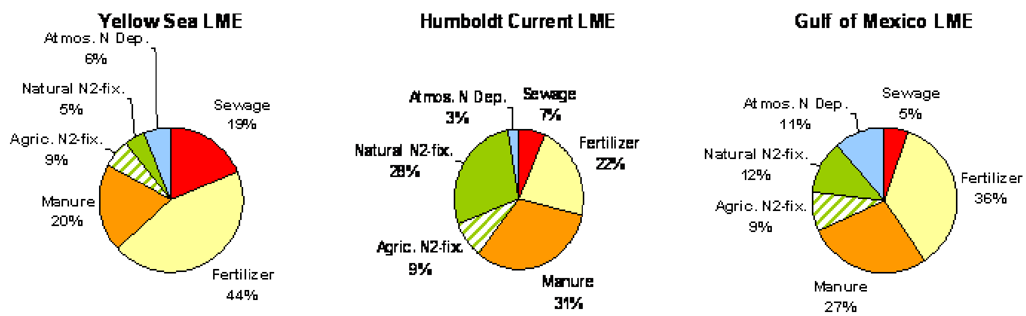

Figure 10. Source attribution of DIN export predicted by the NEWS DIN model to the Yellow Sea, Humboldt Current and Gulf of Mexico LMEs. Units: Tons N/yr.

The relative importance of different watershed sources of DIN to LME loading also varies, e.g., among the Yellow Sea, Humboldt Current and Gulf of Mexico LMEs (Figure 10). Agricultural sources dominate the DIN export in all of these LMEs, but fertilizer contributes the most to export to the Yellow Sea and Gulf of Mexico LMEs while manure is relatively more important than fertilizer to the Humboldt Current LME. In the Yellow Sea LME, sewage is also a significant source (19%) to DIN export, while less so to the Humboldt Current and Gulf of Mexico LMEs. Nitrogen fixation occurring in natural landscapes is a significant source (28%) to the DIN export to only the Humboldt Current LME. Atmospheric deposition is a lesser source of DIN export to all three example LMEs, but contributes the relatively largest percentage (11%) to the Gulf of Mexico LME. The identification of dominant sources of DIN and their relative contribution at the individual LME level is essential for developing effective nutrient management strategies on an ecosystem level.

Implications of Future Conditions in LME Watersheds

At the global scale, river nitrogen export to coastal systems is estimated to have approximately doubled between 1860 and 1990, due to anthropogenic activities on land (Galloway et al., 2004). 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, 1996). Growing food to feed the expanding world population will require increased use of nitrogen and phosphorus fertilizers (Alcamo et al., 1994; Bouwman et al., 1995; Bouwman, 1997). 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, 2001). Thus, unless substantial technological innovations and management changes are implemented, increasing food production and industrialization will undoubtedly lead to increased export of N to coastal ecosystems (Galloway et al. 2004), with resultant water quality degradation.

Based on a business-as-usual (BAU) scenario, inorganic N export to coastal systems is predicted to increase 3-fold by the year 2050 (relative to 1990) from Africa and South

America (Figure 11) (Kroeze and Seitzinger, 1998; Seitzinger et al., 2002b). Substantial increases are predicted for Europe (primarily eastern Europe) and North America. Alarmingly large absolute increases are predicted for eastern and southern Asia; almost half of the total global increased N export is predicted for those regions alone.

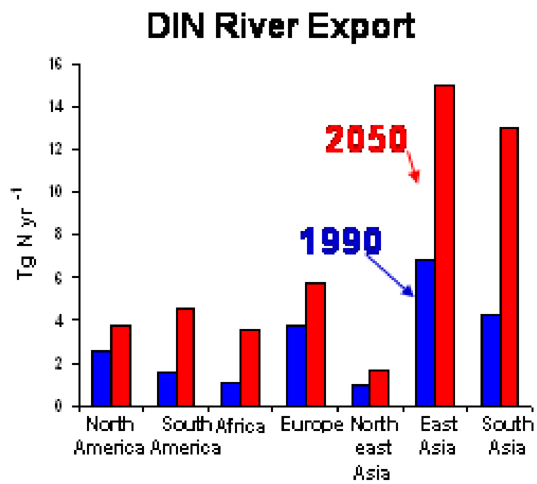

Figure 11. Predicted DIN export to coastal systems in 1990 and 2050 under a business-as-usual (BAU) scenario. Modified from Kroeze and Seitzinger (1998).

The above scenario for 2050 was based on projections made from early 1990 trajectories and using a relatively simple DIN model (Seitzinger and Kroeze 1998). The NEWS model has more parameters and more detail behind the inputs (e.g., fertilizer use by crop type, level of sewage treatment, etc.) (Figure 2) thus facilitating more advanced scenario development and analyses. For example, it is now possible to explore the effects of a range of development strategies, effects of climate change, production of biofuels, increase in dams for hydropower, and consumptive water use (irrigation) on coastal nutrient loading. Using the NEWS model, we are currently analyzing a range of alternative scenarios for the years 2030 and 2050 based on the Millennium Ecosystem Assessment (www.millenniumassessment.org) to provide insights into how changes in technological, social, economic, policy and ecological considerations could alter future nutrient export to coastal systems around the world (Seitzinger et al. in prep.).

Coastal Ecosystem Effects

As noted at the beginning of this chapter, nutrient over-enrichment can lead to a wide range of coastal ecosystem effects. The most direct response of coastal ecosystems to increased nutrient loading is an increase in biomass (e.g., chlorophyll a) of primary producers or primary production rates (Nixon 1995). How might land-based DIN loading be affecting primary production in LMEs? As a preliminary examination, we compared land-based DIN loads predicted by the NEWS model to LME primary production (modeled SeaWiFS data; Sea Around Us Project 2007) (Figure 12). This analysis suggests that land-based DIN export supports a significant portion of primary production at the level of an entire LME. In areas with upwelling, nutrient-rich bottom waters support high rates of photosynthetic production. This is reflected in the generally higher primary productivity than predicted by the regression solely with land-based DIN inputs in LMEs characterized by upwelling (the Guinea Current, Arabian Sea, Pacific Central-American, Humboldt Current, California Current, Gulf of Alaska, Benguela Current, Canary Current, Northwest Australian, and Southwest Australian LMEs).

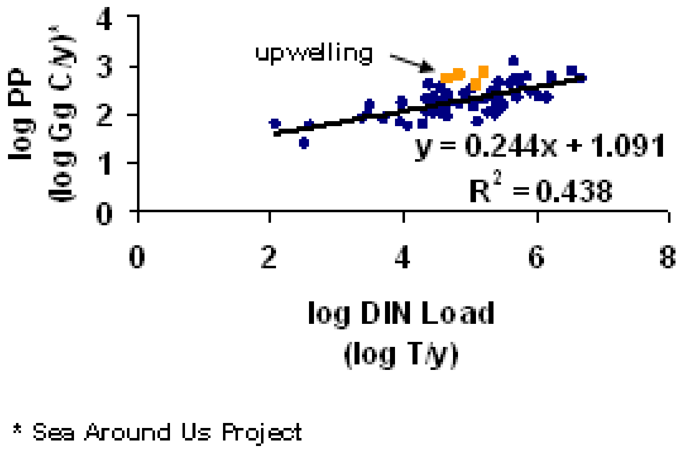

Figure 12. Phytoplankton production vs. DIN load to the 63 LMEs. Orange points are LMEs in upwelling regions. Phytoplankton production rates are from the Sea Around Us Project; DIN loads are from the NEWS model (Dumont et al. 2005). Figure from Lee and Seitzinger submitted.

The above analysis compares land-based N loading to average primary production for waters in the entire LME. In the near shore areas of LMEs, land-based N loading likely supports a much higher proportion of primary production than suggested by the overall relationship in Figure 12 and should be investigated. The additional effects of high nutrient loading to estuaries and near shore waters in LMEs on hypoxia, biodiversity, toxic and nuisance algal blooms, habitat quality, and fisheries yields also warrants further analysis.

Future Needs

We are beginning to make significant advances in understanding the relationship between human activities in watersheds and coastal nutrient loading at a range of scales (e.g., watershed, LME, and global) as illustrated by the application of the NEWS model. However, this is only a start. For example, to date the LME, regional, and global analyses have relied on input databases at the scale of 0.5 ^{o} latitude x 0.5^{o} longitude. The use of higher spatial resolution input databases based on local knowledge from specific LME regions could significantly improve the model predictions. Similarly, additional data for model validation is need. Development of scenarios based on local projections of population, agricultural production, biofuels, dam construction, and climate change, among others could provide information of use to policy makers.

Development of nutrient reduction policies and effective mitigation strategies also requires widely applicable, quantitative relationships between nutrient loading and coastal ecosystem effects. While there is considerable information on nutrient sources and coastal impacts, this information is often much dispersed and has not yet been compiled into a consistent database so that nutrient sources in specific LMEs can be linked to impacts in their associated coastal system. This is a critical next step in order for a toolbox to be developed so that effective policy measures can be formulated and measures taken, and for the outcomes of those policies and measures to be evaluated.

Many technical and political options are available to reduce fertilizer use, decrease nutrient runoff from livestock waste, decrease NOx emissions from fossil fuel burning, and enhance sewage treatment. The fact that many of these tools have not yet been implemented on a significant scale suggests that additional technological options and new policy approaches are needed. In addition, policy approaches to address non-point source pollution are often nonexistent or very limited. To ensure that the science used to develop these technologies and polices is sound and complete, existing data on nutrient sources, mobilisation, distribution, and effects need to be assessed. An approach is needed such as that being developed in GEF-sponsored LME programs and as promoted by the International Nitrogen Initiative (INI: INitrogen.org) where all stakeholders – including scientists, policy makers and private sector leaders – work together to develop a better understanding of the issues and to identify and implement workable solutions.

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