Linking Watersheds to Coastal Systems: A Global Perspective on River Inputs of N, P and C

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The inputs of nutrients, carbon and freshwater from land to the coastal ocean have been markedly altered by anthropogenic activities. As a result, carbon production, ecology, and circulation in the coastal ocean have been altered in ways that are still being discovered. Addressing this challenge will require improved understanding of the linkages between human activities in watersheds, delivery of nutrients and water inputs to coastal systems, and the effects of those changes on coastal systems, in addition to continued studies on natural controls.

Uneven spatial distribution of human population, agriculture, and industrial activity leads to spatial differences in the anthropogenic alterations of nutrient inputs to coastal ecosystems. While many site-specific studies have documented river transport of nitrogen (N), phosphorus (P), carbon (C) and silicon (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. In order to provide regional and global perspectives on changing nutrient transport to coastal systems throughout the world, an international work group (Global NEWS—Nutrient Export from WaterSheds, www.marine.rutgers.edu/global news) 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. Global NEWS was formed in spring of 2002 as an interdisciplinary workgroup of UNESCO's Intergovernmental Oceanographic Commission (IOC, www.ioc.unesco.org) focused on understanding the relationship between human activity and coastal nutrient enrichment. The first version of the NEWS model is based on mid-1990s conditions and was published in a special section of Global Biogeochemical Cycles (1-5). This model is now being used to provide hindcasts and forecasts under a range of scenarios portraying changes in nutrient, carbon and water inputs to coastal systems. In this article we briefly describe the NEWS model and present highlights from the published results corresponding to mid-1990's conditions, focusing on river exports and fate in the coastal zone. Our goal is to stimulate collaborations with the oceanographic community addressing the coupled impacts of marine processes and riverine inputs on carbon, biogeochemistry and ecosystem functioning on the continental shelf.

NEWS Model Basics

NEWS 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). Because the relative bioavailability of different nutrients and nutrient forms (dissolved vs. particulate, inorganic vs. organic) can influence ecosystem response, multi-element, multi-form approaches are needed to predict ecosystem vulnerability or response. The NEWS model uses consistent global databases to predict riverine nutrient export by form as a function of natural and anthropo-

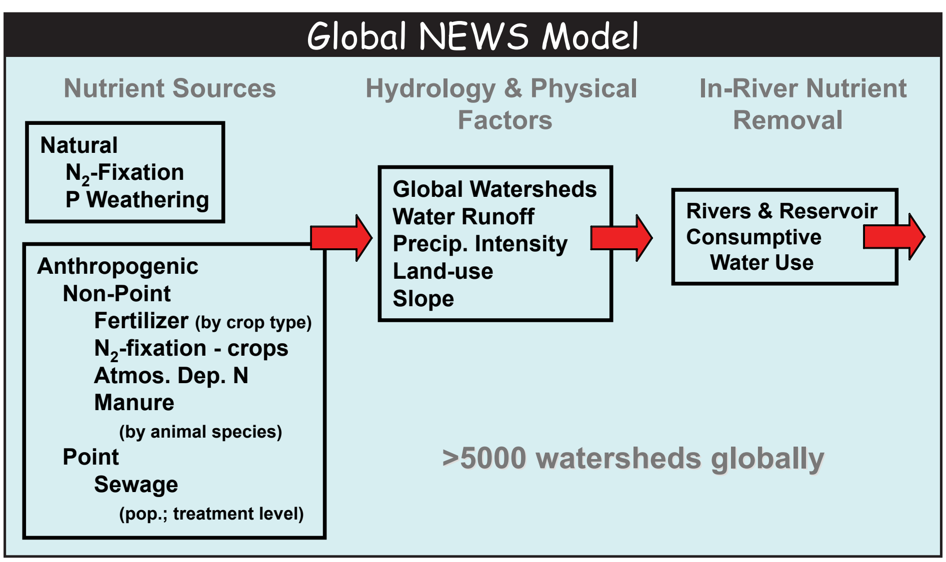

Figure 1. Schematic of some of the major inputs and controlling factors in the Global NEWS model.

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

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

genic characteristics, including point and non-point watershed sources, hydrological and physical factors, and removal within the river system (Figure 1). In addition, it can estimate the relative contribution of each watershed source to export at the river mouth, by form (5). NEWS builds on an earlier model of dissolved inorganic N (DIN) export (6) as well as other models of biogeochemical exports—such as particulates (7)—developed by the community over the last decade.

Contemporary River Nutrient Exports: Forms and Spatial Distributions

There are large spatial variations in river export of elements and elemental forms to the coastal zone. This is illustrated by the watershed yields of dissolved inorganic P (DIP) and dissolved organic P (DOP) (Fig. 2). Yields of DIP and DOP show large variations among watersheds within regions as well as at larger spatial scales. Furthermore, the spatial patterns and range of yields of these two P forms differ. These differences among rivers in both the amount and the form are driven by contrasts in the relative importance of the various sources and controlling factors in the watersheds (5).

There are also important differences between the patterns of N and P river export. The relative magnitude of the various forms of N and P differ (Fig. 3). At the global scale, approximately equal fractions (~40%) of total N (TN) river export are in the form of DIN and particulate N (PN), with dissolved organic N (DON) accounting for ~20%. In contrast, ~80% of total P (TP) export is as particulate P (PP), with relatively small amounts as DIP or DOP. This has important implications for linking nutrient inputs to coastal ecosystem biogeochemistry, as the different forms of N and P have different reactivities. For example, while most of the P is exported as particulate P, only a small portion of that is readily exchangeable into a form (e.g., DIP) that can be rapidly used by phytoplankton.

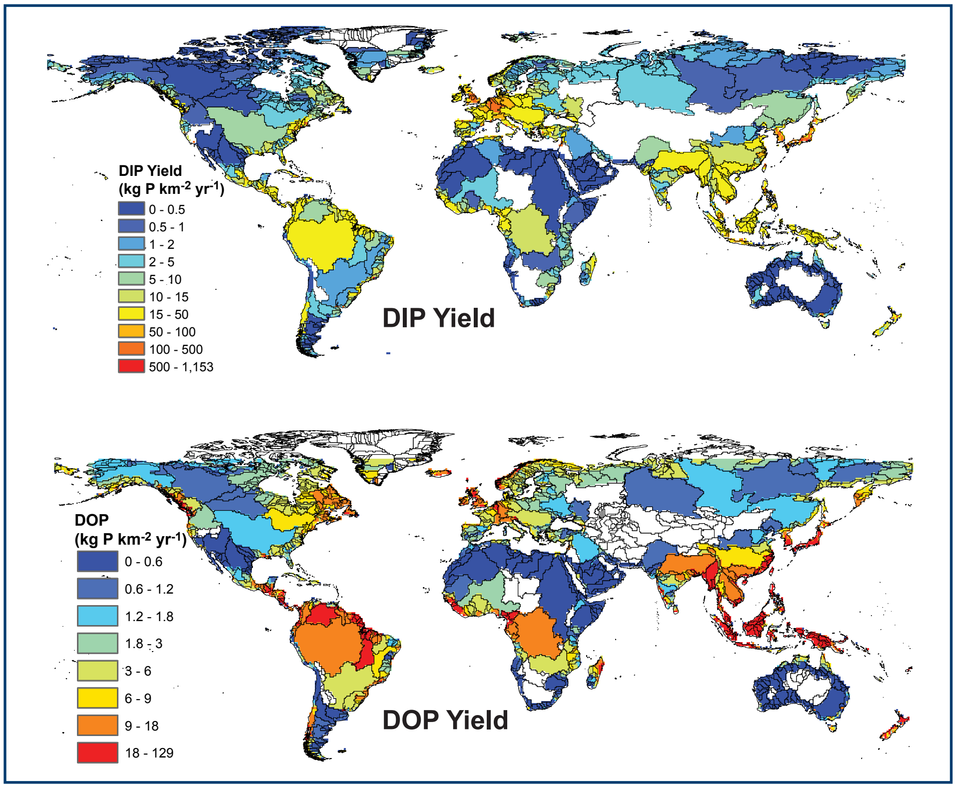

Figure 2. Basin yields of dissolved inorganic and organic phosphorus (DIP and DOP). The amount of P exported at the river mouth is expressed as the watershed average export in kg P per km^2 of watershed per year; total mass export or load equals yield times watershed area.

The latitudinal distribution of river nutrient export to the coast shows strong patterns. Aggregation of the NEWS model output by latitude emphasizes the importance of tropical and subtropical latitudes in N, P and C export. 70-75% of the global river TN, TP and total organic C (TOC) is exported into tropical and subtropical coastal waters (30˚S to 30˚N; Fig. 3). This region also dominates all global particulate fluxes (Fig. 3) due to the occurrence of high runoff and tectonically active mountain ranges in both large rivers (*e.g.*, Amazon, Mekong, Ganges-Brahmaputra) and small mountainous rivers. The former generally discharge into passive, wide shelves, while the latter discharge into active, narrow shelves, with consequences for the sequestration of exported particulates.

Nutrient ratios in coastal systems not only affect nutrient limitation but can also affect phytoplankton species composition. The NEWS model output suggests that the ratio of TN:TP in river export to coastal systems varies widely (Fig. 4). However, TN and TP river exports are only one part of the story. While the NEWS model predicts the individual forms of N and P, determining the bioavailability of each N and P form remains a major scientific challenge. Furthermore, rapid transformations of the different nutrient forms occur in coastal waters and modify the nutrient concentrations and ratios. Nevertheless, a preliminary comparison of the spatial distributions of NEWS N and P exports and *Prorocentrum minimum* (a high-biomass species that forms harmful algal blooms) observations suggests a global relationship between blooms and anthropogenically enhanced dissolved nutrient exports (unpub. data).

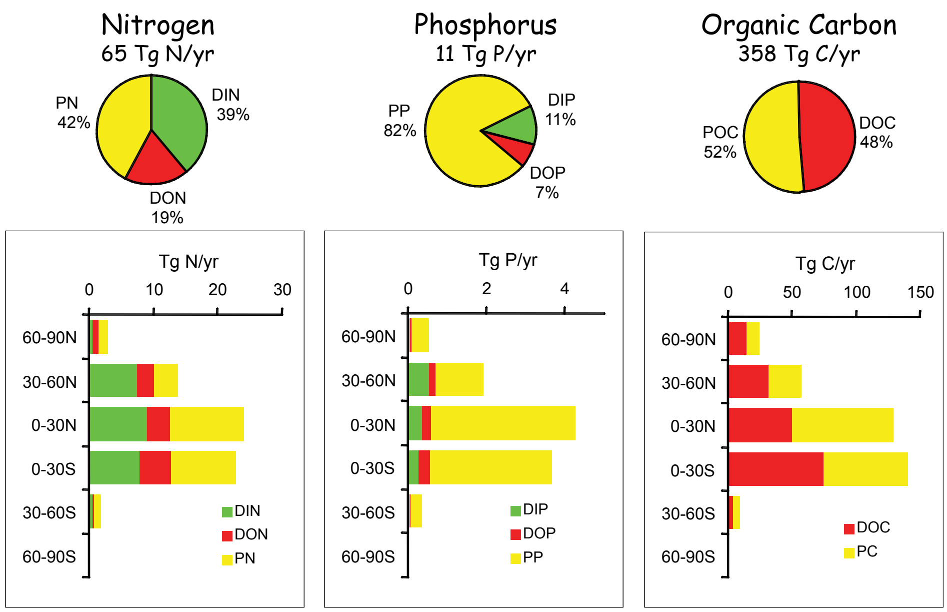

Figure 3. Global and latitudinal partitioning of N, P and C river export to the oceans by nutrient form. For particulates, Global NEWS calculates particulate organic carbon (POC) and total (inorganic + organic) particulate N (PN) and P (PP) forms. PN and PP are typically dominated by organic and inorganic forms, respectively.

Fate of N in Coastal Systems Linked to C

Denitrification is one microbial process that not only decreases the amount of fixed N in an ecosystem, but also decreases the N:P ratio. Denitrification is very effective at removing N in estuarine and continental shelf ecosystems. Based on a spatially explicit model of denitrification in global coastal systems (8), we estimate that of the approximately 65 Tg/yr of TN exported globally by rivers, ~20 Tg are rapidly removed by denitrification in estuarine sediments (Fig. 5). That leaves approximately 45 Tg of N that reaches continental shelves either by large rivers that discharge directly to the shelf (e.g., Mississippi River) or riverine N that is not denitrified in the estuary and is flushed out of the estuary to the shelf. The model suggests that essentially all of that 45 Tg N is denitrified in the shelf sediments.

However, before this N can be denitrified, it must first be incorporated into the C cycle. It is through deposition of organic matter to the sediments, followed by organic matter decomposition that releases the organic N as ammonia, which is then nitrified and denitrified, that most of the river N enters the denitrification pathway. Alternate pathways of N_2 production, such as anaerobic ammonia oxidation, also can occur in coastal sediments; the magnitude of those pathways is an area of active research.

While rivers represent a major pathway for the transfer of nutrients from land to ocean, an additional amount of terrestrially derived N enters the ocean via atmospheric deposition (9). This N is likely ultimately denitrified either in oxygen-minimum zones or transported back on to the shelf. In fact, the continental shelves are a major sink not only for riverine N, but for N derived from N_2-fixation occurring in oceanic waters. Total denitrification on continental shelves may exceed 100 Tg N/yr with contributions from riverine N, atmospheric N and marine N_2-fixation.

The impact of river inputs on the C cycle involves both direct C fluxes and nutrient fluxes that impact ecosystems on continental margins, and hence C production (and potentially, burial). How does the amount of organic carbon delivered by rivers compare to the amount of organic carbon that could be produced from, for example the DIN supplied by rivers to coastal waters? Assuming Redfield stoichiometry, the amount of organic C (OC) delivered by rivers equals about 2-3 times the amount of OC that could be produced from the DIN delivered by rivers (Fig. 6).

Future Nutrient Exports

Continued economic and population growth are expected to result in rapid increases in anthropogenic nutrient inputs to watersheds and human alterations of the hydrological cycle, in addition to climate change driven

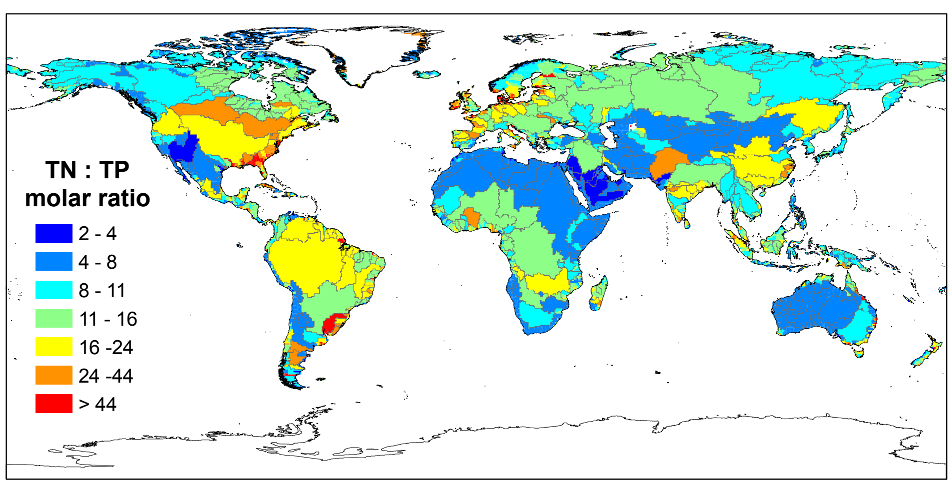

Figure 4. Molar ratio of total N to total P (TN:TP) in river basin exports.

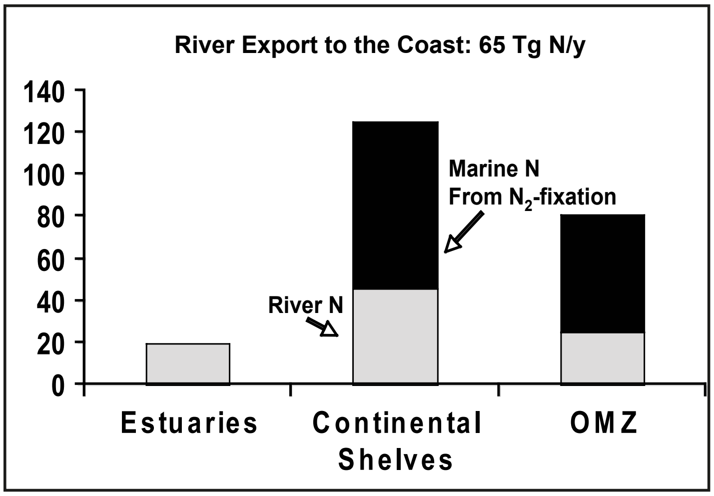

Figure 5. Global denitrification of N in estuaries, continental shelves, and oxygen-minimum zones (OMZ) from land-based (gray) and marine (black) sources (modified from (8)).

by the emission of greenhouse gases. We are applying the NEWS model to global scenarios of future conditions in order to develop a scientific basis for actions to reverse these trends and sustain riverine and coastal ecosystem health. The magnitude and spatial patterns of those changes will depend on many social, economic, policy, climate, and biogeochemical factors. Earlier results (10) for the year 2050 under a business-as-usual scenario indicated that between 1990 and 2050 the global DIN export by rivers would more than double; by 2050, 90% of river export would be considered anthropogenic. Currently, we are examining nutrient export trajectories under the Millennium Ecosystem Assessment scenarios (www.maweb.org/en/Scenarios.aspx) (11) for 2030 and 2050. Preliminary results show contrasting patterns of export among scenarios, regions, and nutrient forms. When completed, this work may help guide policy decisions related to nutrient mobilization.

Evolution of NEWS

The initial model developed by the Global NEWS workgroup is serving as a starting point for ongoing and future enhancements, and for collaborations with other Earth System and policy efforts. Coastal degradation is a global-scale problem that requires the promotion of regional expertise. With support from UNESCO-IOC and the Global Environmental Facility (GEF), we have carried out training workshops for scientists from developing countries and countries with economies in transition, fostering capacity building through the transfer of advanced methods, practices and tools for coastal nutrient management.

In addition to the Millennium Ecosystem Assessment scenario thrust, we are extending the model to sub-basin and sub-annual scales in a project funded by NASA and led by the University of New Hampshire's Water Systems Analysis Group (WSAG, www.wsag.unh.edu). Gaps in nutrient form coverage are being filled in through the development of sub-models for dissolved silica (DSi) and dissolved inorganic carbon (DIC). To directly link human activities on land to coastal responses, we are developing relationships between river nutrient inputs and quantitative indicators of coastal ecosystem health, at regional to global scales. Integration of these Global NEWS activities with other terrestrial and oceanographic efforts will be greatly facilitated by our participation in the recently launched Community Surface Dynamics Modeling System (CSDMS, www.csdms.colorado.edu), which is focusing on interoperability among models spanning the transport of water, sediments and constituents from the land surface to the continental shelf.

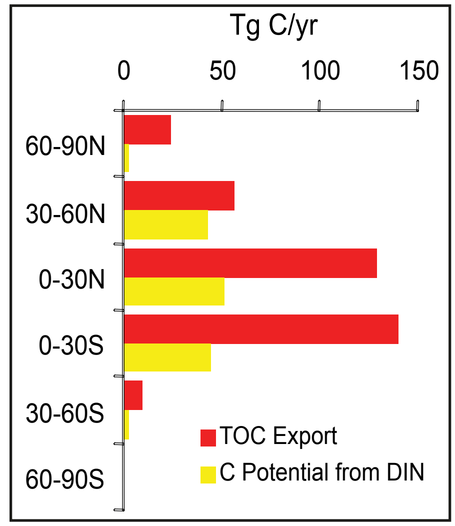

Figure 6. Latitudinal distribution of total organic carbon (TOC) delivered by rivers to the oceans, compared to the amount of organic carbon that could be produced from river DIN exports assuming Redfield stoichiometry.

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