Sources and delivery of carbon, nitrogen, and phosphorus to the coastal zone: An overview of Global Nutrient Export from Watersheds (NEWS) models and their application

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[1] An overview of the first spatially explicit, multielement (N, P, and C), multiform (dissolved inorganic: DIN, DIP; dissolved organic: DOC, DON, DOP; and particulate: POC, PN, PP) predictive model system of river nutrient export from watersheds (Global Nutrient Export from Watersheds (NEWS)) is presented. NEWS models estimate export from 5761 watersheds globally as a function of land use, nutrient inputs, hydrology, and other factors; regional and global scale patterns as of 1995 are presented here. Watershed sources and their relative magnitudes differ by element and form. For example, anthropogenic sources dominate the export of DIN and DIP at the global scale, although their anthropogenic sources differ significantly (diffuse and point, respectively). Natural sources dominate DON and DOP export globally, although diffuse anthropogenic sources dominate in several regions in Asia, Europe and N. America. "Hot spots" where yield (kg km^{-2} yr^{-1}) is high for several elements and forms were identified, including parts of Indonesia, Japan, southern Asia, and Central America, due to anthropogenic N and P inputs in some regions and high water runoff in others. NEWS models provide a tool to examine past, current and future river export of nutrients, and how humans might impact element ratios and forms, and thereby affect estuaries and coastal seas.

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1. Introduction

[2] Over the past 50 years, world population, food production, and energy consumption have increased approximately 2.5-, 3-, and 5-fold, respectively [*United Nations*, 1996] (see also Food and Agriculture Organization, FAOSTAT database collections, 2001, available at http://www.apps.fao.org; and U.S. Census Bureau, Total midyear population for the world: 1950–2050, data updated 26 April 2004, available at http://www.census.gov/ipc/www/worldpop.html). These changes have resulted in a massive mobilization of bioactive nutrients such as nitrogen and phosphorus (N and P) on land as well as important changes in the global hydrological cycle. Through activities such as fertilizer production, fossil fuel consumption, and the planting of leguminous crops, humans have more than doubled the rate at which biologically available N enters the terrestrial biosphere compared to pre-industrial levels [*Vitousek and Matson*, 1993; *Galloway et al.*, 2004]. The global P cycle has also been greatly altered by human activity. P mining and subsequent use as fertilizer has more than doubled P inputs to the environment over natural, background P from weathering [*Mackenzie et al.*, 1998; *Bennett et al.*, 2001; *Fixen and West*, 2002]. Humans have also greatly altered global hydrological systems by tripling the mean time of passage of water through the global river system, increasing the standing stock of river water by 700% over pre-impounded conditions, and dramatically altering river flow in a number of large rivers through water extraction [*Vörösmarty et al.*, 1997].

[3] These changes in global nutrient and hydrologic cycles have had both positive and negative effects on the Earth system and society. The increased use of N and P

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fertilizers and impoundment of rivers have helped make it possible to produce the food and energy necessary to support a large and growing human population [*Galloway and Cowling*, 2002]. However, significant fractions of the anthropogenically mobilized N and P in watersheds enter surface waters and are transported by rivers to coastal marine systems. This has resulted in numerous negative human health and environmental impacts including drinking water degradation, loss of habitat and biodiversity, low dissolved oxygen (DO) conditions leading to fish kills and other stresses, and an increase in frequency and severity of harmful algae blooms, among other effects [*Howarth et al.*, 1996; *Carpenter et al.*, 1998; *Hagstrom et al.*, 2001; *Rabalais*, 2002; *Anderson et al.*, 2002; *Turner et al.*, 2003; *Townsend et al.*, 2003]. N and P inputs to surface waters are projected to continue to increase over the next several decades, both globally and regionally [*Kroeze and Seitzinger*, 1998; *Seitzinger et al.*, 2002b; *Galloway et al.*, 2004; *Bouwman et al.*, 2005a].

[4] In relating global changes in human activities to global changes in river nutrient export and its effects in the coastal zone, we face at least three major challenges: (1) identifying the suite of factors controlling export of nutrients at the global scale; (2) understanding the coupled nature of these export fluxes, and (3) documenting the changing global geography of nutrient export, from the past into the future. Addressing these challenges requires the formulation and application of spatially explicit models appropriate for use at global scales.

[5] Significant progress has been made in the development and application of spatially explicit regional and global models of N export by rivers to the coastal zone as a function of watershed N inputs and biogeophysical properties [e.g., *Howarth et al.*, 1996; *Jordan and Weller*, 1996; *Seitzinger and Kroeze*, 1998; *Caraco and Cole*, 1999; *Seitzinger et al.*, 2002b; *Smith et al.*, 2003; *Green et al.*, 2004; *Van Drecht et al.*, 2003]. However, predicting N export is not sufficient. Though N has traditionally been considered the most commonly limiting nutrient for primary production in coastal environments [e.g., *Howarth*, 1988; *Vitousek and Howarth*, 1991], new evidence points to other limiting elements, such as P and Si. For example, P can be limiting, particularly seasonally, in tropical systems, and in systems with very high anthropogenic N loading [*Fisher et al.*, 1999; *Murrell et al.*, 2002; *Yin et al.*, 2001]. Also, high dissolved organic C (DOC) loadings from agricultural sources contribute to anoxia/hypoxia in coastal waters [*Paerl et al.*, 1998].

[6] It is also important to move beyond flux estimates of single elements or element forms, focusing on ratios of river-exported elements and element forms (inorganic versus organic, dissolved versus particulate). There is growing evidence that element ratios can control the makeup of phytoplankton communities [*Conley et al.*, 1993; *Turner et al.*, 1998]. Additionally, the form of the nutrient (inorganic versus organic; dissolved versus particulate) may determine the impact on receiving coastal marine ecosystems [*Seitzinger et al.*, 2002a; *Sharpley et al.*, 2003]. For example, dissolved organic N (DON) is implicated in the formation of some coastal harmful algal blooms [*Berg et al.*, 1997, 2003]. Furthermore, particulate and dissolved organic nutrients tend to be less bio-available than dissolved inorganic forms (e.g., dissolved inorganic P (DIP) versus particulate P(PP); dissolved inorganic N (DIN) versus particulate N (PN) [*Sharpley et al.*, 2003; *Bronk*, 2002]).

[7] Understanding the biogeochemical linkages between changes in landscape properties (both natural and anthropogenic) in river basins and coastal ecosystems at continental and global scales requires spatially explicit, multielement, multiform predictive models of riverine nutrient export appropriate for use at regional and global scales. The Global Nutrient Export from Watersheds (Global NEWS) work group, a work group of UNESCO-IOC (Intergovernmental Oceanographic Commission), was formed to address many of these issues. Their results to date are presented in the series of papers in this special section of *Global Biogeochemical Cycles*.

[8] In this paper we present an initial overview of Global NEWS models, their structure, inputs, and predictions. We discuss the modern global distribution of nutrient (N, P and C) export and how the factors controlling nutrient export differ for each of the major bioactive elements and forms. Results from individual Global NEWS models are described in more detail in other papers in this special section [*Beusen et al.*, 2005; *Dumont et al.*, 2005, and *Harrison et al.*, 2005a, 2005b]. We also briefly discuss the potential to apply global data sets to higher resolution models [*Sferratore et al.*, 2005], and some of the tools that could contribute to future improvements in NEWS (and other) global nutrient export models [*Dürr et al.*, 2005; *Meybeck et al.*, 2006], and that could facilitate the use of Global NEWS models to assess impacts of current and future coastal nutrient loading.

2. Global NEWS Models

2.1. Model Formulation

[9] The Global NEWS system includes models that can be used to predict export of DIN, DIP, DOC, DON, dissolved organic P (DOP); particulate organic C (POC), PN, and PP. These "NEWS" models are referred to as NEWS-DIN, NEWS-DIP, NEWS-DOC, NEWS-DON, NEWS-DOP, and NEWS-PNU [*Dumont et al.*, 2005; *Harrison et al.*, 2005a, 2005b; *Beusen et al.*, 2005]. Each of these separate models predicts river export of the element form included in its name except for NEWS-PNU, which predicts river export of POC, PN, and PP [*Beusen et al.*, 2005]. The NEWS models are consistent in terms of their input data sets. Some input data sets are shared across all NEWS models, whereas other data sets are used only for a subset of NEWS models (Table 1). For example, the same N fertilizer, N manure, and N sewage input data sets were used to drive NEWS-DIN, and NEWS-DON models, and the same P fertilizer, P manure, and P sewage input data sets were used to drive NEWS-DIP and NEWS-DOP. These N and P input data sets were developed for the same base year (1995), using the same approach for both elements (section 2.2 and Table 1). All Global NEWS models predict nutrient export at the mouth of rivers as a function of natural and anthropogenic

Table 1. Input Data Sets Used in NEWS Models for DIN, DIP, DON, DOP, DOC, PN, PP, and PC

Data set	Resolution	Year	Nutrient Form[a]	Source(s)
Basin delineations	0.5° (5761 exoreic basins globally)	1960–1994	all	STN30 [*Vörösmarty et al.*, 2000a, 2000b]
River networks	0.5°	1960–1994	all	STN30 [*Vörösmarty et al.*, 2000a, 2000b]
Water runoff	0.5°	1960–1994	a, b, c, d, e	STN30 [*Vörösmarty et al.*, 2000a, 2000b]
Population density	0.5°	1995	a, b, c, d	*Klein Goldewijk* [2001]
Fertilizer P inputs by crop type	0.5°	1995	b, d	*Bouwman et al.* [2005a, 2005b]
Manure P inputs by animal type	0.5°	1995	b, d	*Bouwman et al.* [2005a, 2005b]
Fertilizer N inputs by crop type	0.5°	1995	a, c	*Bouwman et al.* [2005a, 2005b]
Manure N inputs by animal type	0.5°	1995	a, c	*Bouwman et al.* [2005a, 2005b]
Biological N_2 fixation	0.5°	1995	a	*Green et al.* [2004]
Atmospheric NO_3^--N deposition	5 × 3.75°	1997	a	F. Dentener[b]
Crop N export	0.5°	1995	a	*Bouwman et al.* [2005a, 2005b]
Land use	0.5°	1995	a, b, c, d, f	*Bouwman et al.* [2005a, 2005b]
Wetland distribution	1 minute		e	*Lehner and Döll* [2004]
Country GNP	country	1995	a, b, c, d	*World Bank* [2000]
Sanitation data sets	country	1995	a, b, c, d	*World Health Organization* (*WHO*)/*UNICEF* [2001]; *Bouwman et al.* [2005a, 2005b]
Sewage treatment	country	1995	a, b, c, d	*WHO/UNICEF* [2001]; *Bouwman et al.* [2005a, 2005b]
Dam properties	714 large dams	2000	a, b, f	*Vörösmarty et al.* [2003]
Pre-dam water discharge	137 rivers	NA	a, b, c, d, e	*Meybeck and Ragu* [1996]
Fournier precipitation	0.5°	1960–1990	f	*New et al.* [1999]
Fournier slope	0.5°	NA	f	*Food and Agriculture Organization/International Institute for Applied Systems Analysis* [2000]; *National Geophysical Data Center* [2002]
Lithology	0.5°	NA	f	*Amiotte Suchet et al.* [2003]

[a]Notation: a, DIN; b, DIP; c, DON; d, DOP; e, DOC; f, PN, PP, and PC.
[b]Global patterns and magnitudes of nitrogen deposition, a revised approach, submitted to *Global Biogeochemical Cycles*, 2004.

biogeophysical properties of their basins; 5761 exoreic basins are included (Table 1).

[10] Whereas previous efforts have generally been limited to a single element or form, the Global NEWS system of models 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). All NEWS models predict annual average nutrient yield (kg C, N, or P km^{-2} basin yr^{-1}) at basin mouths, and all models were calibrated and validated with measured export near the river mouth from rivers representing a broad range of basins sizes, climates, and land uses.

[11] NEWS-DIN, DIP, DOC, DON, and DOP models incorporate "mechanistic" components for some terms based on literature values and calibrate the relationship for

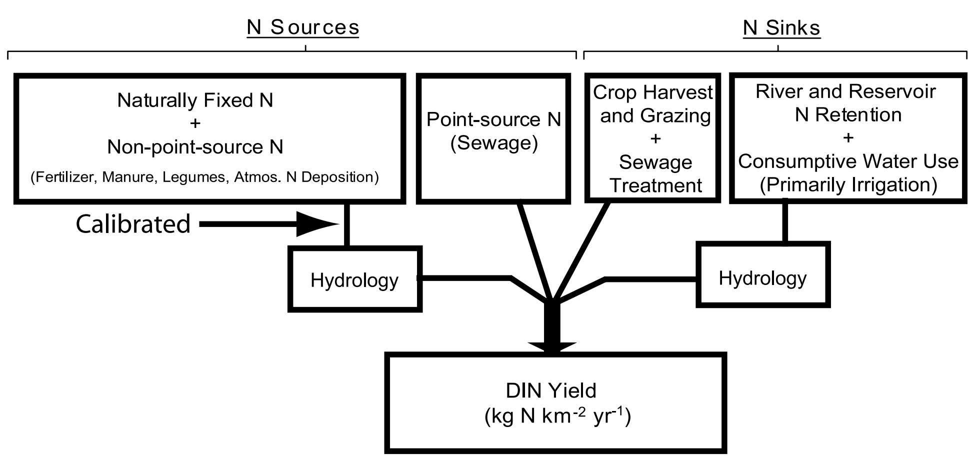

Figure 1. A conceptual diagram for one of the NEWS submodels (NEWS-DIN), showing the model's structure, major N sources and sinks, and the influence of hydrology on predictions of DIN export. Except for NEWS-PNU, which is a multiple regression model, NEWS models are organized similarly to NEWS-DIN, with nutrient sources and sinks modified by hydrology and human activity. Calibrated components are indicated.

others (e.g., Figure 1 and *Dumont et al.* [2005] and *Harrison et al.* [2005a, 2005b]]. Examples of "mechanistic" components in NEWS-DIN and NEWS-DIP, are the terms for DIN and DIP removal in dammed reservoirs on rivers. These relationships were derived from field studies and relate N or P removal to physical properties of the reservoirs in a watershed. Also, the N and P input databases used in the models are based on relationships derived from the literature. For example, N and P in manure are calculated for various livestock species (i.e., pigs, cows, chickens, sheep, goats and horses) based on literature values and then applied to gridded livestock populations [*Bouwman et al.*, 2005a, 2005b]. In NEWS-DIN, N inputs to watersheds from biological N_2-fixation in agricultural areas were based on measured fixation rates for the predominant N_2-fixing crops (seed legumes, open fields, rice, and sugar cane) and estimated crop type by watershed [*Green et al.*, 2004]. NEWS-DIN, NEWS-DIP, NEWS-DOC, NEWS-DON, and NEWS-DOP all are similar in having a low number of calibrated coefficients (four or fewer in each case) and a relatively high degree of reliance on literature-based relationships (see *Dumont et al.* [2005] and *Harrison et al.* [2005a, 2005b] for additional detail). In each NEWS model (except NEWS-PNU), nutrient sources and sinks are treated explicitly, and therefore these NEWS models can be used to estimate the relative importance of various watershed sources and sinks of nutrients. In future studies, it will be possible to examine how nutrient sources and sinks are likely to change with changes in land use, water use, and climate (J. A. Harrison et al., Global dissolved inorganic phosphorus (DIP) export to the coastal zone: 1970–2030, manuscript in preparation, 2005).

[12] The NEWS-PNU predicts POC, PN, and PP as functions of observed relationships between TSS and particulate nutrient loads [*Beusen et al.*, 2005]. TSS loads are based on a multiple regression model, where total suspended solids (TSS) are predicted as a function of percent grassland and wetland rice, precipitation intensity, basin rugosity, lithology, and sediment trapping in reservoirs. Thus, unlike other NEWS models, NEWS-PNU cannot easily be used to estimate the relative contributions of diverse sources of exported nutrients.

[13] In addition to similarities in structures, inputs, and outputs, NEWS models are also similar in their treatment of hydrology. All NEWS models for dissolved nutrient forms are constructed so that hydrology exerts an influence on the contribution of diffuse anthropogenic and diffuse natural nutrient sources, with nutrient export increasing as runoff increases. They also incorporate nutrient retention due to consumptive water use (e.g., irrigation). In the case of NEWS-PNU, precipitation intensity is an important factor. For NEWS-DIN, NEWS-DIP, and NEWS-PNU, dammed reservoirs also affect downstream transport of nutrients. In each of these models, longer water residence times result in lower predicted DIN, DIP and particulate C, N and P exports.

2.2. Global NEWS Input Databases

[14] The recent development of biogeophysical databases for input parameters has been critical for the application of models globally. More than one global database is currently available for some of the specific biogeophysical parameters used in global river nutrient export models. *Van Drecht et al.* [2005] present and analyze the similarities and differences in the input and output terms of four global data sets that have been used in various global models for estimating the N surface balance for the base year 1995, with a focus on non-point-source N terms. Significant differences were identified among the different data sets for the same parameter, suggesting that use of incompatible input databases can confound model intercomparisons [*Van Drecht et al.*, 2005].

[15] The NEWS models all use a common, internally consistent set of input data sets (Table 1) to facilitate intercomparison of model predictions for different nutrients and forms. Care was taken such that all input data sets represent conditions as close to 1995 as possible. Most input data sets have a resolution of at least $0.5 \times 0.5°$ (Table 1). All of the models use common hydrologic inputs, including both modeled runoff at 0.5° resolution [*Fekete et al.*, 2002], basin delineations [*Vörösmarty et al.*, 2000a, 2000b], water extraction, and water impoundment (dams) [*Vörösmarty et al.*, 2003].

[16] One database that was not used in development of current NEWS models, but could be useful in the ongoing development of a global Si export model or to improve existing NEWS-DIP or NEWS-PNU models is an improved lithology database. Such a database ($0.5° \times 0.5°$ spatial resolution) has been developed by *Dürr et al.* [2005]. This database significantly improves upon previous lithological maps by including 15 rock types, encompassing not only crystalline rocks, but also sedimentary rocks such as sandstone, carbonate rocks, and evaporites.

3. NEWS Results

[17] NEWS models allow us to compare river nutrient export by nutrient element, form, and source for the first time at regional, continental and global scales. In sections that follow, we compare magnitudes, sources, and hot spots of C, N, and P forms. We do this primarily at continental and global scales. Individual NEWS model papers in this special section discuss model predictions at watershed and regional scales for individual elements and forms. Comparison of the NEWS model output at watershed and regional scales are reserved for future papers (e.g., S. P. Seitzinger and J. Harrison, manuscript in preparation, 2005, and others).

3.1. Magnitude of Total N, P, and C Export

[18] One major advance of the NEWS models over previous models is that they estimate N, P and C export by form (dissolved inorganic, dissolved organic and particulate). However, in this section, we have added the export of the various forms of an element to obtain estimates of total export (e.g., TP, TN or TOC), to facilitate comparison of NEWS model predictions with previous estimates. NEWS models suggest that as of the mid-1990s, 367, 66, and 11 Tg yr^{-1} of TOC, TN, and TP, respectively, were exported by rivers globally (Table 2). At the continental scale, South America is the largest exporter of C and N, though it is fourth in terms of exoreic land area (Table 2 and Figure 2). Oceania is the largest exporter of P, although it

Table 2. NEWS-Model-Estimated River Export of Nutrients by Form and Continent as Well as Global Totals in Tg C, N or P yr^{-1} and Exoreic Surface Area[a]

Continent	DOC	DON	DOP	DIP	DIN	POC	PN	PP	Surface Area (1×10^6 km^2)	Molar C:N	Molar C:P	Molar N:P	Molar C:N:P
Oceania[b]	22	1.5	0.09	0.09	2.3	57	8.5	2.61	3.2	7.2	80.2	11.2	80:11:1
North America	23	1.5	0.08	0.12	2.8	20	3.0	0.92	22.3	7.0	100.3	14.4	100:14:1
South America	59	3.8	0.21	0.20	6.5	40	6.3	1.82	17.5	7.2	99.3	13.8	99:14:1
Europe	8	0.7	0.04	0.20	2.3	7	1.1	0.33	8.2	4.3	68.8	16.0	69:16:1
Australia	1	0.1	0.003	0.01	0.2	3	0.5	0.14	5.5	6.0	68.2	11.3	70:12:1
Northern Asia[b]	13	1.0	0.07	0.18	2.7	19	2.8	0.85	22.3	5.8	75.2	13.0	75:13:1
Southern Asia[b]	19	1.4	0.09	0.17	5.5	28	3.8	1.26	9.8	5.1	78.6	15.4	79:15:1
Africa	24	1.6	0.09	0.12	2.4	24	3.6	1.10	25.6	7.3	94.5	13.0	95:13:1
Total	**170**	**11.50**	**0.67**	**1.09**	**24.8**	**197**	**29.6**	**9.03**	**114.0**	**6.5**	**87.9**	**13.5**	**88:14:1**

[a]Exoreic surface area is in units of 10^6 km^2. See *Dumont et al.* [2005], *Harrison et al.* [2005a, 2005b], and *Beusen et al.* [2005] for additional details regarding watershed, continental and global flux estimates.

[b]Oceania was defined to include Indonesia. River basins were assigned to northern or southern Asia on the basis of the average latitude of 0.5° cells within each basin. Basins with average latitudes greater than 30°N. were assigned to northern Asia. Basins with average latitudes less than 30°N. were assigned to southern Asia.

has the smallest land area. The high fluxes in these regions are likely due to the high rates of water runoff predicted for much of northern South America and Oceania [*Fekete et al.*, 2002]. Oceania demonstrates the highest estimated C, N and P yields (kg C, N or P km^{-2} yr^{-1}).

[19] NEWS predicted TOC, TN and TP export are similar to previous estimates using different approaches. NEWS TOC export (367 Tg C yr^{-1}) is similar to that of *Ludwig et al.* [1996] (380 Tg C yr^{-1}) which was based on global spatial DOC and POC models. It is also similar to TOC estimated from measured river data by *Meybeck* [1982] (395 Tg C yr^{-1}) and a nonspatial estimate (396 Tg C yr^{-1} [*Mackenzie et al.*, 1993]). The global TN export predicted by the NEWS models (66 Tg N yr^{-1}) is similar to that predicted by a TN model by *Boyer et al.* [2006] (59 Tg N yr^{-1}) and about 40% higher than *Bouwman et al.* [2005a]. Direct comparison of NEWS and the Boyer et al. and Bouwman et al. estimates are complicated by differences in model approach. Boyer et al., and Bouwman et al. based their models on TN data, and it is not clear if these measured values include all N forms. For example, particulate N may not be completely included. On the other hand, adding results of different NEWS models may also result in errors. The *Boyer et al.* [2006] model is an empirical model relating TN inputs per landscape area to the total flux of N discharged in rivers. It differs from the NEWS models in several ways; it does not distinguish different N forms (DIN, DON or PN) and does not explicitly include hydrology or N removal processes. To our knowledge, there are no previous spatially explicit estimates of TP export to coastal systems globally. The NEWS-predicted TP export (11 Tg P yr^{-1}) is similar to the global TP export estimated from measured river data by *Meybeck* [1982] (9 Tg P yr^{-1}) and somewhat less than an independent, nonspatial estimate (20 Tg P yr^{-1} [*Mackenzie et al.*, 1993]).

[20] The molar C:N:P in exported river water is 88:14:1 according to NEWS model predictions, and this ratio varies somewhat by continent and region (Table 2). C:P ratios are the most variable with ratios ranging from 69:1 to 100:1, among continents. C:N and N:P ratios are somewhat less variable, ranging from 4 to 7:1 and 11 to 16:1, respectively, among continents (Table 2). While Europe and southern Asia contain some of the most anthropogenically altered watersheds, the ratios of total C:N:P in river export do not appear to be greatly altered. However, as discussed below, when different element forms are considered, strong anthropogenic signals are apparent.

3.2. Magnitude of C, N, and P Export by Element Form

[21] Export of DOC and POC are predicted to be approximately equal at both global and continental scales (Table 2). However, there is some regional variability, with Oceania, southern Asia, and Australia demonstrating a higher proportion as POC than other continents, and South America demonstrating a higher proportion as DOC (Table 2 and Figure 2).

[22] NEWS models predict that global DIN and PN export are roughly equivalent (25 Tg N yr^{-1} and 30 Tg N yr^{-1}, respectively), and each is more than twice as large as DON export (12 Tg N yr^{-1}; Table 2). There is some regional variability to this pattern, however. DIN accounts for over half of the predicted TN export in Europe and southern Asia (Table 2 and Figure 2), both regions that are heavily impacted by anthropogenic inputs. PN constitutes over half of the TN exported to coastal zones of Oceania and Australia (69% and 62%, respectively) and also is the largest single N form exported from Africa and South America. DON export accounts for approximately 10–25% of the TN export across all continents, with the highest percent DON in South America (23%), and the lowest in Australia (8%).

[23] With respect to P, NEWS model predictions are consistent with numerous previous studies suggesting that particulate forms dominate P export globally [e.g., *Meybeck*, 1982; *Froelich*, 1988]. However, this is the first time that continent-scale differences in PP:DIP ratios have been estimated. The PP:DIP ratio ranges from 1.7 for Europe to 29 for Oceania, and, in general, lower PP:DIP ratios are predicted for systems with more human activity. Continental DOP:DIP ratios are somewhat lower and less variable, ranging from 0.2 for Europe to 1.1 for South America. Because it is likely that <25% of PP is bioavailable, even

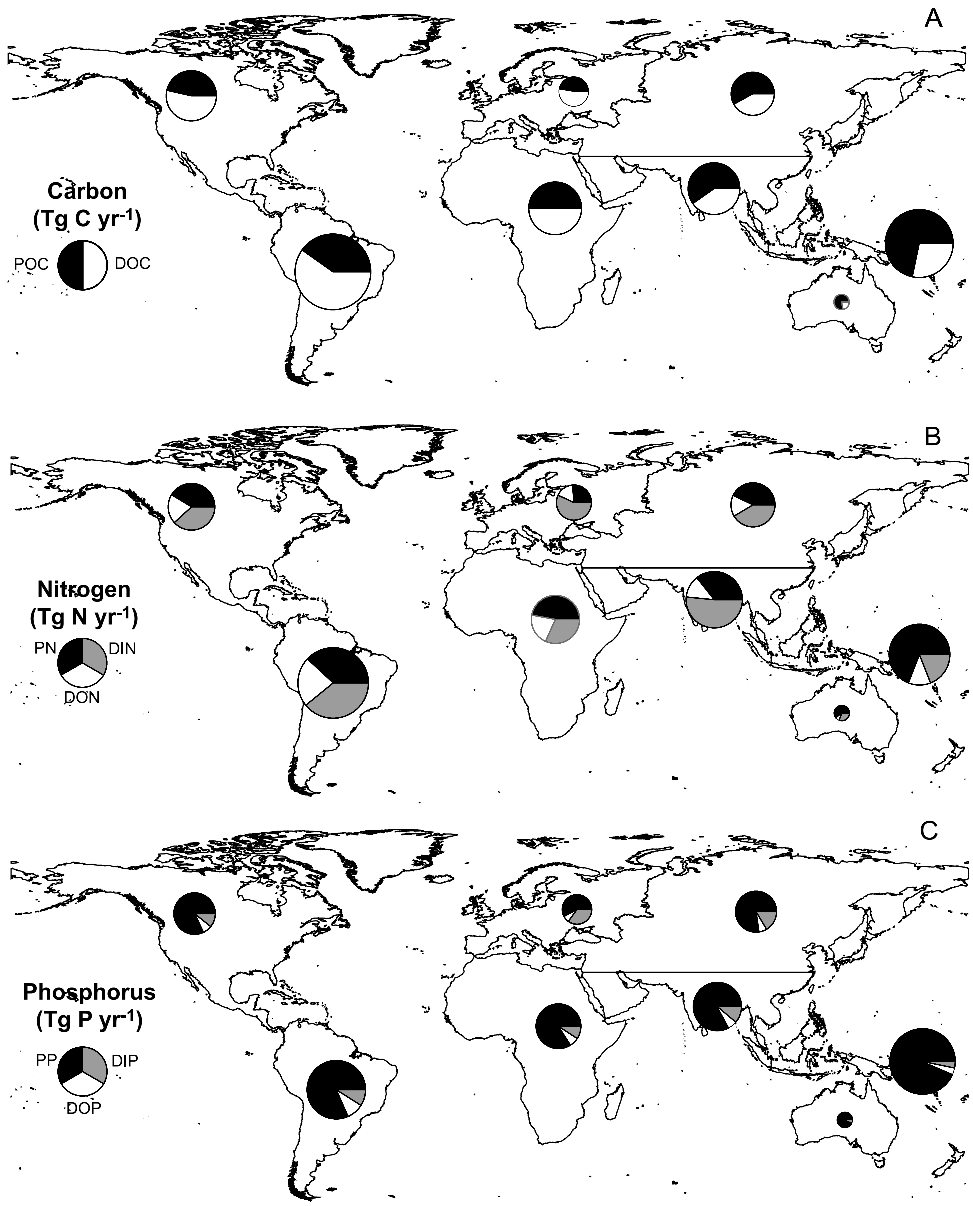

Figure 2. NEWS-estimated nutrient export by form (Tg C, N, or P yr^{-1}) for each continent for (a) carbon, (b) nitrogen, and (c) phosphorus. Size of pies scales with total predicted C, N, and P export (See Table 2 for values), and pie wedges represent the percent of C, N and P exported as particulate (black), dissolved inorganic (gray), and dissolved organic (white) forms. Asia has been divided into northern and southern regions as described in Table 2 footnote, and division is indicated with solid, horizontal line.

when P-rich particulates are subjected to desorption in estuaries [*Froelich*, 1988] the bioavailable PP:DIP ratio is likely to be substantially lower than the simple PP:DIP ratio. This means that DIP and DOP are likely to be more important to surface fresh waters and coastal zones (as opposed to PP) than is suggested by Figure 2.

3.3. Sources and Controlling Factors

[24] According to NEWS-DIN, anthropogenic sources dominated the export of DIN at the global scale as of the mid-1990s [*Dumont et al.*, 2005] (Figure 3). Only 36% of DIN export is from natural biological sources (N_2 fixation). Diffuse (nonpoint) sources dominated the anthropogenic component of DIN export, with approximately equal contributions from inorganic fertilizer use, animal manure, and agricultural N_2 fixation (Figure 3). Atmospheric N deposition was estimated to contribute substantially less than these other anthropogenic diffuse sources globally. Point sources accounted for only about 2% of DIN export globally (Figure 3).

[25] Predicted major sources of DIP export contrast markedly with DIN export. While a similar proportion of total

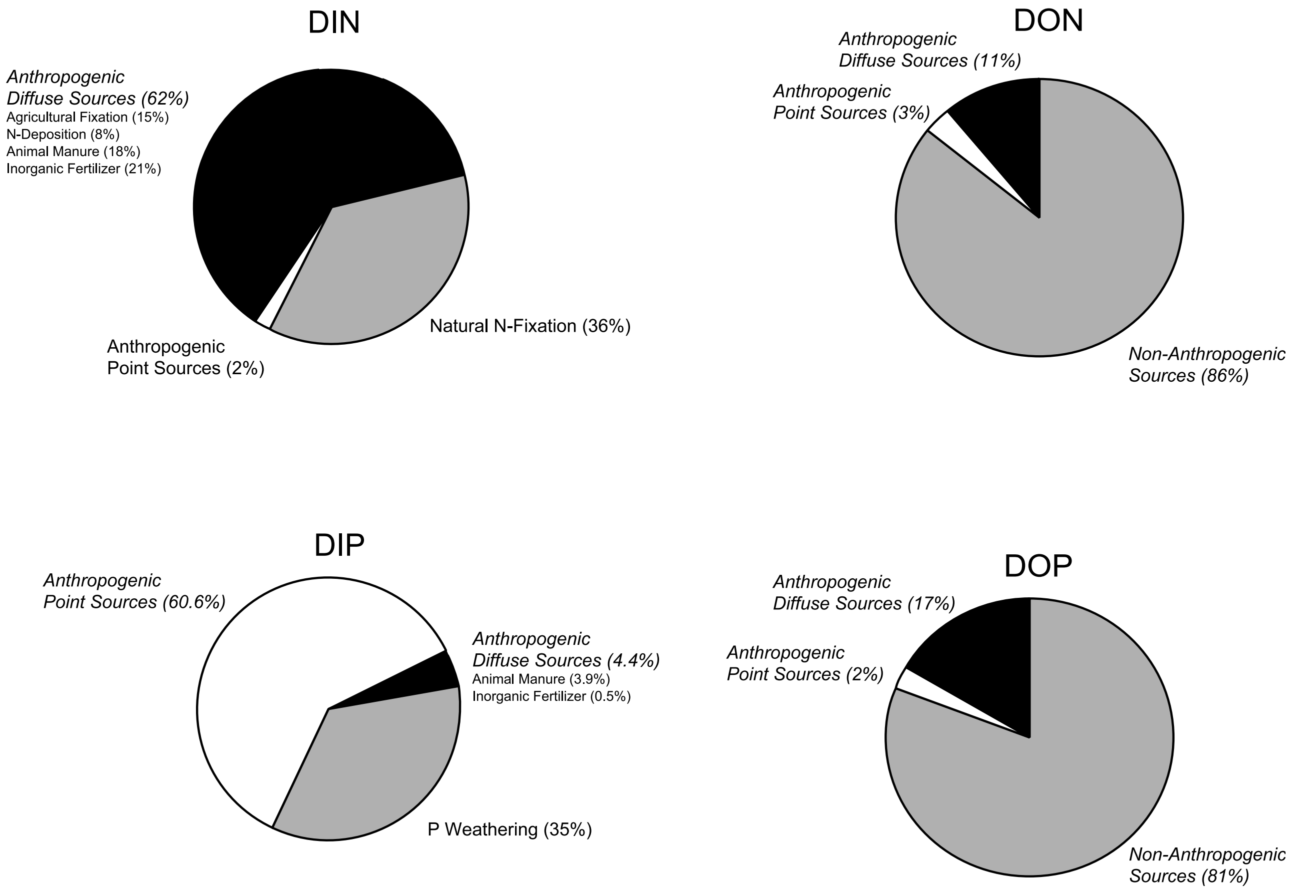

Figure 3. NEWS-model estimated global sources of DIN, DIP, DON, and DOP to the coastal zone, with anthropogenic point sources, anthropogenic nonpoint sources, and natural sources represented as white, black, and gray pie slices, respectively. Note that the size of pies is not proportional to predicted nutrient export. For nutrient export values, see Table 2.

DIP and DIN export is from natural sources (~35%) at the global scale, the natural source of DIP is from chemical weathering of rocks. This contrasts with the natural source of DIN, which is primarily biological N_2 fixation (Figure 3). Anthropogenic sources of DIP export also differ from DIN; according to NEWS-DIP, point-source- (sewage) derived P is the dominant source of DIP export at the global scale, with diffuse agricultural sources accounting for less than 5% of DIP export [*Harrison et al.*, 2005a]. Globally, there is considerable spatial variation in the major sources of DIN or DIP export. In any one basin or continent the major sources can differ markedly from the total global picture, as demonstrated in the individual papers in this special section [*Dumont et al.*, 2005; *Harrison et al.*, 2005a, 2005b].

[26] NEWS-DON and DOP suggest a substantially different pattern of sources relative to DIN and DIP. First, natural sources account for over 80% of DON and DOP export globally (Figure 3) [*Harrison et al.*, 2005b]. The anthropogenic source is primarily from diffuse agricultural sources (~10–15% of total export), with point sources being a minor component (<5% of the total exported DON or DOP). Globally, there is considerable spatial variation in the relative contribution of natural versus anthropogenic sources of DON or DOP export. According to NEWS-DON and NEWS-DOP nonanthropogenic N and P sources account for >75% of the DON and DOP export for much of the world, but there are numerous watersheds in eastern and southern Asia where anthropogenic sources account for over 50% of DON or DOP export [*Harrison et al.*, 2005b]. Anthropogenic sources are also predicted to account for >50% of DON and >25% of DOP export throughout much of western Europe and in some basins in central and southwestern United States.

[27] Water discharge is a major driver controlling export of all elements and element forms in the NEWS models. In NEWS-DIN, NEWS-DIP, NEWS-DOC, NEWS-DON, and NEWS-DOP, runoff influences the predicted export of natural and diffuse anthropogenic DIN, DIP, DON, and DOP. For DON and DOP, water discharge alone can explain 70% and 88% of the total variation in measured export, respectively. However, for DIN and DIP, discharge alone can explain a much smaller fraction of the total variation in measured export (20% and 28% for DIN and DIP, respectively). Anthropogenic sources of N and P account for a relatively larger portion of the total variation in DIN and DIP export, compared to DON and DOP export. According to NEWS models, consumptive water use (in addition to water discharge) is an important hydrological modifier of

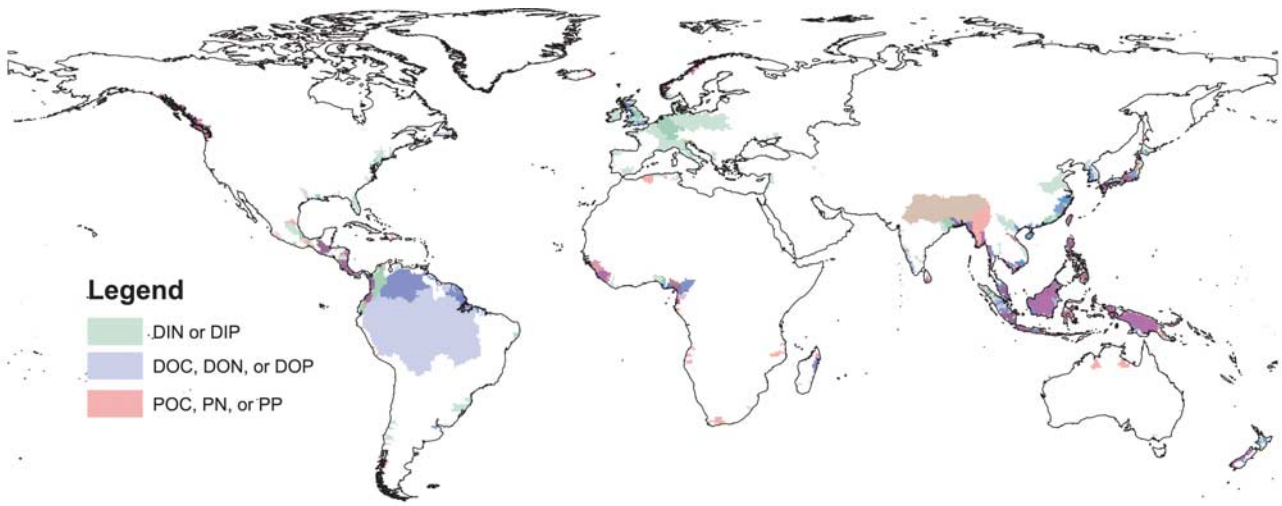

Figure 4. Hot spots for river nutrient yield (kg C, N, or P km^{-2} yr^{-1}). River basins with the highest predicted DIN and DIP yields (top 10% globally) are shaded green. River basins with the highest predicted DOC, DON and DOP yields (top 10% globally) are shaded blue, and river basins with the highest predicted POC, PN, and PP yields (top 10% globally) are shaded pink. In each case, increasing color intensity suggests a greater number of C, N and/or P forms in the top 10%. Basins with a brownish or purple cast (e.g., basins in Central America and Indonesia are basins where multiple nutrient forms are predicted to fall within the top 10% globally.

nutrient export to coastal systems in heavily dammed river basins. Future anthropogenic modification of the global water cycle, both through river engineering and through climate change, is likely to affect nutrient transport from land to coastal systems, with associated biological and biogeochemical changes in coastal systems. Natural climate variability will also affect patterns of coastal nutrient loading due to associated variability in runoff and discharge.

3.4. Hot Spots of Yield for Multiple Elements/Forms

[28] There are several regions where predicted yield (kg C, N or P km^{-2} yr^{-1}) is high for one or more elements and forms (Figure 4). For this analysis we first identified basins in which the NEWS models predicted that yield for a nutrient was in the top 10% of all basins. We then created one map that contained the combined results for each of the eight nutrient forms (Figure 4). One of the most striking features is the identification of regions that have high predicted yields of all nutrient forms (e.g., parts of Indonesia, Japan, southern Asia, and Central America). Dissolved inorganic forms dominate regions of Europe, China, and parts of Japan. Other regions are dominated by both dissolved organic and particulate nutrients (e.g., British Columbia in Canada; southeast Alaska).

[29] If we combine information on the magnitude of yields with information on nutrient sources, it becomes apparent that anthropogenic activities are principally responsible for some hot spots and natural processes are principally responsible for others. High DOC, DON, and DOP yields result from high rates of runoff in Oceania, southeast Asia, and northern South America. In contrast, anthropogenic activities appear to be the principal driver of the high DON and DOP yield in a number of Japanese basins. The high percent of landscape covered by wetlands in the Amazon basin, combined with high rates of runoff, contribute to high, predicted DOC yields in that region. High predicted DIN and DIP yields in Europe and the northeast United States are mainly due to high anthropogenic N and P inputs in these regions. On the other hand, a mix of natural and anthropogenic inputs and high water runoff account for the high, predicted DIN and DIP yields in northern South America. Indonesia is a particularly interesting case because many Indonesian basins are in the top 10% for all elements and forms. This is due to a combination of high runoff, high relief, and high levels of anthropogenic activity.

4. Future Directions

4.1. Developing Relationships Between Local and Global Nutrient Export Models

[30] The NEWS models were specifically developed to obtain patterns of nutrient export from river basins at regional and global scales. These NEWS models contrast in their degree of spatial resolution and in their degree of mechanistic formulation with models specifically developed for use in an individual watershed such as the Riverstrahler model [e.g., *Billen and Garnier*, 1999]. The Riverstrahler model has been developed and extensively applied and tested in the Seine watershed [*Billen and Garnier*, 1999; *Billen et al.*, 2001]. It has also been applied to the Danube and Red rivers [*Garnier and Billen*, 2002; *Garnier et al.*, 2002]. Input databases for the Riverstrahler model are generally at the reach scale, and the model can be used to simulate seasonal dynamics of nutrient export. The feasibility of upscaling the Riverstrahler model to global application was examined using the Seine River watershed as a test watershed but using the global databases used for the

NEWS models [*Sferratore et al.*, 2005]. The Riverstrahler model predicted annual fluxes of DIN, DIP, TN and TP, and SiO_2 within a factor of 2 of measured export, and accurate predictions relied heavily on correct predictions of water discharge. These results are promising in that they suggest it may be possible to scale local watershed models up and scale global models down, given appropriate nutrient input and hydrological information.

4.2. Projections of Coastal Nutrient Loading and Ecosystem Effects

[31] Though relatively little is presented in this special section about the specific impacts of nutrient inputs, this is an active and important area for research, and one to which the NEWS models can contribute significantly in future applications. The NEWS models provide the first opportunity to project future inputs of multiple nutrients and forms at the global scale in a spatially explicit manner. To facilitate future use of NEWS models to understand coastal impacts of nutrient loading, a new coastal segmentation scheme (COSCAT) has been developed by *Meybeck et al.* [2006]. COSCAT represents an improvement upon other coastal segmentation schemes in that it explicitly takes both land-based and marine features into account. Such a database will facilitate understanding the regional implications of anthropogenic increases in land-based nutrient inputs, and (in conjunction with coastal typology efforts [e.g., *Maxwell and Buddemeier*, 2002]) will greatly enhance future efforts to use NEWS and other global nutrient export models to explore relationships between land-based nutrient inputs and coastal response.

4.3. Summary

[32] The NEWS model system constitutes the first spatially explicit, multielement (N, P and C), multiform (dissolved inorganic, dissolved organic, and particulate) predictive model system of river nutrient export that is appropriate for use at regional and global scales [*Dumont et al.*, 2005; *Harrison et al.*, 2005a, 2005b; *Beusen et al.*, 2005]. NEWS models explain a substantial portion of the variation in measured mean annual N, P and C export, by form, from large watersheds globally. Export from 5671 watersheds globally is estimated by the NEWS models. NEWS models provide the first spatially explicit global estimates of DON, DOP, PP and total P export. They also constitute the first estimates of sources of DIP, DON and DOP in watersheds globally and regionally, as well as the first estimate of the contribution of wetlands to DOC export at those scales. The results of each of the individual models are detailed in their respective papers in this special section of *Global Biogeochemical Cycles* [*Dumont et al.*, 2005; *Harrison et al.*, 2005a, 2005b; *Beusen et al.*, 2005].

[33] At the continental scale, the largest exporter of total N and total organic C is South America, though it is fourth in terms of exoreic land area. The largest exporter of P is Oceania, although it has the smallest land area. Oceania also demonstrates the highest estimated total N, P and organic C yields (kg N, P or C km^{-2} yr^{-1}).

[34] There are large regional variations in the magnitude of export of different forms of the same element, according to the NEWS models. For example, DIN accounts for over half of the predicted TN export in Europe and southern Asia. In contrast, PN constitutes over half of the TN exported to coastal zones of Oceania and Australia and also is the largest single N form exported from Africa and South America.

[35] NEWS models demonstrate that the relative importance of sources varies by element and form. Anthropogenic sources dominated the export of DIN and DIP at the global scale. However, DIN and DIP sources differ significantly. Diffuse anthropogenic sources are the principal anthropogenic DIN sources, while point sources constitute the principal anthropogenic DIP source, at the global scale. In any one basin or continent the major sources can differ markedly from the total global picture. In contrast to DIN and DIP, natural sources account for over 80% of DON and DOP export globally. However, there are numerous watersheds in eastern and southern Asia where anthropogenic sources account for over 50% of DON or DOP export, and watersheds in western Europe and some basins in central and southwestern United States where >50% of DON and >25% of DOP is from anthropogenic sources.

[36] The NEWS models demonstrate that there are several "hot spots" where predicted yield is high for several elements and forms, including parts of Indonesia, Japan, southern Asia, and Central America. However, it is not always anthropogenic activities that are principally responsible for these hot spots; natural processes dominate in some hot spots. Indonesia is particularly interesting in that many Indonesian basins are in the top 10% for all elements and forms; this is due to the combination of high runoff, high relief, and high levels of anthropogenic activity.

[37] Global NEWS used a multielement approach because different elements and element ratios limit productivity and community composition in coastal systems regionally. The multiform approach was used because different forms of the same element (e.g., DIN, DON and PN) not only have different coastal ecosystem effects, but also different sources and sinks within a watershed. The NEWS models set the stage for assessing and understanding the effects of past, current and possible future changes in land-use, population growth, and hydrology on nutrient transport to and biological processes in estuaries, large river plumes, and coastal seas.

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