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Global Patterns of Dissolved Inorganic and Particulate Nitrogen Inputs to Coastal Systems: Recent Conditions and Future Projections

S. P. Seitzinger[1]*, C. Kroeze[2], A. F. Bouwman[3], N. Caraco[4], F. Dentener[5], and R. V. Styles[1]

[1] *Institute of Marine and Coastal Sciences, Rutgers/National Oceanic and Atmospheric Administration Cooperative Marine Education and Research Program, Rutgers University, 71 Dudley Rd, New Brunswick, New Jersey 08901-8521*

[2] *Environmental Systems Analysis Group, Wageningen University, P. O. Box 9101, 6700 HB Wageningen, The Netherlands*

[3] *National Institute for Public Health and the Environment, P. O. Box 1, 3720 BA Bilthoven, The Netherlands*

[4] *Institute of Ecosystem Studies, Box AB, Route 44A, Millbrook, New York 12545*

[5] *Joint Research Centre, Institute for Environment and Sustainability, Climate Change Unit, TP280 I-21020 Ispra (Va), Italy*

ABSTRACT: We examine the global distribution of dissolved inorganic nitrogen (DIN) and particulate nitrogen (PN) export to coastal systems and the effect of human activities and natural processes on that export. The analysis is based on DIN and PN models that were combined with spatially explicit global databases. The model results indicate the widely uneven geographic distribution of human activities and rates of nitrogen input to coastal systems at the watershed, latitudinal, and regional-continental scales. Future projections in a business-as-usual scenario indicate that DIN export rates increase from approximately 21 Tg N yr^{-1} in 1990 to 47 Tg N yr^{-1} by 2050. Increased DIN inputs to coastal systems in most world regions are predicted by 2050. The largest increases are predicted for Southern and Eastern Asia, associated with predicted large increases in population, increased fertilizer use to grow food to meet the dietary demands of that population, and increased industrialization. Results of an alternative scenario for North America and Europe in 2050 indicate that reductions in the human consumption of animal protein could reduce fertilizer use and result in substantial decreases in DIN export rates by rivers. In another scenario for 2050, future air pollution control in Europe that would reduce atmospheric deposition of nitrogen oxides in watersheds is predicted to decrease DIN export by rivers, particularly from Baltic and North Atlantic watersheds. Results of a newly developed global PN river export model indicate that total global PN and DIN export by rivers in 1990 are similar, even though the global distribution of the two differ considerably.

Introduction

The production of food and energy has markedly increased the amount of newly fixed nitrogen (N) entering terrestrial and aquatic ecosystems during the last century. Biological N_2-fixation was the major source of newly fixed N before ~1800 and amounted to approximately 90–130 Tg N yr^{-1} (Galloway et al. 1995). As of ~1990, the amount of newly fixed N entering terrestrial systems annually had about doubled due to the production of synthetic fertilizer, increased biological N_2-fixation associated with agricultural crops, and increased atmospheric NO_y deposition associated with fossil fuel combustion (Galloway et al. 1995; Galloway and Cowling 2002). While most of this newly fixed N initially enters the terrestrial biosphere, a portion is transferred from terrestrial to aquatic systems, resulting in increased N in streams and rivers that transport N to coastal ecosystems. In addition, some N is directly discharged or deposited (i.e., atmospheric NO_y) to coastal ecosystems. The environmental consequences of nutrient enrichment of coastal ecosystems (e.g., increased phytoplankton production, increased turbidity with subsequent loss of submerged aquatic vegetation, oxygen deficiency, decrease in biodiversity, etc.) are becoming increasingly well documented (e.g., Smetaček et al. 1991; Nixon 1995; Vitousek et al. 1997; National Research Council 2000; Cloern 2001; Rabalais 2002).

These large global increases in N input to ter-

* Corresponding author; tele: 732/932-6555 ext. 342; fax: 732/932-1792; e-mail: sybil@imcs.rutgers.edu.

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restrial, and consequently to coastal, systems are not evenly distributed throughout the world. For specific watersheds, the relationship between N use on land and N export by rivers has been examined (e.g., Caraco and Cole 1999a,b; Billen and Garnier 1999; Castro et al. 2000; van Breemen et al. 2002; Boyer et al. 2002). Other studies have examined patterns at the regional scale (Howarth et al. 1996; Jordan and Weller 1996). Measurements of nutrient export, as well as analyses of the effect of human activities in watersheds, have mainly focused on North America and Europe, although there are numerous exceptions (e.g., Meybeck 1982; Lewis et al. 1999).

Here we examine the global distribution of dissolved inorganic nitrogen (DIN) and particulate nitrogen (PN) export to coastal systems and the effect of human activities and natural processes on that export. There are many world regions with little or no data on N export to coastal systems. This analysis is therefore based on DIN and PN models that were combined with spatially explicit global databases. We begin with an examination of the distribution of DIN export as of 1990. Next, the model predicted DIN export in 2050 is presented based on three theoretical scenarios. First, a global perspective is examined based on a business-as-usual (BAU) scenario. Then two regional scenarios are examined, one for Europe and North America in which the effects on DIN export are examined as a result of decreased N fertilizer use associated with a change in the human diet, and another for Europe in which NO_y deposition decreases due to changes in fuel combustion technologies. Aspects of the DIN model results have been published elsewhere (e.g., Kroeze and Seitzinger 1998; Seitzinger and Kroeze 1998; Seitzinger et al. 2000; Kroeze et al. 2001). We develop additional insights into the distribution of human activities and rates of N input to coastal systems at a number of scales, including watershed, latitudinal, and regional-continental scales. We include additional analyses of the alternative scenarios for 2050. Global maps are presented of the grid databases for human population, synthetic fertilizer use, and atmospheric NO_y deposition for 1990 and 2050 that were used in the model. A newly developed global PN river export model is described along with a preliminary analysis of the global distribution of PN export relative to DIN export.

Methods

Our DIN and PN export models were based on existing models that we modified for our particular application (described below). Both models were applied in a geographic information system (GIS) framework with global databases to develop spatially explicit estimates of the export to coastal ecosystems of DIN or PN (a dissolved organic nitrogen, DON, model is currently under development). The grid size of the inputs for both models was 1° latitude by 1° longitude, except as noted below. Model calculations were performed either on a watershed base or on a grid base as described in previous papers and below.

DIN Model

Base Case 1990

The DIN export model was based on a regression model originally developed by Caraco and Cole (1999a) that described nitrate plus nitrite export by 35 major world rivers as a function of N inputs to watersheds from human sewage, synthetic fertilizer use, and atmospheric NO_y deposition. Hereafter, nitrate is used to refer to nitrate plus nitrite. Caraco and Cole (1999a) describe the original model formulation and Seitzinger and Kroeze (1998) present details of the modifications to the model and specific application to the global databases. The basic model equation for nitrate export by rivers to coastal systems (NO_3exp_{riv}) that we used is:

$$NO_3exp_{riv} = 0.7[1.85Popd \times Urb + 0.4WaterRunoff^{0.8} \times (Ppt_{ws} + Fert_{ws})] \quad (1)$$

N export associated with human sewage was estimated for a watershed by multiplying the human population in a watershed (Popd) by a per capita sewage N production rate (1.85 kg N person^{-1} d^{-1}). The amount of sewage N entering a river was calculated as the per capita sewage N production times the fraction of the population that was categorized as urban (Urb). Nonpoint N inputs to rivers from fertilizer and atmospheric deposition were calculated as the amount of synthetic N fertilizer used ($Fert_{ws}$), or atmospheric NO_y deposition (wet plus dry; Ppt_{ws}), respectively, in a watershed multiplied by a water runoff factor ($0.4WaterRunoff^{0.8}$) to capture hydrological effects. This nonlinear hydrological component results in a higher proportion of fertilizer and atmospheric N deposition exported from a watershed with high rainfall compared to an arid watershed. The fraction of the total nonpoint and sewage N input to the river that is exported at the mouth of the river as nitrate is defined by the river export coefficient (0.7) (Caraco and Cole 1999a). This coefficient accounts for a number of processes and factors including the removal of a portion of the nitrate by denitrification in the river and the fact that only a portion of the N exported from the watershed is in the form of nitrate.

When this model (Eq. 1) was applied to global databases the agreement between model predicted nitrate export was similar ($r^2 = 0.84$) to measured export for a wide range of world rivers. A similar correlation was found by Caraco and Cole (1999a; $r^2 = 0.89$) in the original development of the model equation, indicating that the modifications made to the model and the use of these particular global databases with the model are appropriate. DIN export (nitrate plus ammonium) was calculated from nitrate export assuming that 84% of DIN is nitrate (Meybeck 1982).

Year 2050 Scenario

Predicted export of DIN to coastal systems in the year 2050 first was estimated under a BAU scenario (i.e., assuming that current trends continue) using grid projections for 2050 of population density, fertilizer use, and NO_y deposition (Kroeze and Seitzinger 1998).

In an alternative scenario (DIET scenario), we investigated the potential effects of a change in fertilizer use, associated with a change in the human diet in Europe and North America on DIN export by rivers in 2050 (based on Kroeze et al. 2001). The DIET scenario is the same as the BAU 2050 scenario except for future fertilizer use. According to the BAU 2050 projections, worldwide fertilizer use may increase by 145% between 1990 and 2050. This increase is caused by population growth, as well as dietary changes. The human diet is increasingly based on animal proteins and animal production requires in general more N inputs than crop production. In the DIET scenario we assume that for regions that we consider today industrialized, human diets will change towards a larger share of plant proteins than assumed in the BAU scenario for 2050. The 2050 synthetic fertilizer use in the DIET scenario therefore is lower than the 2050 BAU scenario. We used an analysis by Bleken (1997) to estimate the effect of changed diets on fertilizer use in agriculture. The DIET scenario assumes that in Europe and North America people will change their diets in such a way that overall N inputs to soils (in exoreic watersheds) do not exceed 40 kg N person^{-1} yr^{-1} by 2050. This is consistent with a change towards diets similar to those in Italy in 1963 or in Turkey in 1993. Since our assumptions are based on gross simplifications, our analysis must be considered a first step in analyzing the potential effects of dietary changes on the N cycle. Our most important assumptions are that the reduced synthetic fertilizer use is the only difference in N inputs between the DIET and BAU scenario, that atmospheric deposition and biological N_2 fixation are the same in the DIET and 2050 BAU scenario, and that for regions where we assume dietary changes, the availability of organic fertilizers remains at the 1990 level. The last assumption may not be realistic for all world regions because dietary changes likely affect the number of livestock. Our scenario may imply import or export of manure (for details see Kroeze et al. 2001).

In a second alternative scenario for Europe, we analyzed to what extent reductions in NO_y deposition rates in European watersheds may reduce the amount of DIN exported by rivers to the North Atlantic coastal zone and European seas. This analysis was performed using calculated regional patterns of NO_y deposition from the Regional Air pollution INformation System, RAINS (Alcamo et al. 1990; Amann et al. 1998; IIASA 2001). RAINS is an integrated assessment model for air pollution in Europe, and includes information on future fuel use and technologies to reduce emissions. In the Nitrogen Deposition (NDEP) scenario, future fuel use in European countries is assumed to develop as envisaged in official country projections included in RAINS version 7.02. We assume that all countries will apply maximum emission control in order to reduce emissions of NO_x from the electricity sector, industry and transport. We used RAINS version 7.02 to calculate NO_y deposition on land, by combining the RAINS official energy pathway for future fuel use and the RAINS maximum feasible reduction strategy for reducing emissions of N oxides. The NDEP scenario reflects the technical potential to reduce NO_x emissions in Europe. These NO_y deposition rates were used as input to the DIN model to calculate DIN export rates by rivers. All other model inputs for the NDEP scenario were the same as the BAU 2050 scenario (for details refer to Kroeze et al. 2001).

PN Model

The PN export model was based on a particulate carbon (PC) export model of world rivers by Ludwig et al. (1996). We modified this model to account for reservoir retention of total suspended solids (TSS) and for the C:N ratio of particulate matter in rivers (Fig. 1). PC export by major world rivers was calculated as a function of TSS, which in turn was calculated as a function of a precipitation index (I_{Four}), slope of the land (Slope), and water runoff (Q) according to Ludwig et al. (1996):

$$TSS_f export = 0.0176(Q \times Slope \times I_{Four}) + 45 \quad (2)$$

($r = 0.90$, $p < 0.001$, $n = 58$; Ludwig et al. 1996). Units for TSS_f are tons km^{-2} yr^{-1}, Q is mm yr^{-1}, Slope is in radians, and I_{Four} equals $\Sigma(PP_i^2/APPT)$ where i equals 1 to 12; PP is precipitation total in month i, and APPT equals total annual precipita-

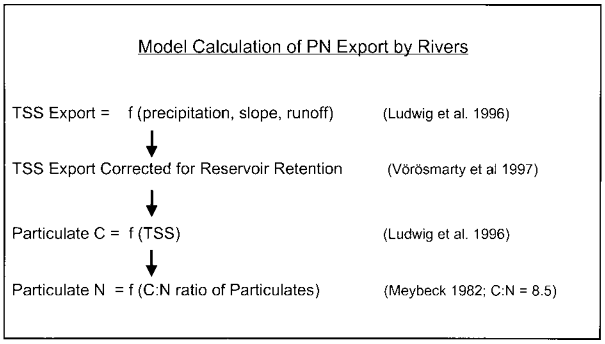


Fig. 1. Flow diagram of model calculation of particulate N export by rivers as detailed in the text.

tion. This TSS model was originally developed using data from rivers either without major dams or before dams were in place on a river (Ludwig et al. 1996). To correct the TSS export (Eq. 2) for reservoir retention, we used information from Vörösmarty et al. (1997) in which they estimated the fraction of TSS in major watersheds by world region or continent that is retained by reservoirs. We assumed that the fraction of water on a continent that is subject to decreased sediment export equals the fraction of water discharged into regulated basins for that continent, that the fraction of total sediment per continent in regulated basins equals the fraction of water discharged in regulated basins, and that the fraction of total sediment per continent in regulated basins that is removed in reservoirs equals the fraction of water discharged in regulated basins times an average trapping efficiency based on the mean water residence time of reservoirs per continent. PC export was then estimated according to Ludwig et al. (1996) as a nonlinear function of the calculated TSS to account for the decreasing proportion of TSS that is organic matter as TSS concentration increases:

$$\%POC = -0.160(\log cTSS)^3 + 2.83(\log cTSS)^2 - 13.6(\log cTSS) + 20.3 \quad (3)$$

($r = 0.83$, $p < 0.001$, $n = 19$) where $cTSS = TSS_f/runoff \times 1000$ (mg l^{-1}). Particulate organic carbon (POC) export in tons C km^{-2} yr^{-1} was calculated as $\%POC \times TSS_f$. We estimated PN from PC by using a particulate C:N ratio of 8.5 (by atoms), which is relatively constant across a wide range of world rivers (Meybeck 1982). PN export in the absence of reservoirs was explored by conducting a model run without the above-described reservoir trapping of particulates.

Databases

1990 and 2050 BAU DIN Model

The gridded 1° × 1° resolution human population database was from Lerner et al. (1988) updated to the year 1990 using Food and Agricultural Organization data (Bouwman et al. 1995). The grid-based 2050 population database was compiled using United Nations country-based (medium) projections (United Nations 1996) for population growth through 2050. The gridded 2050 database was created by multiplying the 1990 population in each grid cell by the 1990–2050 United Nations predicted population increase in the country where the grid cell was located.

For allocating 1990 N fertilizer application we used a 1° × 1° resolution database of countries (Lerner et al. 1988) and the 1990 N fertilizer use from Food and Agricultural Organization (1992). N fertilizer use was assigned to grid cells covered by arable land given by Olsen et al. (1983). The average country N application rate was calculated as the country N fertilizer use divided by the sum of the area of arable land plus permanent crops (Food and Agricultural Organization 1992). Where the country total arable land area from Olsen et al. (1983) was different from the Food and Agricultural Organization (1992) statistics, we used country-specific correction factors for the average N application rate using data from Food and Agricultural Organization (1992) on areas of arable land and permanent crops, so as to arrive at the correct country total N use. We recognize that the use of mean N application rates is not realistic. Grid-based data on the distribution of N application rates within countries were not yet available on the global scale.

For fertilizer use in 2050, we used fertilizer growth rates for 13 world regions distinguished in the Integrated Model to Assess the Greenhouse Effect (IMAGE; Alcamo et al. 1994) and applied these to 1990 grid country-based fertilizer use from Bouwman et al. (1995). The 2050 fertilizer growth rates for developing countries are detailed in Bouwman (1997). For other world regions we used the IMAGE conventional wisdom projections (Kreileman and Bouwman 1994). The regional and national projections for population and fertilizer use were gridded using the country-to-grid information as available in the Emission Database for Global Atmospheric Research (Olivier et al. 1996).

The grid NO_y database for 1990 includes modeled dry and wet deposition of NHO_3 and dry deposition of natural and anthropogenic NO_x (NO, NO_2, NO_3, N_2O_5, and PAN; Dentener and Crutzen 1994). The deposition fields were extensively used and evaluated in previous studies (e.g., Prospero et al. 1996; Holland et al. 1997) and were interpolated to a 7.5° × 7.5° grid for our use. The NO_y deposition database for 2050 was calculated by the Moguntia model using emissions of NO_x in 2050 which were based on activity data underlying the widely used IS92a scenario (Houghton et al. 1995). Natural emissions were left unchanged. When comparing this scenario for NO_x with the very recently developed Special Report on Emission Scenarios used in the Intergovernmental Panel on Climate Change Third Assessment Report (Prather et al. 2001), the IS92a emissions are rather similar to those of the B2 marker scenarios. Relative to 2000 both scenarios calculate for 2050 an increase of anthropogenic NO_x emissions by a factor of 1.7. SRES-B2 assumes a regionally heterogeneous development of the world economy, but within all regions there is social awareness on, for example, pollution issues.

Watersheds were located using the global hydrographic database (GGHYDRO) of Cogley (1994) that we modified to increase the number of watersheds that were delineated in high population density areas. Each grid cell was assigned to one of 177 different watersheds that drain to estuarine grid cells at the mouth of the major rivers. N input from the watershed area below the river mouth (e.g., cities located on estuaries below river mouths) also was included in the estimated river export. Not included in our analysis were watersheds that drain to inland drainage basins (endoreic runoff), or freshwater input due to melting of polar ice caps. While water runoff may change in the future due to climate change or land use, the extent of change is uncertain, so we used the water runoff database from 1990 for the 2050 projections (GGHYDRO; Cogley 1994).

PN Model

The following grid databases were used for the PN river export model calculations: monthly and annual precipitation (Legates and Willmont 1992); slope (Moore and Mark 1986 in grid format from Ludwig personal communication). Water runoff and watershed delineations were from our modification of GGHYDRO (Cogley 1994) as used for the DIN model.

Results and Discussion

DIN Export to Coastal Systems

Base Case 1990

The global pattern of model-predicted DIN export to coastal systems can be examined from a number of perspectives. Normalizing the DIN export to watershed area (yield; kg DIN km^{-2} watershed yr^{-1}; Fig. 2) provides a perspective that is analogous to the units of N input to the watershed from sewage based on human population density, synthetic fertilizer use, and NO_y atmospheric deposition (Figs. 3, 4, and 5, respectively). There is relatively low DIN yield ($<$ 100 kg km^{-2} watershed yr^{-1}) from watersheds in a number of regions including throughout most of South America, Africa, and Australia (Fig. 2). This is a reflection of the generally low population densities, synthetic fertilizer use, and NO_y atmospheric deposition currently throughout much of these continents. Some exceptions to the low DIN yields in these continents include the near coastal areas of South America (western coast and portions of eastern coast) and in Africa along the Mediterranean coast and the Gulf of Guinea.

There are large areas with relatively high yields of DIN predicted in the United States, Central America, Europe, Southern and Eastern Asia, Indonesia, and the Pacific Islands. The combination of N sources that account for these high DIN yields is somewhat different among these regions. All of these regions have extensive areas with high use of synthetic fertilizer ($>$ 3,000 kg km^{-2} watershed yr^{-1}; Fig. 4). The United States and Europe also have areas with high NO_y deposition ($>$ 350 kg N km^{-2} watershed yr^{-1}; Fig. 5), and Europe and Southern and Eastern Asia have high population densities ($>$ 100 persons km^{-2} watershed; Fig. 3).

We converted area-based N inputs and export for each watershed to total kg N per watershed and then aggregated the data at various scales in order to facilitate quantitative comparisons among major world regions. In the following analyses the N inputs and exports from a watershed are geographically assigned to the location of the estuarine grid cell where the river discharges.

The total global DIN export as of 1990 was approximately 21 Tg N yr^{-1}, according to the DIN model calculations (Seitzinger and Kroeze 1998). This estimate is similar to previous estimates for N export to coastal systems which have not been based on spatially explicit information with the exception of the recent paper of van Drecht et al. (2001). For example, our model predicted global DIN export is similar to the global nitrate-N export estimated by Duce et al. (1991; 20 Tg NO_3-N yr^{-1}). It is also in reasonable agreement with total N export estimates of Galloway et al. (1995) and van Drecht et al. (2001), assuming that 60% of the total N exported globally is inorganic (Meybeck 1982). It is higher than the 1970 total N estimate of Meybeck (1982), which may reflect the actual increase in human population, synthetic fertilizer use and industrialization between 1970 and 1990. Our model predicted DIN export from watersheds draining into the North Atlantic Ocean from North America are consistent with estimates of total N export by Howarth et al. (1996), after taking into account the relative proportions of DIN, PN, and DON in those rivers, as explained in Seitzinger and Kroeze (1998).

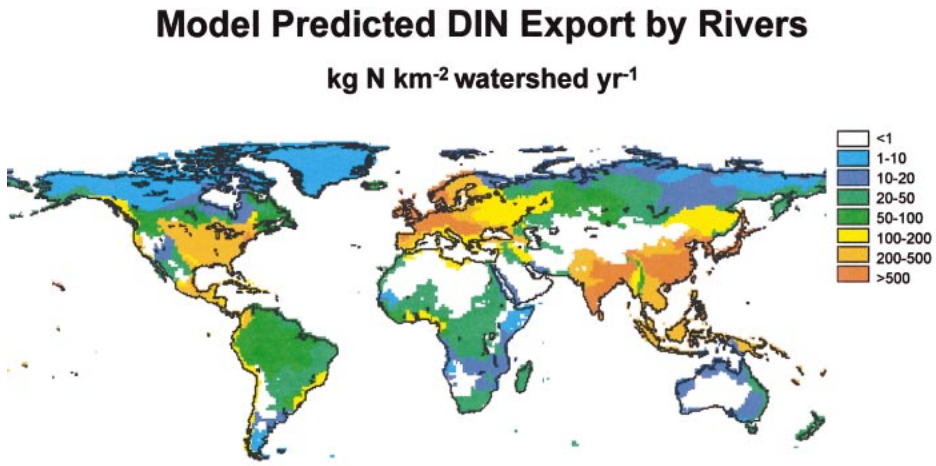


Fig. 2. Model predicted DIN export in 1990 to coastal systems by rivers. Units are in kg N km^{-2} watershed yr^{-1} (modified from Seitzinger and Kroeze 1998).

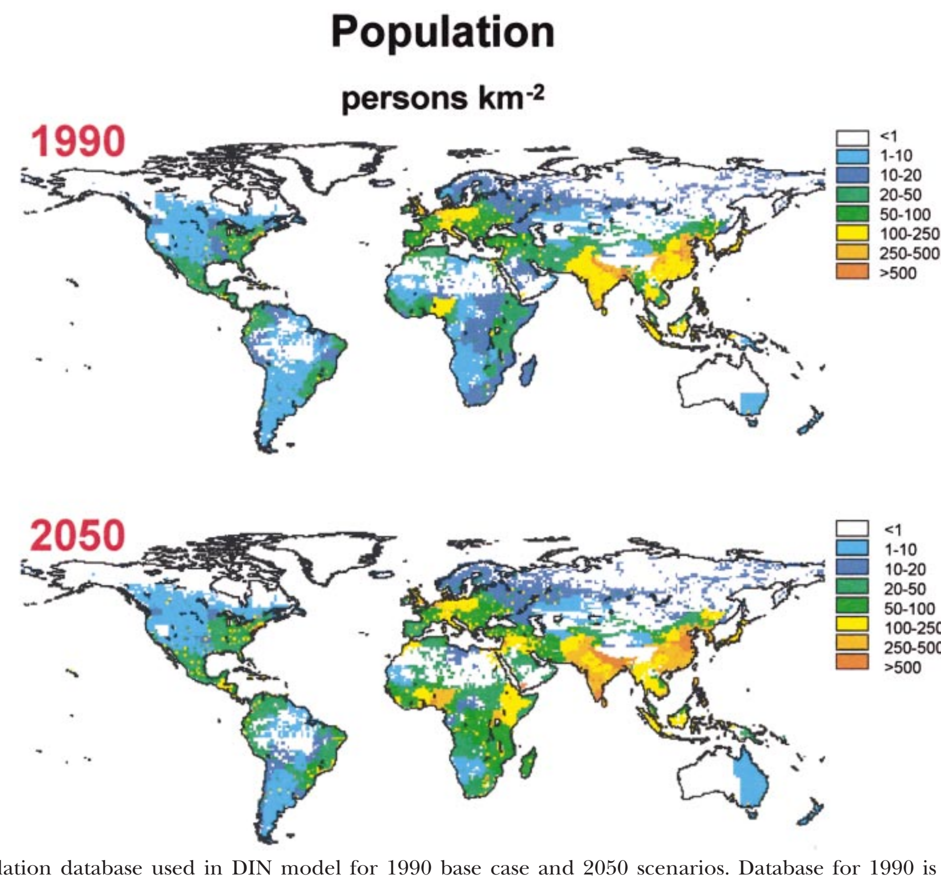
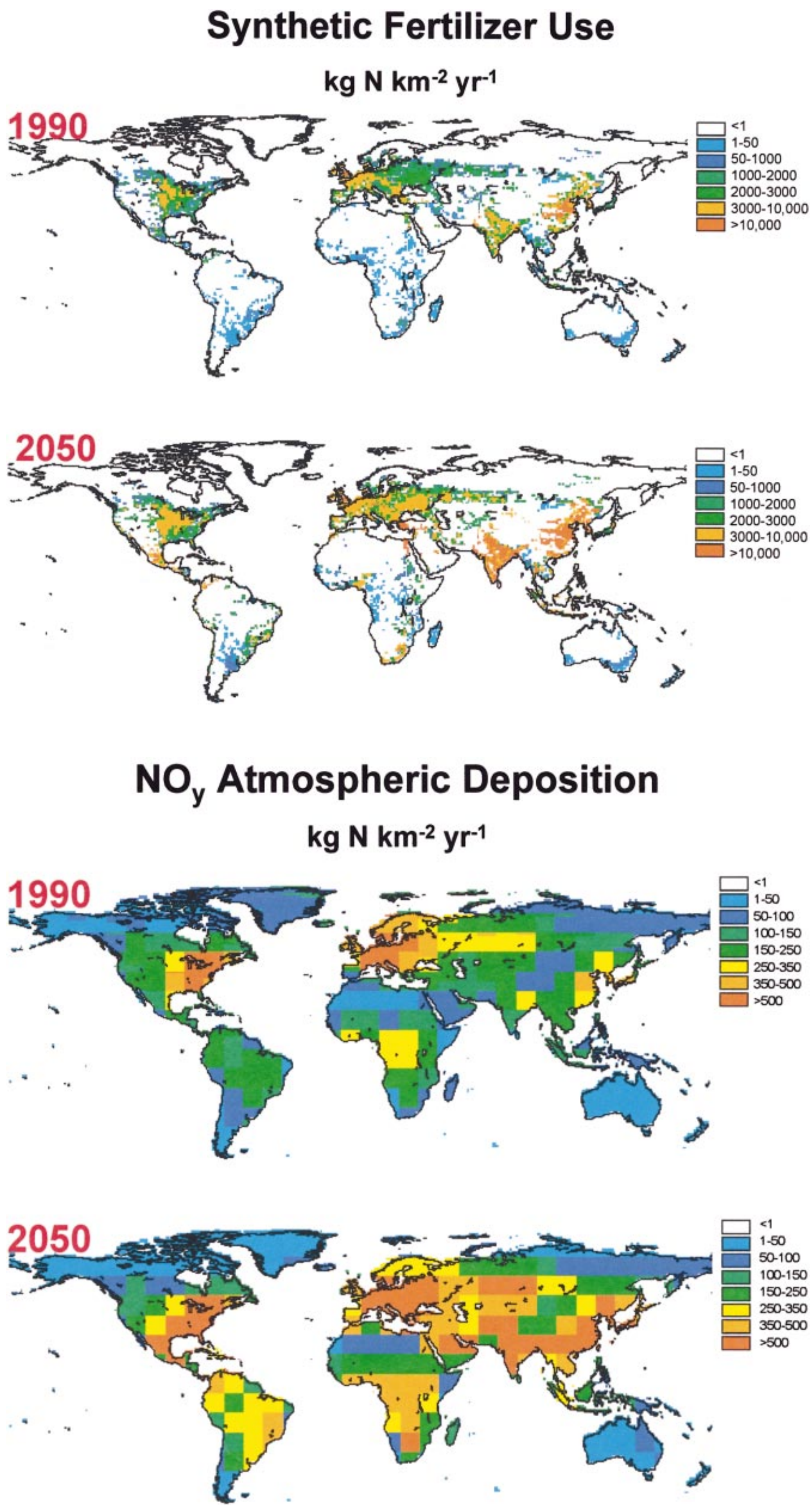


Fig. 3. Population database used in DIN model for 1990 base case and 2050 scenarios. Database for 1990 is from Lerner et al. (1988) updated to 1990 by Bouwman et al. (1995), and for 2050 from United Nations (1996) projections.

Regional-continental Scale Comparisons. There are considerable differences in the model-predicted total DIN export among continents and world regions. Total DIN export to coastal areas in South America, Africa, and Australia combined (2.6 Tg N yr^{-1}) account for only 12% of the global DIN export (Fig. 6). Total DIN export from South America (1.5 Tg N yr^{-1}) is similar to total DIN export from Africa (~1 Tg N yr^{-1}) as of 1990. DIN export to coastal areas in North America between


Synthetic Fertilizer Use
kg N km-2 yr-1
1990
<1
1-50
50-1000
1000-2000
2000-3000
3000-10,000
>10,000
2050
<1
1-50
50-1000
1000-2000
2000-3000
3000-10,000
>10,000
NOy Atmospheric Deposition
kg N km-2 yr-1
1990
<1
1-50
50-100
100-150
150-250
250-350
350-500
>500
2050
<1
1-50
50-100
100-150
150-250
250-350
350-500
>500

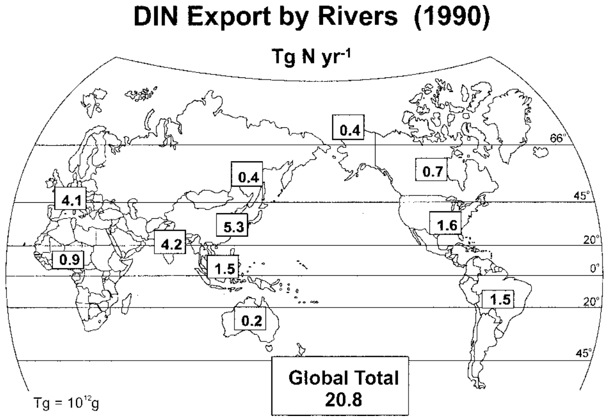


Fig. 6. Geographical distribution of model-predicted DIN export by rivers to coastal systems, including inland seas in 1990. Model output was aggregated in geographical regions as follows: total DIN export from the continents of South America, Africa, Australia, and Europe (exclusive of the Arctic Ocean); total DIN export to the Arctic Ocean from all continents (0.4 Tg N yr^{-1}); for Asia total DIN export to coastal regions between 45–66°N (0.4 Tg N yr^{-1}), 20–45°N (5.3 Tg N yr^{-1}), Southeast Asia and the Pacific Islands (1.5 Tg N yr^{-1}), and to the Indian Ocean (exclusive of Africa); for North America total DIN export between 45–66°N, and 20–45°N are shown.

20–45°N alone (United States and northern Mexico; 1.6 Tg N yr^{-1}) is similar to export from all of South America. The United States and northern Mexico contrasts with major areas of Asia, where approximately 5.3 Tg N yr^{-1} are exported from Eastern Asia between 20–45°N alone (primarily China but also Korea and Japan; hereafter, we refer to this region as Eastern Asia). A similar amount, 4.2 Tg N yr^{-1}, is exported from Southern Asia to coastal areas in the Indian Ocean (hereafter we refer to this area as Southern Asia). DIN export from Eastern and Southern Asia combined accounts for almost half (47%) of the DIN exported to coastal systems globally. DIN export from all European watersheds (4.1 Tg N yr^{-1}) is also relatively high, and similar to that from Eastern and Southern Asia. An interesting feature of European drainage basins is that only ~35% of the DIN is exported to coastal areas on the Atlantic Ocean; the remaining 65% is exported to the Mediterranean, Baltic, Black, and Caspian Seas (Seitzinger and Kroeze 1998).

In the following three sections we compare the total N inputs and model-predicted DIN export by region by combining the information from all watersheds draining into that region. The model calculations are performed on a grid or watershed scale and there are nonlinear components of the model, so the model-predicted DIN export cannot be directly extrapolated from the summed data. There are interesting patterns that can be observed by comparing N inputs and model predictions at these larger scales.

Comparison of DIN Export and N Inputs among Four World Regions. Total DIN export from China, India, and Europe are similar and high relative to other major world regions. Examination of the watershed areas and N inputs reveals that each of these regions has a different balance of inputs that result in a similarly large DIN export (Fig. 7). The area of watershed draining to coastal areas of Europe is three to four times as large as to China or India, respectively (Fig. 7). Human population in 1990 was approximately a billion in all three regions. The total amount of synthetic fertilizer used was similar in watersheds draining to coastal Europe and China and about 40% less in India. Atmospheric NO_y deposition was relatively low in China and India compared to Europe that received approximately five times as much NO_y. The United States (between 20–45°N) showed yet a different combination, with a watershed area about half that of Europe and twice that of China or India, low population relative to Europe, China or India, a total synthetic fertilizer use similar to India, and NO_y deposition intermediate between Europe and the two Asian regions.

Relationship of DIN Export with Human Population at Regional-continental Scales. At regional-continental scales, population was a good predictor of DIN export (Fig. 8; $r^2 = 0.91$). There is variation among regions, but approximately 4 kg DIN are exported to coastal systems $person^{-1}$ yr^{-1}. This applies to developing regions such as China, India, the Asian Pacific Islands, and South America, as well as to highly developed areas such as Europe and the United States. The relationship with population is not a direct reflection of sewage production but rather the combined result of the use and associated N losses from the production of food for, and consumption of food by, the population, in addition to the combustion of fossil fuel to meet their energy demands. It also suggests that the net import or export of food, and the fertilizer used to grow that food, is relatively small compared to the

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Fig. 4. Synthetic fertilizer use database used in DIN model for: 1990 base case, and 2050 BAU and NO_y deposition scenarios. Database for 1990 is from Bouwman et al. (1995) and for 2050 projections is from Bouwman (1997).

Fig. 5. NO_y deposition database used for DIN model for 1990 base case and 2050 BAU and DIET scenarios. Database for 1990 is from Dentener and Crutzen (1994); 2050 projections are described in the text.

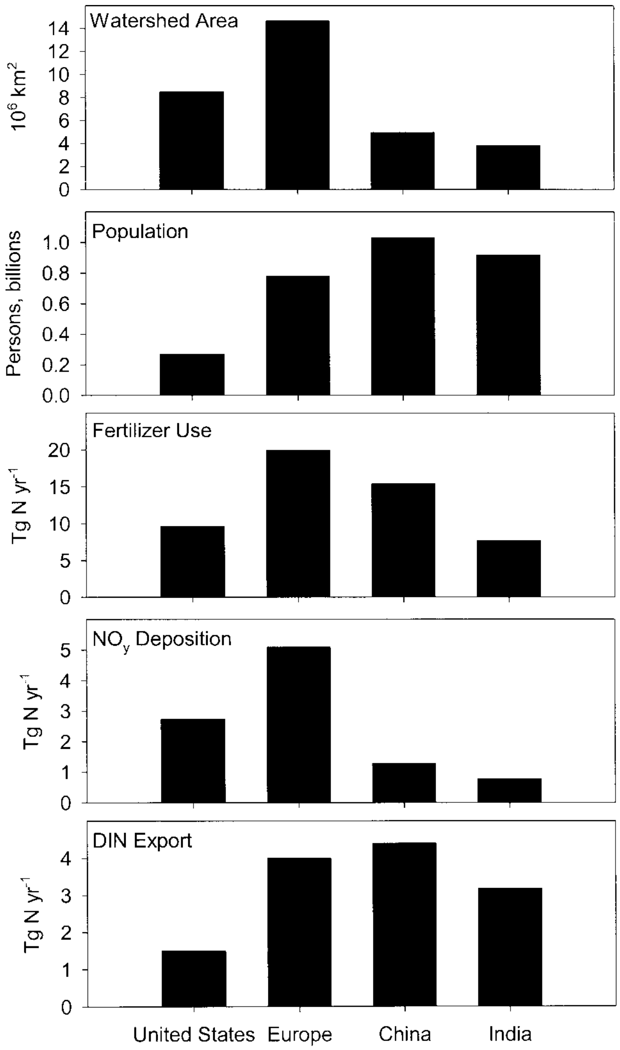

Fig. 7. Comparison of four major world regions by watershed area and 1990 population, synthetic fertilizer use, NO_y deposition, and DIN export to coastal systems. Note that the above numbers are for the total area, population, N input and export for all watersheds that drain to estuarine grid cells for the region indicated (e.g., the total population in all watersheds that drain to European coastal zones are assigned to Europe, even though a portion of the watershed may be located in Asia).

consumption of the agricultural production within these larger regions. It suggests that most of the deposition of NO_y resulting from the combustion of fossil fuel remains within these large regions. This is consistent with a recent analysis of the net import or export of N in fertilizer, by cultivation, and from combustion for major world regions (Galloway and Cowling 2002). That analysis suggests that the total net import or export of N is less than 20% of the sum of these N categories. This is not necessarily the case at the watershed scale, where considerable food and NO_y are exported

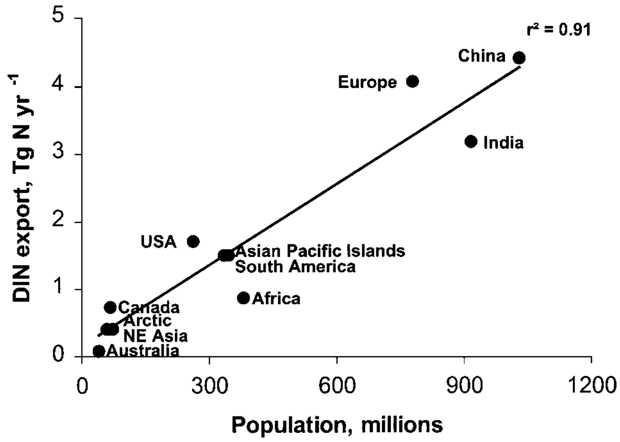

Fig. 8. Model-predicted DIN export in 1990 versus human population for major world regions.

across watershed boundaries (Howarth et al. 1996; Jordan and Weller 1996; Boyer et al. 2002).

Latitudinal Distribution of N Inputs to Watersheds and DIN Export. There are strong latitudinal patterns of N inputs and resulting DIN export (Fig. 9). Approximately 90% of the DIN export is to coastal systems in the Northern Hemisphere. This is consistent with the high percent of continental land mass draining into the Northern Hemisphere (70%; excluding Antarctica), and human population (86%), synthetic fertilizer use (94%), and NO_y deposition (80%) in those watersheds (Fig. 9). Within the Northern Hemisphere there are latitudinal differences in the distribution of N inputs and consequently DIN export. Watershed area is similar between 20–45°N, 45–66°N, and 66–90°N, but fertilizer use is almost twice as large in the midlatitudes (20–45°N) as between 45–66°N. This is similar to the pattern of sewage N, although the magnitude of sewage N is a factor of 10 or more less than fertilizer use, owing to the low transfer efficiency of N from agriculture to food for human consumption (Bleken 1997; Smil 2001). The latitudinal pattern of NO_y deposition differs from fertilizer and sewage. Total NO_y deposition is similar in the mid and higher latitudes, and still considerable above the Arctic Circle (66–90°N). The magnitude of NO_y deposition, in general, is intermediate between fertilizer inputs and sewage. The relative amounts of fertilizer, NO_y deposition, and sewage, as well as the total inputs, to individual watersheds may differ considerably from the latitudinal patterns noted here (Howarth et al. 1996; Castro et al. 2000; Boyer et al. 2002; van Breemen et al. 2002). The ratio of anthropogenic N inputs to DIN export by latitude appears to be highest in the tropical regions (0–20°N and S) and decreases towards the higher latitudes (Fig. 9). This pattern

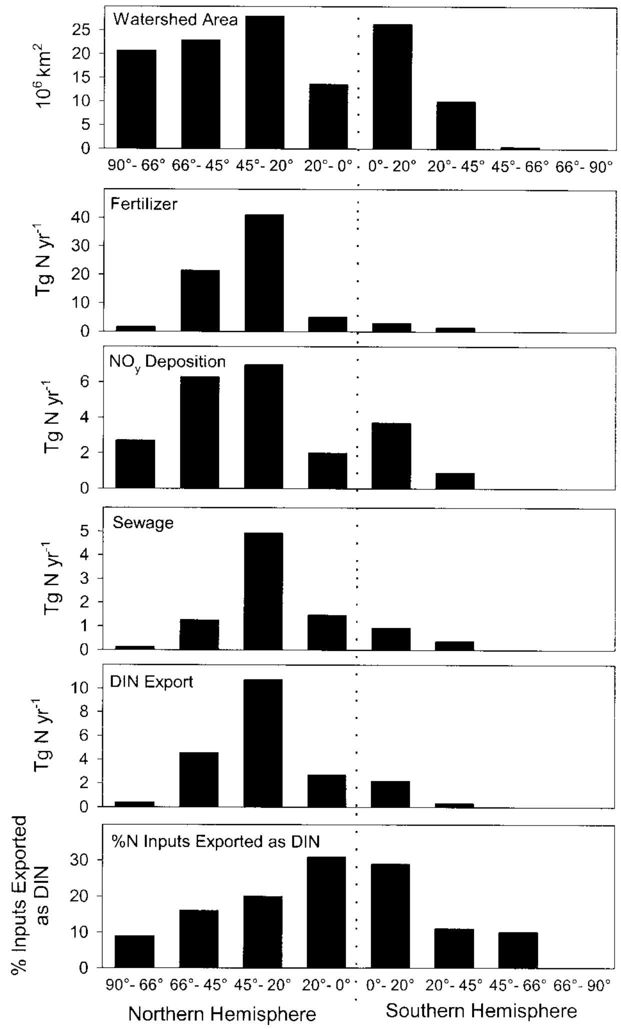

Fig. 9. Latitudinal distribution of watershed area, N inputs and DIN export in 1990.

appears in both the northern and southern hemispheres. This cannot be explained simply by the distribution of N inputs and watershed area. A higher water runoff in the tropical regions may in part be responsible for this pattern, and the model does not explicitly account for natural DIN export (i.e., from biological-N_2 fixation).

2050 Scenario

How might the magnitude and spatial distribution of DIN export by rivers change in the future? This question is not easily answered, as it depends on future human population increases in the different world regions, increases in the use of synthetic fertilizer to grow the food to feed the increasing population and to meet their demands for a high quality diet, and industrialization increases in developing countries. Many of these changes will be dictated by political and economic factors (Heilig 1999; Smil 2001).

BAU 2050. We first analyzed possible future developments based on assumptions consistent with BAU trends. This BAU scenario assumes that current trends continue as envisaged in the early 1990s, but does not include changes in legislation such as the Helsinki Commission (HELCOM), Oslo and Paris Commission (OSPAR) agreements, or changes in economic conditions that became apparent since 1990. The BAU scenario is described in detail in Kroeze and Seitzinger (1998).

DIN export globally is predicted to approximately double by the year 2050 (47 Tg N yr^{-1}) relative to 1990 under the BAU scenario (Kroeze and Seitzinger 1998). Increases in all major world regions are predicted; however, those increases are not evenly distributed (Fig. 10). Large population increases are not expected in North America between 1990 and 2050, although some increases in atmospheric NO_y deposition are predicted, as are increases in synthetic fertilizer use, accounting for the approximately 50% increase in DIN export by 2050 (Figs. 3, 4, and 5). In Europe, population is anticipated to remain stable or decrease in some regions. In Eastern Europe considerable increases in industrialization and synthetic fertilizer use were anticipated by 2050, contributing to the approximately 55% increase in DIN export from Europe. Since the breakup of the USSR in the early 1990s, there has been a decrease in fertilizer use in many parts of Eastern Europe (HELCOM 2001). How the economic and policy changes in this region will affect DIN export by rivers in the coming decades remains to be seen.

In contrast to North America and Europe where population is not anticipated to increase markedly,

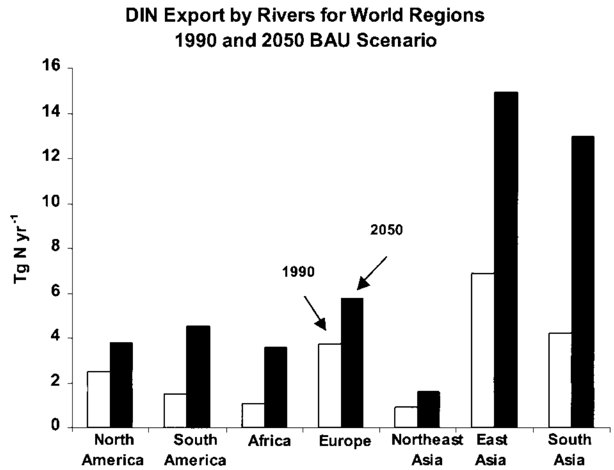

Fig. 10. Model-predicted DIN exported for world regions in 1990 and 2050 for a business-as-usual scenario (modified from Kroeze and Seitzinger 1998).

the populations of Africa and South America were predicted to increase considerably (Fig. 3). Model calculations suggest that DIN export from both of these continents will approximately triple, relative to the fairly low export in 1990 (Fig. 10). This result is due to a combination of increased synthetic fertilizer use and atmospheric NO_y deposition (Figs. 4 and 5). The largest absolute increases in DIN export are predicted for Southern and Eastern Asia, where large increases in synthetic fertilizer use to provide food to supply the dietary needs of the rapidly increasing population in those regions are predicted. Substantial increases in industrialization and associated fossil fuel combustion, resulting in increased NO_y deposition are also predicted. Almost half of the total global increase in DIN export between 1990 and 2050 is predicted for Eastern and Southern Asia.

This regional perspective provides insight in the potential effects on DIN export to coastal systems in the future due to a changing geographical distribution of population, food production, and energy production. It also suggests large regions where coastal eutrophication may increase substantially. Changes in N inputs to some watersheds will likely be driven by food and energy demands in distant regions, indicating the need for a global approach to managing N as suggested by Galloway and Cowling (2002). In order to avoid the large increases in DIN export predicted under the 2050 BAU scenario, considerable changes will likely be required in agricultural practices, technology, and potentially human behavior. We have used the model to begin to explore some of these potential scenarios.

DIET Scenario: Results for Europe and North America. How might a change in diet effect DIN export to coastal areas in Europe and North America by 2050? In the BAU scenario, N inputs to European watersheds from synthetic fertilizer and manure increased by 47% between 1990 and 2050 (Fig. 11). The increase is largest in watershed regions draining into the Mediterranean Sea (109%) and lowest in European watersheds draining into the North Atlantic (18%). In the DIET scenario, the total N inputs in 2050 are considerably reduced compared to the 2050 BAU scenario. Total N inputs to the European watersheds are 10% higher than in 1990. For watersheds draining into the North Atlantic Ocean and the Baltic Sea, we observe considerable reductions in N inputs (25% and 10%, respectively, relative to 1990) in the DIET scenario. In other watershed regions fertilizer use still increases between 1990 and 2050, but to a lesser extent than in the BAU scenario. These differences among regions are associated with the relative share of animal proteins in total protein intake per person in the BAU scenario. The higher the BAU animal protein intake, the larger are the reductions required to meet the DIET scenario requirements.

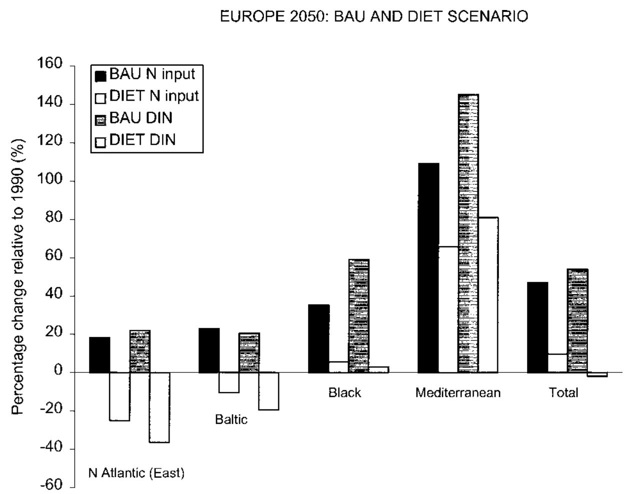

Fig. 11. Changes between 1990 and 2050 in the business-as-usual (BAU) and DIET scenario for Europe. Shown are changes in N inputs to watersheds (synthetic fertilizer + manure) and DIN export by rivers to European Seas. Units: percentage change relative to 1990. Modified from Kroeze and Seitzinger (1998) and Kroeze et al. (2001).

In the BAU scenario, we calculate that DIN export rates to European seas may increase by 54% between 1990 and 2050 (this is excluding the effect of current national and international policies; Fig. 11). For the DIET scenario we calculate that DIN export rates to European seas are 2% lower than in 1990, so that relatively moderate changes in the human diet may avoid an increase in DIN export rates by rivers between 1990 and 2050. These reductions may add to current policy plans to reduce N inputs to European seas.

For North America, dietary changes alone may not be sufficient to avoid an increase in DIN export to the coastal oceans. We calculate that DIN export rates by North American rivers to the North Atlantic and North Pacific coastal oceans may double between 1990 and 2050 (BAU), while in the DIET scenario this increase amounts to 50% (Fig. 12). The effects of a shift from animal proteins towards plant proteins has largest effects on DIN export into the western North Atlantic, and in particular in the area between 20°N and 45°N. Total N inputs from synthetic fertilizers and manure in this region are 23% lower in the 2050 DIET scenario than in 1990, and DIN export rates are 5% higher than in 1990 (as opposed to 68% higher in the BAU 2050 case).

Decrease in NO_y Deposition in Europe. In Europe, there is a large potential for reducing emissions of

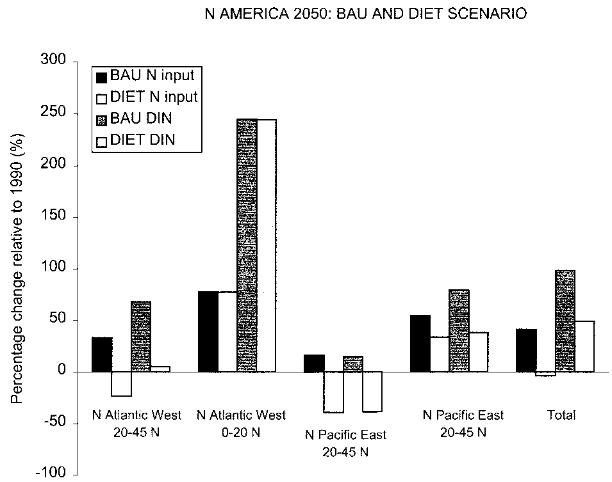

Fig. 12. Changes between 1990 and 2050 in the business-as-usual (BAU) and DIET scenario for North America. Shown are changes in N inputs to watersheds (synthetic fertilizer + manure) and DIN export by rivers to the oceans. Units: percentage change relative to 1990. Modified from Kroeze and Seitzinger (1998) and Kroeze et al. (2001).

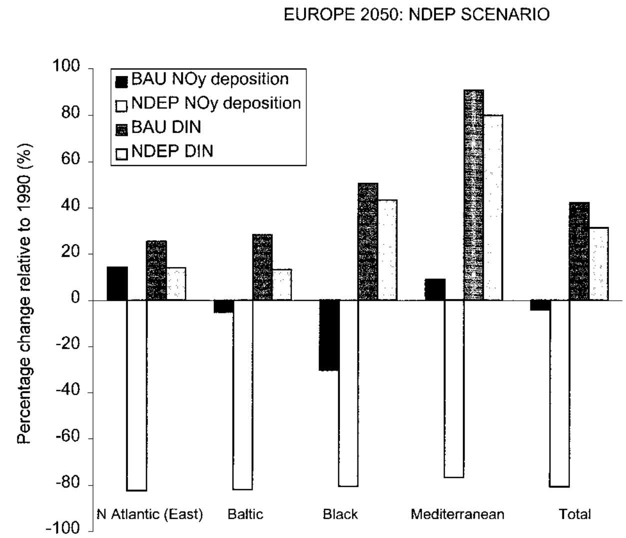

Fig. 14. Changes between 1990 and 2050 in the business-as-usual (BAU) and low NO_y deposition (NDEP) scenario for Europe. Shown are changes in NO_y deposition on watersheds and DIN export by rivers to European Seas. Units are percentage change relative to 1990. Modified from Kroeze et al. (2001).

N oxides associated with energy use and industrial activities. In this analysis, we compared a situation where we assume maximum emission reduction (the NDEP scenario) to the BAU scenario discussed above; the emission reductions were taken from the RAINS model (the RAINS unabated case; Fig. 13). In this BAU scenario, we find that NO_y deposition rates in Europe in 2050 are 4% lower than in 1990 (Fig. 14). This reduction is caused by current trends in energy use. In the NDEP scenario, the NO_y deposition rates are about 80% lower than in 1990 in all watershed regions as a result of emission control (Fig. 14). These reductions may affect DIN export rates by rivers, since part of the N deposited onto the watersheds may be transported from the soil to the rivers. We calculate that in Europe, DIN export by rivers may increase by 42% between 1990 and 2050 in the BAU scenario, while reducing NO_y deposition rates may lower this increase to 31% (Fig. 14). This is a considerable reduction, given the fact that it is a side effect of air pollution control primarily aimed at reducing acidification and tropospheric smog formation. We

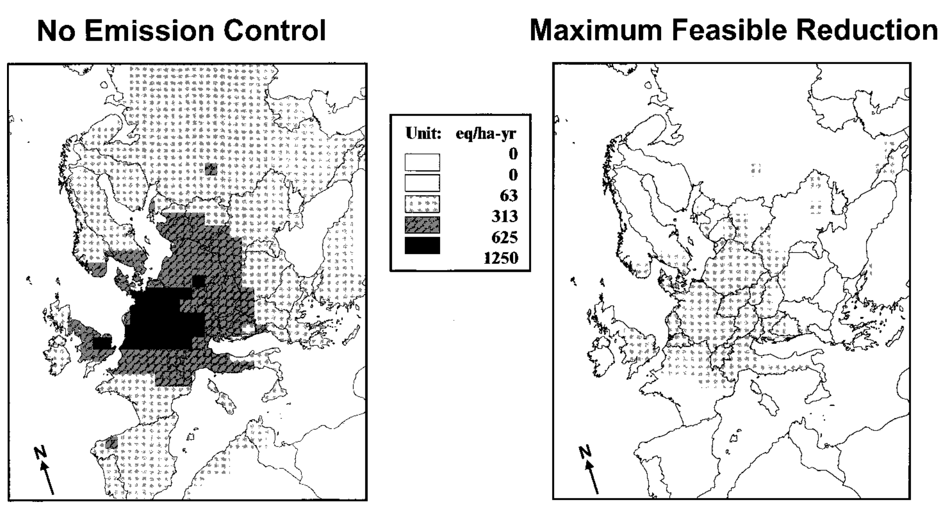

Fig. 13. NO_y deposition rates in Europe in 2010, calculated by the RAINS model (version 7.02) (Alcamo et al. 1990; Amann et al. 1998; IIASA 2001), and used as a basis for the 2050 BAU scenario (no emission control case) and the NDEP scenario (maximum feasible emission control case). Units are acid equivalents ha^{-1} yr^{-1}.

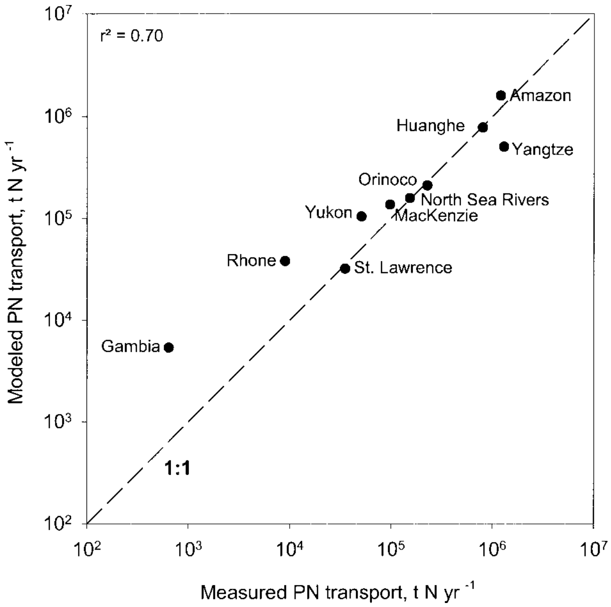

Fig. 15. Comparison of PN export predicted by model and measured PN export for various rivers in 1990. Results of linear regression analysis shown ($r^2 = 0.7$). Data sources: Amazon and Orinoco (Lewis et al. 1999); Huanghe (Zhang et al. 1992); Yangtze (Milliman et al. 1984); North Sea Rivers (Radach and Lenhardt 1995 cited in Baretta et al. 1995); MacKenzie, Yukon, St. Lawrence (Telang et al. 1991); Rhone (Moutin et al. 1998); and Gambia Rivers (Lesack et al. 1984). Units are tons N yr^{-1}; 1 ton = 10^6 g.

do not account for reduced N deposition rates directly to the water surface of rivers, estuaries, and continental shelves. Reductions in these inputs may add to the effect of emission control on N inputs to aquatic systems.

PN Export to Coastal Systems

The above analyses address only DIN export to coastal systems. PN and DON are also important components of the total N export. PN and DON not only account for a substantial portion of the total N exported from terrestrial to coastal systems but also contribute to nutrient enrichment and eutrophication (Seitzinger et al. 2002). To date, we have not had a global view of the spatial distribution of either PN or DON export.

A comparison of measured PN export for a range of world rivers compares reasonably well with model predicted export of PN ($r^2 = 0.7$; Fig. 15). The number of rivers in the comparison is not very large ($n = 10$). There are considerably fewer major world rivers with available well-documented PN export data over annual cycles compared to the number of rivers for DIN data. The model is better at predicting PN export from rivers with high rates of export relative to those with low export. These model predictions should be considered a first cut

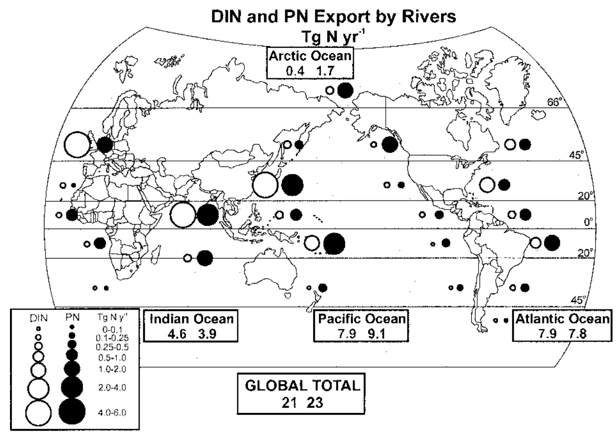

Fig. 16. Comparison of model predicted DIN and PN export to coastal systems in 1990. Model predictions are indicated as DIN or PN export summed by latitudinal zone (0–20°, 20–45°, 45–66°, > 66°N and S) for each ocean basin. For the Indian Ocean, DIN and PN export to all regions north or south of the equator are shown.

at examining the global scale spatial distribution of PN export.

Total PN export by rivers globally is predicted to be 23 Tg N yr^{-1} (Fig. 16). This is similar to the PN export estimated previously by Meybeck (1982; 21 Tg N yr^{-1}). It is also similar in magnitude to our predicted global DIN export (1990; 21 Tg N yr^{-1}). By ocean basin (e.g., Indian Ocean, Pacific Ocean, Atlantic Ocean), PN and DIN inputs to coastal systems are predicted to be similar (Fig. 16). At smaller scales the predicted export of DIN and PN differ. DIN export from Europe is predicted to be more than twice as large as PN export, which is consistent with measured values. From the United States and northern Mexico total DIN export is estimated to be approximately twice as large as PN export. The opposite pattern is predicted for South America and rivers entering the Arctic Ocean where PN export is estimated to be more than twice as large as DIN export. The higher export of PN relative to DIN for South America is consistent with the average ratio of PN:DIN export measured in 25 tropical watersheds (average 1.7:1; Lewis et al. 1999). The predictions for the Arctic are consistent with the ratio of PN:DIN for the MacKenzie (~4) and Yukon (~2) rivers (Telang et al. 1991). The generally higher ratio of PN:DIN in regions such as South America, Africa, and the Arctic, compared to the United States, Europe, and Eastern and Southern Asia may reflect the stronger influence of human activities on DIN export compared to PN export.

Anthropogenic N inputs were not needed as a parameter in the PN model to obtain a reasonably good prediction of PN export by rivers with large

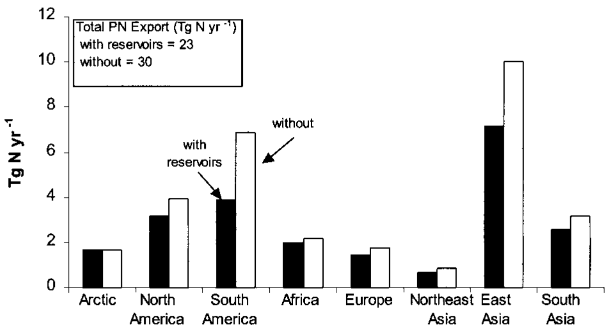

Fig. 17. Model-predicted export of PN to coastal systems with reservoirs and with all reservoirs removed. See text for details.

anthropogenic activities in their watersheds (Fig. 15). In the original development of the PC multiple regression model (Ludwig et al. 1996), upon which our PN model was built, a range of factors that might potentially control PC export were examined. Neither population density nor cultivated area were found to improve the model fit (Ludwig et al. 1996). We do not know the exact reasons for this. Agriculture can increase soil erosion in landscapes with susceptible soils and with rolling or hilly landscape, and might be expected to be an important component of predicting PN export to coastal systems in certain regions. A large proportion of eroded soil, however, is retained in basins and not exported to the river mouth, potentially dampening an agricultural signal on TSS or PN export. Future investigations are needed to better assess the anthropogenic factors controlling PN export.

The anthropogenic factor that we did find was important in obtaining a good fit between model predicted and measured PN export was reservoir trapping of particulates ($r^2 = 0.7$ with reservoirs and $r^2 = 0.4$ without reservoirs). As explained above (methods), data used in the original TSS model formulation were from major rivers before reservoir construction. By removing the effect of reservoir trapping from the model, we can obtain insight into the magnitude and geographical distribution of the effect of reservoirs on PN export. Global PN export increased from 23 to 30 Tg N yr^{-1} when the trapping of TSS and consequently PN by reservoirs was removed from the model calculations (Fig. 17). This suggests that globally, reservoirs are decreasing the export of PN by approximately 25%. This is consistent with the recent analysis of global reservoirs on TSS export by Vörösmarty et al. (1997); the effect of reservoirs on TSS and PN export differ somewhat because of the nonlinear relationship between TSS and PC (Eq. 3), and consequently PN. The geographic distribution of the reservoir effect on PN export varies. The largest decrease in PN export due to reservoirs is predicted for South America and Eastern Asia.

Conclusions

We have used a spatially explicit empirical modeling approach to begin to develop a comprehensive global perspective of N export to coastal systems and the effects of human activities on N export. We have developed separate models for DIN and PN export. A DON model, the other major form of N, is in progress. We have chosen to model each of these forms separately because of differing controls on their export and different bioavailability and effects on coastal ecosystems. The model results indicate the widely uneven distribution of human activities and rates of N input to coastal systems around the world. This is illustrated at many scales, including at the watershed, latitudinal, and regional-continental scales. The results also suggest the potentially large increases in DIN export in the future in many world regions, particularly in Eastern and Southern Asia. In order to avoid future large increases in N export to coastal systems, a multiplicity of innovative approaches will likely be required. The effects on DIN export of two approaches were explored for North America and Europe: reductions in N fertilizer use resulting from a reduction in human consumption of animal protein, and decreases in NO_y deposition due to a combination of future fuel use and technologies to reduce NO_y deposition. Both scenarios indicated substantial reductions in DIN export in certain regions. Future measurement, modeling, and synthesis activities at many scales and in many world regions, in concert with policy and economic analyses, will be required to minimize environmental degradation while at the same time meet the food and energy demands of society (Galloway and Cowling 2002). This work is just one step towards meeting that challenge.

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Ludwig, W. Personal Communication. Centre de Formation et de Recherche sur l'Environnement Marin, University de Perpignan, 52 Avenue de Villeneuve, 66860 Perpignan, France.

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