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Regional nitrogen budgets and riverine N & P fluxes for the drainages to the North Atlantic Ocean: Natural and human influences

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Abstract. We present estimates of total nitrogen and total phosphorus fluxes in rivers to the North Atlantic Ocean from 14 regions in North America, South America, Europe, and Africa which collectively comprise the drainage basins to the North Atlantic. The Amazon basin dominates the overall phosphorus flux and has the highest phosphorus flux per area. The total nitrogen flux from the Amazon is also large, contributing 3.3 Tg yr^{-1} out of a total for the entire North Atlantic region of 13.1 Tg yr^{-1}. On a per area basis, however, the largest nitrogen fluxes are found in the highly disturbed watersheds around the North Sea, in northwestern Europe, and in the northeastern U.S., all of which have riverine nitrogen fluxes greater than 1,000 kg N km^{-2} yr^{-1}.

Non-point sources of nitrogen dominate riverine fluxes to the coast in all regions. River fluxes of total nitrogen from the temperate regions of the North Atlantic basin are correlated with population density, as has been observed previously for fluxes of nitrate in the world's major rivers. However, more striking is a strong linear correlation between river fluxes of total nitrogen and the sum of anthropogenically-derived nitrogen inputs to the temperate regions (fertilizer application, human-induced increases in atmospheric deposition of oxidized forms of nitrogen, fixation by leguminous crops, and the import/export of nitrogen in agricultural products). On average, regional nitrogen fluxes in rivers are only 25% of these anthropogenically derived nitrogen inputs. Denitrification in wetlands and aquatic ecosystems is probably the dominant sink, with storage in forests perhaps also of importance. Storage of nitrogen in groundwater, although of importance in some localities, is a very small sink for nitrogen inputs in all regions. Agricultural sources of nitrogen dominate inputs in many regions, particularly the Mississippi basin and the North Sea drainages. Deposition of oxidized nitrogen, primarily of industrial origin, is the major control over river nitrogen export in some regions such as the northeastern U.S.

Using data from relatively pristine areas as an index of change, we estimate that riverine nitrogen fluxes in many of the temperate regions have increased from pre-industrial times by 2 to 20 fold, although some regions such as northern Canada are relatively unchanged. Fluxes from the most disturbed region, the North Sea drainages, have increased by 6 to 20 fold. Fluxes from the Amazon basin are also at least 2 to 5 fold greater than estimated fluxes from undisturbed temperate-zone regions, despite low population density and low inputs of anthropogenic nitrogen to the region. This suggests that natural riverine nitrogen fluxes in the tropics may be significantly greater than in the temperate zone. However, deforestation may be contributing to the tropical fluxes. In either case, projected increases in fertilizer use and atmospheric deposition in the coming decades are likely to cause dramatic increases in nitrogen loading to many tropical river systems.

Introduction

Human activity has greatly altered the nitrogen cycle on land, in aquatic systems, and in the atmosphere (Berner & Berner 1987; Galloway et al. 1995). Currently, global fixation of atmospheric N_2 for fertilizer, in combustion of fossil fuels, and by leguminous crops exceeds that by all natural sources, and changes in land use cause large additional amounts of nitrogen to be released from long-term reservoirs in both vegetation and soil (Vitousek 1994). These disturbances have been linked to a number of environmental concerns, including coastal eutrophication (Howarth 1988; Nixon 1992, 1995; National Research Council 1993; Gabric & Bell 1993; Paerl 1993; Justic et al. 1995; Rabalais et al., in press), acidification of freshwater lakes and streams (Driscoll et al. 1987; Henriksen & Brakke 1988; Kelly et al. 1990; Murdoch & Stoddard 1992), forest decline (Schulze 1989), climate change (Keller et al. 1986; Khalil & Rasmussen, 1992; Vitousek & Matson 1993), and shifts in community structure (Tilman 1984; Crabtree & Bazzaz 1993; Bowman et al. 1995) and in ecosystem function (McNulty et al. 1991; Aber et al. 1993; Burton et al. 1993; Neff et al. 1994). Accelerated nitrogen cycling has also been suggested to increase the sequestration of carbon in forests, slowing the rise of atmospheric carbon dioxide (Schindler & Bayley 1993). However, gaps in our understanding of nitrogen dynamics over large spatial scales often limit our ability to clearly identify the areas of greatest concern, and to predict the response of systems to future change.

The foundations of ecosystem ecology and biogeochemistry are based in part on studies of small-scale watersheds. Much less attention has been given to evaluating material fluxes through the landscape at larger scales, and we are only beginning to understand the rules that govern regional exchanges of nitrogen between atmospheric, terrestrial and aquatic systems. These exchanges may be especially crucial to the functioning of freshwater and coastal ecosystems, as even relatively small changes in the processing and retention of nitrogen applied to the terrestrial landscape could have a large impact on the downstream aquatic environment. In fact, several studies have noted much greater fluxes of nitrate in rivers over the past few decades. Nitrate concentrations in the Mississippi River have more than doubled since 1965 (Turner & Rabalais 1991; Justic et al. 1995; Rabalais et al., in press), and Pacés (1982) estimated that nitrate in many European rivers has probably increased 5- to 10-fold since the turn of the century. Such increases are presumably in response to increased use of nitrogen fertilizer, cultivation of nitrogen-fixing crops, greater population density, and increased atmospheric deposition of nitrogen. Total nitrogen fluxes have also probably increased, but historical data on total nitrogen in rivers are extremely rare.

Our overall objective in this study was to estimate total nitrogen export (TN) in all of the major rivers draining into the North Atlantic Ocean, to assess how much that export has changed since pre-industrial times, and to identify the principal agents of that change. The work presented here is part of a larger collaborative effort to assemble a nitrogen budget for all components of the North Atlantic region: atmosphere, watersheds, coastal systems, and the open ocean. Although the focus of the paper is on nitrogen, estimates of phosphorus (TP) are also developed because of the potentially valuable information provided by considering N:P ratios. In some cases, we have had to extrapolate estimates based on fluxes of organic carbon or other indirect approaches, but most of our estimates are derived from direct data on water fluxes and concentration of TN and TP (including dissolved and particulate inorganic and organic forms). These data are summarized by dividing the total study area into 14 major watershed regions. In addition to the estimates of TN and TP export by rivers, we present data on population density, sewage and wastewater inputs, fertilizer application, atmospheric deposition, fixation of nitrogen by leguminous crops, and the net import or export of nitrogen in agricultural products.

We chose the North Atlantic region for several reasons. One, when all components of the region are considered, it is probably the best studied area on the planet, and we therefore had the best chance to derive a reasonably accurate nitrogen budget for an entire ocean basin. In discussing transport of C, N, and P in the world's rivers, Meybeck (1982) notes that "it is very difficult to get information on more than half the river water discharging to the ocean" as a whole, and fewer data are available for TN than for C and P. However, for the North Atlantic Basin, we have direct data for TN fluxes in the majority of watersheds representing approximately 80% of the total freshwater discharge. Two, much of the region has been and continues to be significantly affected by human activity, and we wished to assess the impacts of such activity on regional-scale biogeochemistry. Finally, the region is comprised of a great diversity of environments, thereby allowing comparisons of many of the world's major biome types within the confines of our study boundaries.

Regional boundaries and data sources

We divide the watersheds which flow into the North Atlantic Ocean into 14 regions (Figure 1; Table 1). Seven of these regions are in North America, 2 are in Central and South America, 4 are in Europe, and one is in Africa. Regions are selected to coincide with discrete portions of the coastal ocean. The definition of the size and boundaries of regions is dictated in part by the availability of data and by previous studies. All estimates reported here are at the scale of these large regions, although estimates for many of the regions are calculated by summing fluxes for watersheds and smaller areas within the regions. Most nutrient flux estimates are for average periods during the 1980's, although estimates for a few regions are based on late 1970's data. We have explicitly not considered inputs from land into the Mediterranean Sea; net nitrogen fluxes between the Mediterranean and the Atlantic Ocean proper are addressed by the oceanic working group (Michaels et al., this volume).

North Canadian rivers

The "north Canadian rivers" region is defined to be all drainages into Hudson Bay plus the drainages which flow into the Atlantic from Labrador and Newfoundland; this is a large area which includes 40% of Canada (Laycock 1987). Data for area, population, and freshwater discharges are all from Laycock (1987). Annual fluxes of total nitrogen (TN) and total phosphorus (TP) from this region are estimated as the product of the average TN and TP concentrations in 6 rivers in the region (17 μM N and 0.44 μM P; Paré & Goulet 1980; Schetagne 1981; Schetagne & Roy 1985) and annual water discharge to Hudson Bay and coastal discharges of streams and rivers in Labrador and Newfoundland (Laycock 1987).

St. Lawrence

The "St. Lawrence" region includes the drainage basins of the Great Lakes (van der Leeden et al. 1990) plus areas of Canada labeled by Laycock (1987) as "St. John-St. Croix," "maritime coastal," and "North Shore-Gaspé." The area of this region is calculated from information in Laycock (1987) and van der Leeden (1975). Freshwater discharge is the sum of discharge for the St. Lawrence River (Pocklington & Tan 1987) and regional discharge from the

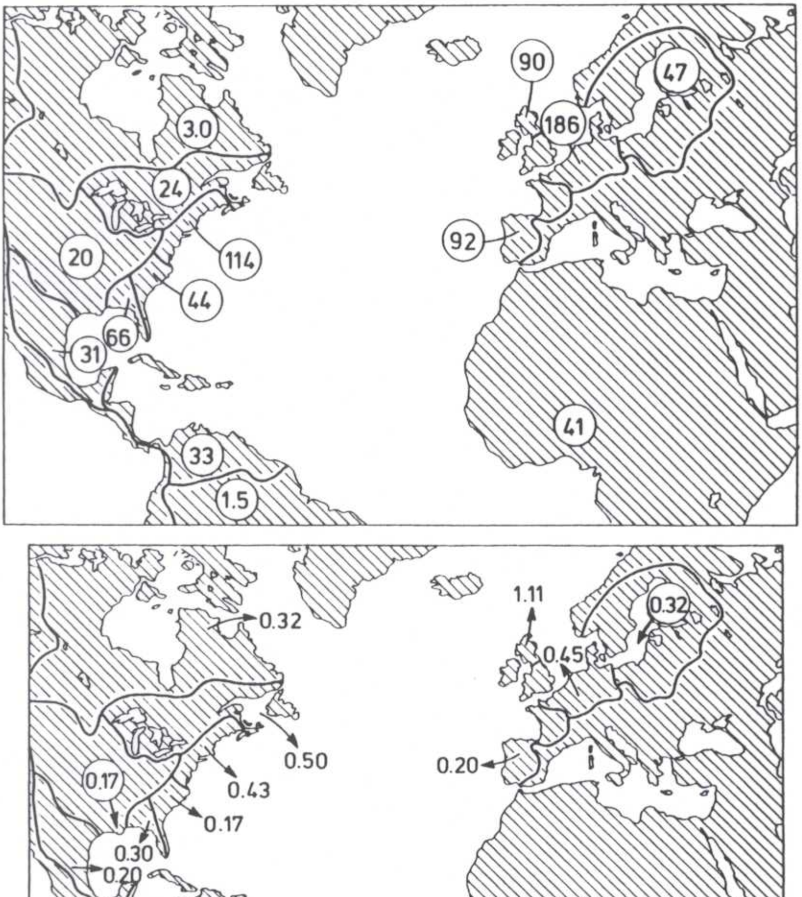

Figure 1. Population density of each of the 14 regions in individuals per km^2 (top, a), and water discharge per area in m^3 m^{-2} yr^{-1} (bottom, b).

St. John-St. Croix, maritime coastal, and North Shore-Gaspé areas (Laycock 1987). Population for the St. Lawrence region is estimated by summing the population of the St. John-St. Croix, maritime coastal, and North Shore-Gaspé areas (Laycock 1987) and the St. Lawrence and Great Lakes basins; population in the St. Lawrence and Great Lakes basins is the product of land