005/94A

HHF HOW 1.13

Nutrient Cycling in Agroecosystems **52:** 213–223, 1998.

An assessment of human influences on fluxes of nitrogen from the terrestrial landscape to the estuaries and continental shelves of the North Atlantic Ocean

Robert W. Howarth
Program in Biogeochemistry & Environmental Change, E309 Corson Hall, Cornell University, Ithaca, NY 14853, USA

Key words: atmospheric deposition, coastal eutrophication, denitrification, fertilizer, nitrogen, nitrogen budgets, regional biogeochemistry, sewage

Abstract

Our analysis for the International SCOPE Nitrogen Project shows that the fluxes of nitrogen in rivers to the coast of the North Atlantic Ocean vary markedly among regions, with the lowest fluxes found in northern Canada (76 kg N km^{-2} yr^{-1}) and the highest fluxes found in the watersheds of the North Sea (1450 kg N km^{-2} yr^{-1}). Non-point sources of nitrogen dominate the flux in all regions. The flux of nitrogen from the various regions surrounding the North Atlantic is correlated (r^2 = 0.73) with human-controlled inputs of nitrogen to the regions (defined as net inputs of nitrogen in food, nitrogen fertilizer, nitrogen fixation by agricultural crops, and atmospheric deposition of oxidized nitrogen), and human activity has clearly increased these nitrogen flows in rivers. On average, only 20% of the human-controlled inputs of nitrogen to a region are exported to the ocean in riverine flows; the majority (80%) of these regional nitrogen inputs is stored in the landscape or denitrified. Of all the nitrogen inputs to regions, atmospheric deposition of NO_y is the best predictor of riverine export of nitrogen from non-point sources (r^2 = 0.81). Atmospheric deposition of this oxidized nitrogen, most of which derives from fossil-fuel combustion, may be more mobile in the landscape than are regional inputs of nitrogen from fertilizer, nitrogen fixation in agriculture, and nitrogen in foods and feedstocks. Agricultural sources of nitrogen, although larger total inputs to most temperate regions surrounding the North Atlantic Ocean, appear to be more tightly held in the landscape. Deposition of ammonium from the atmosphere appears to be a very good surrogate measure of the leakiness of nitrogen from agricultural sources to surface waters. This suggests a management approach for controlling 'surplus' nitrogen used in agricultural systems. The sum of NO_y and ammonium deposition proves to be an amazingly powerful predictor of nitrogen fluxes from non-point sources to the coastal North Atlantic Ocean for temperate-zone regions (r^2 = 0.92; p = 0.001). By comparing fluxes with some estimates of what occurs in watersheds with minimal human impact, it appears that human activity has increased riverine nitrogen inputs to the ocean by some 11-fold in the North Sea region, by 6-fold for all of Europe, and by 3-fold for all of North America. These increased flows of nitrogen have clearly led to severe eutrophication in many estuaries, and have probably contributed to some eutrophication on the continental shelf in the North Sea and in the Gulf of Mexico. In other regions, however, the input of nitrogen to continental shelves is dominated by cross-shelf advection from deep-Atlantic waters, and the increased inputs from rivers are relatively minor.

Introduction

Human activity has greatly altered the cycle of nitrogen on land and in the atmosphere and has caused at least a doubling in the rate of fixation of molecular N_2 into biologically available forms of nitrogen over natural biological rates (Galloway et al., 1995; Vitousek et al., 1997). The increase in nitrogen fixation is particularly dramatic over the past few decades, and the rate continues to climb exponentially (Vitousek et al., 1997). Nitrogen regulates primary productivity in many terrestrial and marine ecosystems (Vitousek and Howarth, 1991), and the global increase in nitrogen cycling has led to an increase in productivity with concomitant loss of biological diversity and resources in many of these ecosystems where nitrogen availability was formerly low (Berendse et al., 1993; Howarth, 1993; Tilman, 1987; Vitousek et al., 1997). Increased nitrogen cycling has also acidified soils and surface waters, contributed to the loss of soil nutrients in some ecosystems, and contributed to changes in atmospheric chemistry linked to global warming and smog formation (Vitousek et al., 1997).

One of the best documented problems from accelerated nitrogen cycling is the eutrophication of estuaries and coastal seas (Howarth, 1993; Justic et al., 1995; Nixon, 1995; Nixon et al., 1996). A recent report from the US National Academy of Sciences concluded that ‘perhaps the most pressing problem in many estuarine and marine systems today is that of nutrient enrichment’ leading to eutrophication (Boland et al., 1993, p. 54). Eutrophication in coastal waters has led to increased anoxia and hypoxia, loss of seagrasses and macroalgal beds, alteration of foodwebs, loss of biological diversity, and increased incidences of nuisance algal blooms (Howarth, 1993; Nixon, 1995). While not all estuarine systems are nitrogen limited, nitrogen availability does regulate primary production in many estuaries and coastal seas (Downing, 1997; Howarth, 1988; Howarth et al., 1995; Nixon et al., 1996). Understanding the controls on nitrogen inputs to these systems is essential if coastal eutrophication is to be better managed.

The International SCOPE Nitrogen Project was established to assess how humans have altered the nitrogen cycle at regional and global scales, and to determine the consequences of this alteration. The first activity of the Nitrogen Project was to evaluate the nitrogen cycle of the North Atlantic Ocean (Galloway et al., 1996; Howarth, 1996). Part of this effort was to quantify nitrogen inputs in rivers and sewage to the coast, separately estimating these inputs for 10 major geographical regions surrounding the temperate-zone portion of North Atlantic Ocean (Howarth et al., 1996). Here, I will briefly summarize some of the major findings of that study.

Estimating regional nitrogen fluxes

Table 1. Area, population density, and freshwater discharge for 10 temperate-zone regions surrounding the North Atlantic Ocean. See Howarth et al. (1996) for sources of data

	Drainage area (10^6 km^2)	Population density (individuals km^{-2})	Water discharge (m yr^{-1})
North Canada rivers	3.98	3.0	0.32
St. Lawrence basin	1.60	24.0	0.50
NE coast of US	0.48	114.0	0.43
SE coast of US	0.35	44.0	0.17
Eastern Gulf of Mexico	0.35	66.0	0.30
Mississippi River basin	3.23	20.0	0.17
Baltic Sea drainages	1.50	47.0	0.32
North Sea drainages	0.84	186.0	0.45
NW European coast	0.34	90.0	1.11
SW Eutropean coast	0.55	92.0	0.20

The temperate-zone regions considered in the SCOPE North-Atlantic analysis were the watersheds of the Baltic Sea, the drainages to the North Sea, southwestern Europe (largely Portugal, Spain, and France), northwestern Europe (western Norway, Ireland and part of the United Kingdom), the drainages to Hudson’s Bay and the northeastern shore of Labrador (‘north Canadian rivers’), the Great Lakes and St. Lawrence River basin, the northeastern US from Maine through Chesapeake Bay, the southeastern US watersheds from Virginia through Florida which drain east into the North Atlantic, the watersheds of the southeastern US which drain into the Gulf of Mexico (‘eastern Gulf of Mexico’) and the Mississippi River basin. Further information on these regions and their boundaries is presented by Howarth et al. (1996). These regions vary in population density from a low of 3 individuals per km^2 in the watersheds of Hudson’s Bay to a high of 186 for the North Sea region (Table 1). Annual water discharge varies from 0.17 m for the southeastern U.S. and for the Mississippi River basin to 1.1 m for northwestern Europe (Table 1).

In estimating nitrogen exports from these regions, the SCOPE Nitrogen Project used the best available data for each region rather than use a consistent, uniform approach. The quality of the estimates vary among regions. Details and most data sources are described by Howarth et al. (1996). The estimate for the Mississippi River basin was derived by multiplying measured total nitrogen concentrations by water discharge estimates (Turner and Rabalais, 1991). For the northeastern coast of the US, the drainages of the North Sea, and for the southwestern coast of Europe, estimates were based on summing flux estimates for each individual river within the region. This approach was also used for the UK portion of northwestern Europe, but the Irish and Norwegian contributions were

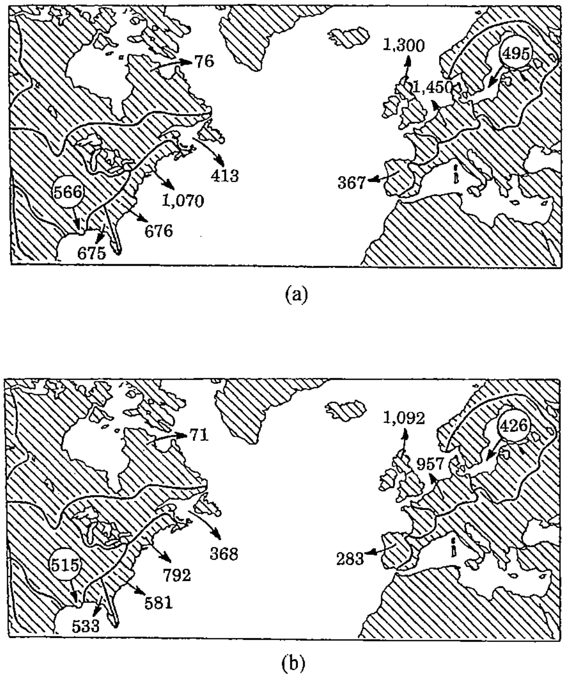


Figure 1. Regional export (per area of watershed) to the coast of total nitrogen in rivers and sewage (top, a) and regional export per area in rivers (per area of watershed) of total nitrogen from non-point sources (bottom, b). Top is modified from Figure 2a of Howarth et al. (1996). Bottom is calculated from data in Howarth et al. (1996). Fluxes are expressed as kg N km^{-2} yr^{-1}.

taken from published estimates for these portions. The estimate for the St. Lawrence basin is the sum of an estimated export from the Great Lakes plus published regional estimates for the drainages into the St. Lawrence river which are downstream of the Great lakes. The estimate for the Baltic Sea is the sum of estimates for municipal, industrial, and riverine inputs into each of the sub-basins of that sea (Larsson et al., 1985). The estimate for northern Canadian rivers is based on a regional hydrologic budget and extrapolation of nitrogen concentrations from 6 watersheds. For the southeastern US, total nitrogen export is taken as the sum of an estimate for regional nitrate flux plus estimates of organic nitrogen export which are extrapolated from a regional estimate for organic carbon export. For most regions, nitrogen export estimates are for average conditions during the 1980s. These estimates for total nitrogen fluxes include all forms of nitrogen, organic as well as inorganic and both dissolved and particulate. Flux estimates per area of watershed are presented in Figure 1a.

The SCOPE Nitrogen Project also estimated the contribution of human sewage to total nitrogen export

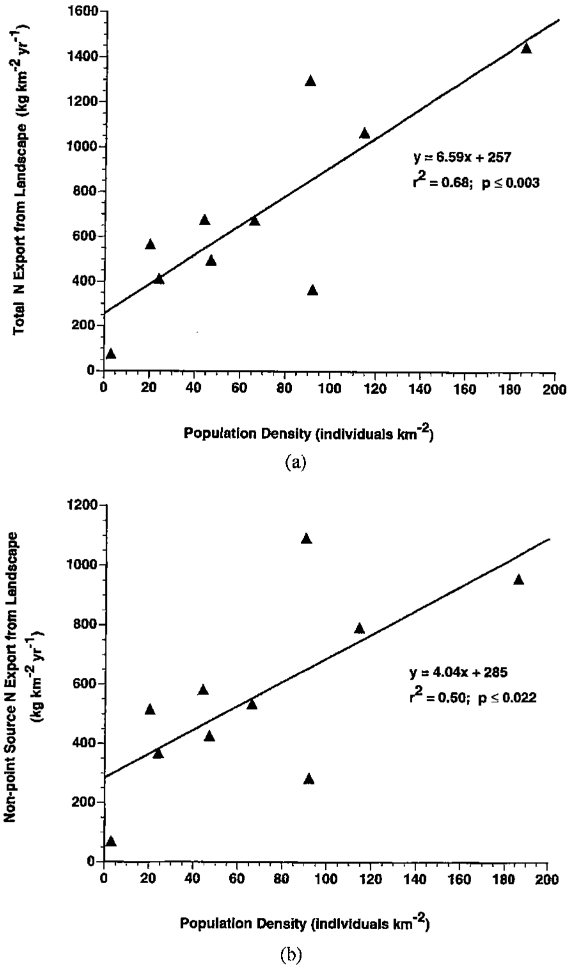


Figure 2. Relationship between the human population density in regions and the total nitrogen export from the landscape to the coast (top, a) and the flux of nitrogen from non-point sources in the landscape to the coast (bottom, b). Nitrogen fluxes are expressed per area of watershed. Each point represents one of the 10 temperate regions which export material to the North Atlantic Ocean.

from each region (Howarth et al., 1996). These estimates were derived from data on what percentage of the population in each region is sewered and an assumed load of 3.3 kg N yr^{-1} per person in sewage (Meybeck et al., 1989). The amount of nitrogen exported from each region which was due to non-point sources can be estimated by subtracting the regional sewage flux from the total nitrogen export for each region (Figure 1b).

Total nitrogen exports vary markedly among the regions (Figure 1a), with the lowest fluxes found in Hudson's Bay (76 kg N km^{-2} yr^{-1}) and the highest fluxes found in the watersheds of the North Sea (1450 kg N km^{-2} yr^{-1}). These regional fluxes of total nitrogen (expressed per area of watershed) are well correlated with population density (Figure 2a; r^2 = 0.68; p = 0.003). In an earlier study for the major rivers of the world, Peierls et al. (1991) reported that nitrate fluxes are correlated with population density (on a log–log plot), and from the slope for this log–log relationship, Cole et al. (1993) concluded that human waste alone was sufficient to explain the correlation. However, for the regions of the North Atlantic Ocean considered in our SCOPE analysis, nitrogen in sewage and wastewater contributes only 15% of the total nitrogen flux overall. For individual regions, human waste contributes as little as 7% of the total nitrogen flux in northern Canadian rivers to as much as 34% for the North Sea (Howarth et al., 1996). In all regions, non-point sources dominate the flux of nitrogen to the coast (compare Figure 1a and 1b). The regional fluxes of nitrogen from non-point sources (per area of watershed) are also correlated with population density (Figure 2a; r^2 = 0.50; p = 0.022). Presumably, this reflects mobilization of nitrogen by human activity beyond just sewage disposal.

Table 2. Inputs to the landscape of nitrogen due to human activity for the 10 temperate-zone regions surrounding the North Atlantic Ocean. Based on Table 4 in Howarth et al. (1996), and reprinted by permission. Fluxes are kg N km^{-2} yr^{-1} (per area of watershed). For the estimate of total nitrogen inputs from human activity, the export of nitrogen in foods and feedstocks (if any) is subtracted from other sources. Direct deposition from the atmosphere to coastal waters is not included in this table

	NO_y deposition	Fertilizer	N fixation by crops	Net import (+) or export in foods	Total
North Canada rivers	70	160	30	-50	210
St. Lawrence basin	610	330	260	-30	1170
NE coast of US	1200	600	750	1000	3550
SE coast of US	1020	1170	370	450	3010
Eastern Gulf of Mexico	760	1260	250	580	2850
Mississippi River basin	620	1840	1060	-1300	2220
Baltic Sea drainages	480	1730	30	20	2220
North Sea drainages	1090	5960	5	-5	7050
NW European coast	1090	2870	50	-320	3700
SW Eutropean coast	460	3370	15	-65	3780

Regional sources of nitrogen and their relation to regional nitrogen export

For each region, the SCOPE Nitrogen Project estimated the inputs of nitrogen due to human activity. The anthropogenic sources of nitrogen considered were the deposition of oxidized nitrogen compounds from the atmosphere (NO_y), use of inorganic nitrogen fertilizer, nitrogen fixation by agricultural crops, and the net movement of nitrogen into or out of a region in food and animal feedstocks (Howarth et al., 1996). We did not consider the deposition of ammonia and ammonium (NH_x) as an input of nitrogen to a region since transport of these species through the atmosphere generally occurs only over fairly short distances (Howarth et al., 1996; Prospero et al., 1996). Thus, we viewed NH_x deposition as a recycling of nitrogen within a region rather than as an additional source of nitrogen to the region. Since NO_y comes largely from the combustion of fossil fuels, its deposition needs to be considered as a regional input of nitrogen. Estimates for NO_y deposition due to human activity were based on the GCTM model and include a subtraction of background natural levels for each region from the estimate of current depositional rate (Howarth et al., 1996; Prospero et al., 1996). For regions in the United States, estimates for nitrogen fertilizer use, movement of nitrogen in food and feedstocks, and nitrogen fixation by agricultural crops are from Jordan and Weller (1996). For the other regions, nitrogen fertilizer use was estimated from Matthews (1994), and estimates for fluxes of nitrogen in foods and for nitrogen fixation in agriculture were based on FAO data and a series of assumptions on nitrogen contents and rates of nitrogen fixation which are detailed by Howarth et al. (1996).

For most regions, inorganic fertilizer is the largest single input of nitrogen (Table 2). However, NO_y deposition dominates in the northeastern US and in the St. Lawrence basin. Surprisingly, these estimates suggest that nitrogen fixation by agricultural crops is a large input of nitrogen for the regions within the US but not for the regions in Europe or for the northern Canadian rivers. Whether this difference is real or is an artifact due to the separate approaches for estimating nitrogen fixation in these regions (see paragraph above) should receive further investigation. Most of the European regions neither import nor export much nitrogen in foods and feedstocks, but several of the regions in the US are large importers of nitrogen in foods, and the Mississippi River basin exports a great deal of nitrogen in foods (Table 2). The total input of nitrogen from human activity varies more than 30-fold among regions, with the lowest being in northern Canada where riverine exports are also lowest and the

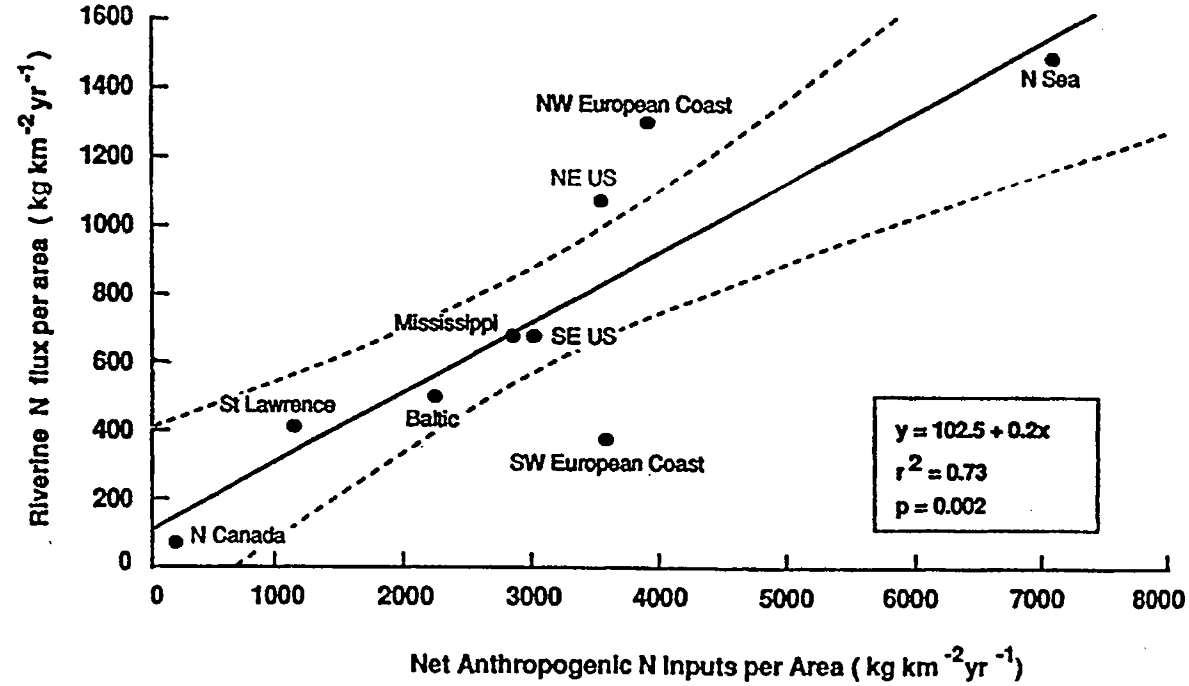


Figure 3. Regression of the sum of net anthropogenic nitrogen inputs per region (from Table 2) vs. regional export of total nitrogen in rivers (from Figure 1a). The dashed lines represent 95% confidence limits. Reprinted by permission from Howarth et al. (1996).

highest being in the North Sea where riverine exports are highest.

That total nitrogen export from regions is indeed related to human inputs of nitrogen to the landscape is confirmed by linear regression (Howarth et al., 1996). When expressed per unit area of watershed, the regional nitrogen export is well correlated with the sum of the human-controlled inputs of nitrogen to the regions (Figure 3; $p = 0.002$; $r^2 = 0.73$). Interestingly, the slope for the relationship is 0.2; that is, on average 20% of the anthropogenic inputs of nitrogen to a region are exported from the region to the North Atlantic Ocean. The percentage exported is somewhat higher than this for the northeastern US and for northwestern Europe and is somewhat lower than this for southwestern Europe.

Fate of human-controlled nitrogen inputs to the landscape

The SCOPE Nitrogen Project attempted to determine the fate of majority of the anthropogenic input of nitrogen (some 80% on average) which is not exported in rivers. It is extremely difficult to estimate nitrogen sinks at the scale of large regions, but the SCOPE analysis generated some tentative conclusions. Although nitrate contamination in groundwater is a severe public health problem in some localized regions, a 'worst-case' estimate for the rate of nitrogen buildup in groundwaters at the regional scale indicated that this could be at most a few percent of the total human-controlled inputs of nitrogen to a region (Howarth et al., 1996). Accumulation of nitrogen in aggrading forests may be a larger sink, but overall less than one quarter of the anthropogenic inputs of nitrogen into the temperate-zone regions surrounding in the North Atlantic Ocean can be thus stored; this conclusion is based on the assumptions that all nitrogen deposited onto forests (whether as NO_y or NH_x) is stored in the forest and that deposition is uniformly distributed in each region so that the percent of total deposition which occurs onto forests can be estimated from the distribution of forests in a region (Howarth et al., 1996). By difference, Howarth et al., (1996) concluded that most of the anthropogenic nitrogen inputs to the regions of the North Atlantic basin must be denitrified within the region. It may also be possible that some nitrogen is accumulating in agricultural soils (van Breemen, personal communication).

Howarth et al. (1996) proposed that the largest denitrification sinks in the landscape may be the anoxic

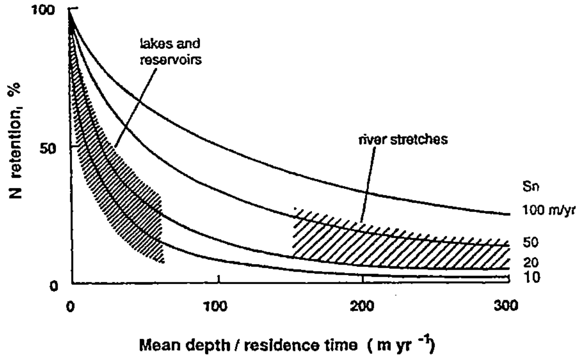


Figure 4. A model of nitrogen retention by surface waters as a function of the mean depth of the water and the residence time of the water body. Nitrogen retention is largely a result of denitrification. The model was originated by Kelly et al. (1987) for unstratified lakes and was extended to flowing waters by Howarth et al. (1996). S_n is a mass transfer coefficient depending upon benthic denitrifying activity and water column nitrate concentrations. Reprinted by permission from Howarth et al. (1996).

sediments of wetlands, lakes, and rivers. Kelly et al. (1987) demonstrated that nitrogen retention by lakes, which is largely due to denitrification, can be predicted from the mean depth and water residence time of the lake; longer residence times and shallower depths result in more retention, presumably because there is more contact time between nitrogen in the water column and the site of denitrification in the sediments. Howarth et al., (1996) showed that this model could also be applied to rivers and streams to predict denitrification (Figure 4). Interestingly, the same relationship of an inverse relationship between the ratio of depth to residence time and the percent nitrogen retained in a system well explains nitrogen retention in estuaries (Nixon et al., 1996). Using this model, Howarth et al., (1996) suggested that on average from 5% to 20% of the total anthropogenic nitrogen inputs to the regions of the North Atlantic Ocean might be denitrified in streams and rivers, and that probably somewhat less than another 20% of these inputs might be denitrified in lakes and reservoirs. This suggests that substantial denitrification or nitrogen storage must also occur elsewhere in the landscape. Many studies have demonstrated that wetlands can denitrify up to 90% of the nitrogen which enters them, and wetlands may well be the major sink of nitrogen in the landscape. However, the amount of nitrogen denitrified in wetlands varies with local physiographical and hydrological conditions and it has not yet proven possible to estimate denitrification in wetlands at the scale of large regions (Howarth et al., 1996). Although not previously considered in the SCOPE analysis, the role of denitrification in agricultural soils and other non-wetland soils should also be considered. At present, the fate of the majority of nitrogen added to the landscape by human activity remains poorly known.

Predictors of regional nitrogen exports from non-point sources

For most of the temperate regions surrounding the North Atlantic Ocean, nitrogen fertilizer is the single largest source of nitrogen to the region. In only two regions, the St. Lawrence/Great Lakes basin and the northeastern US, is atmospheric deposition of NO_y a larger input. Leaching of nitrogen fertilizer is a widely discussed environmental problem, and this if often assumed to be the largest non-point source contributor to nitrogen pollution in rivers (Seitzinger and Kroeze, this volume). Surprisingly, though, atmospheric deposition of NO_y is a better predictor than is nitrogen fertilizer use in predicting the flux of nitrogen from non-point sources in the landscape to the coast of the North Atlantic Ocean. In fact, nitrogen fertilizer use is not significantly related to non-point source nitrogen fluxes for the regions of the North Atlantic (Figure 5a; $r^2 = 0.28$; $p = 0.12$), while anthropogenic NO_y deposition powerfully predicts these fluxes to the coast (Figure 5b; $r^2 = 0.81$; $p = 0.0004$).

Using a best-fit multiple regression analysis, the SCOPE analysis suggested that NO_y deposition was weighted 7-fold more heavily than agricultural nitrogen terms as predictors of riverine nitrogen export from the North Atlantic regions (Howarth et al., 1996). This is consistent with the analysis shown here for linear relationships between NO_y deposition or nitrogen fertilizer use and non-point source nitrogen export from the landscape: the slope for the regression with NO_y deposition as the independent variable is 8-fold greater than the slope for the regression with nitrogen fertilizer as the independent variable.

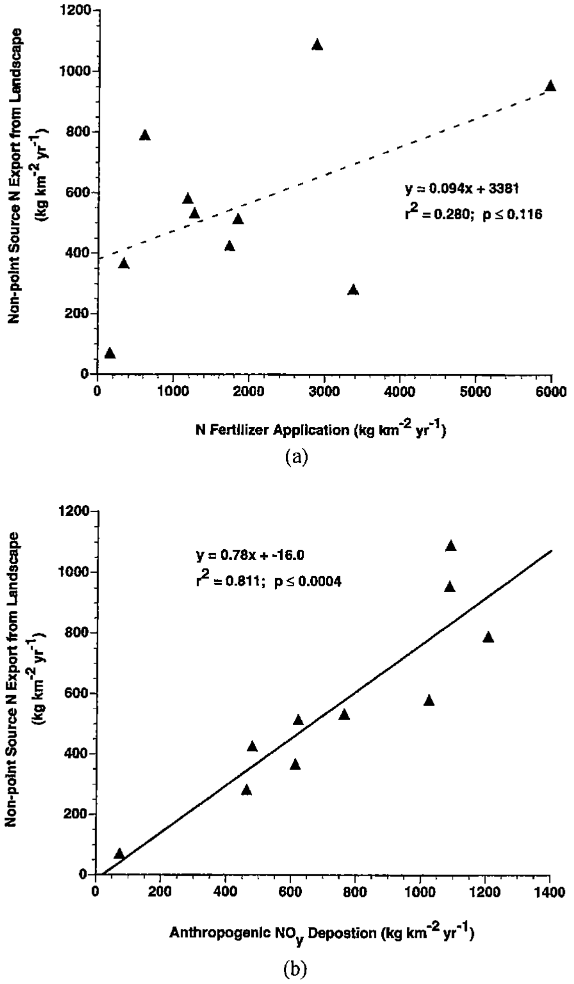
Non-point source N export=0.78 (anthropogenic NO_y deposition)-16.

(S.E. of slope = 0.13; S.E. of intercept = 108; residual S.E. = 143)

Non-point source N export = 0.094 (nitrogen fertilizer) + 380.

(S.E. of slope = 0.053; S.E. of intercept = 135; residual S.E. = 280)

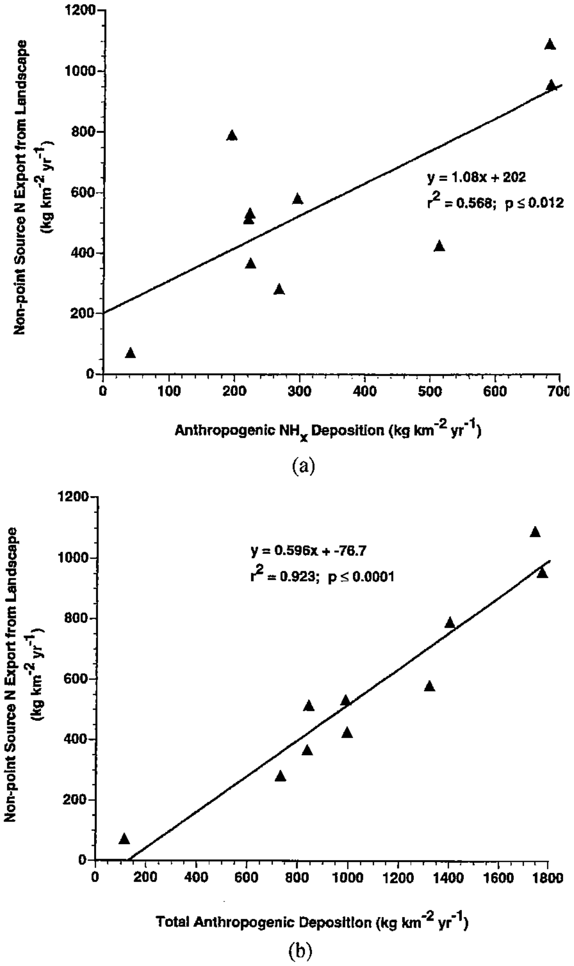
These relationships suggest that a much larger percentage of nitrogen added to the landscape as NO_y deposition is exported in rivers than is true for the application of nitrogen fertilizer. This strongly suggests



(a)

(b)

Figure 5. Relationship between nitrogen fertilizer application and the flux of nitrogen from non-point sources in the landscape to the coast (top, a) and the relationship between anthropogenic NO$_y$ deposition and the flux of nitrogen from non-point sources in the landscape to the coast (bottom, b). Each point represents one of the 10 temperate regions which export material to the North Atlantic Ocean. All values are per area of watershed.



(a)

(b)

Figure 6. Relationship between anthropogenic NH$_x$ deposition and the flux of nitrogen from non-point sources in the landscape to the coast (top, a) and the relationship between total anthropogenic deposition and the flux of nitrogen from non-point sources in the landscape to the coast (bottom, b). Each point represents one of the 10 temperate regions which export material to the North Atlantic Ocean. Total anthropogenic deposition includes estimates for wet and dry atmospheric deposition of oxidized and reduced forms of nitrogen from human-controlled sources. All values are per area of watershed.

the need to better control nitrogen emissions from the combustion of fossil fuels.

As noted above, NH$_x$ deposition at the scale of large regions is largely due to recycling of nitrogen from agricultural sources within a region. Consequently, in the SCOPE analysis, Howarth et al. (1996) did not consider NH$_x$ deposition as a nitrogen source to the region so as to avoid double accounting of inputs. Nonetheless, NH$_x$ deposition may contribute significantly to nitrogen export from a region as it recycles nitrogen inputs from agricultural sources through the atmosphere. In fact, anthropogenic NH$_x$ deposition is well correlated with the export of nitrogen from non-point sources to the coast for the regions surrounding the North Atlantic Ocean (Figure 6a; $r^2 = 0.57$; $p = 0.012$). The slope of this regression is approximately 1 (1.08; S.E. = 0.33). Note, however, that this does not necessarily imply that all ammonium deposited from the atmosphere is exported to the coast in rivers. An alternative and probably more accurate interpretation is that ammonium deposition, at the scale of large regions, is a good surrogate measure for leakage of nitrogen from agricultural systems. In well managed agricultural systems, nitrogen fertilizer is applied at the time of crop need and not in excess of crop need. However, increasingly in the developed countries, nitrogen is supplied in excess, and excess nitrogen accumulates dramatically in animal feedlots (Bleken and Bakken, 1997; Isermann and Isermann, 1997). The resulting surplus nitrogen both leaches to surface waters and volatilizes to the atmosphere as ammonia. NH_x deposition may be a good surrogate, integrative measure of this leakage of agricultural nitrogen.

The sum of anthropogenically controlled deposition, both NH_x and NO_y (wet and dry), is amazingly well correlated with the export of nitrogen from non-point sources from the 10 temperate regions surrounding the North Atlantic Ocean (Figure 6b; $r^2 = 0.93$; $p = 0.001$). My best interpretation of this surprisingly strong relationship is that both NO_y deposition (with most of this nitrogen coming from fossil fuel combustion) and agricultural sources of nitrogen are major contributors to non-point source nitrogen pollution of surface waters, with NH_x deposition being an excellent surrogate measure of the leakiness of surplus nitrogen from agricultural systems in the temperate regions of the North Atlantic basin. A priority for future analysis by the SCOPE Nitrogen Project is to determine whether or not other regions of the world fit this pattern.

Extent of human alteration of regional nitrogen exports to the coast

The regression of human-controlled inputs of nitrogen to regions vs. riverine nitrogen export from the regions (Figure 3) demonstrates that humans have had a large influence on nitrogen inputs to the coastal zone of the North Atlantic Ocean. The intercept of this regression, approximately 100 kg N km^{-2} yr^{-1} (Figure 3), is far lower than the current flux of nitrogen from all of the regions except northern Canada. However, the intercept is not precisely predicted by the regression and so cannot be used to estimate the extent of human perturbation of nitrogen cycling with any precision; the 95% confidence limit for the intercept extends up to 400 kg N km^{-2} yr^{-1} (Figure 3).

The analysis of the SCOPE Nitrogen Project used another approach to attempt to quantify the extent of human influence on nitrogen export from the regions of the North Atlantic basin: comparison with current fluxes from ecosystems and regions which are relatively undisturbed by humans. The reference systems chosen included the estimate for the current modern flux from northern Canadian rivers (Figure 1a), historical data from the late 1880s for the Connecticut River in the northeastern US, the current flux for the Mackenzie and Lena Rivers, and the export from an old-growth forest in Oregon (USA) which receives relatively little atmospheric deposition (Howarth et al., 1996). These systems provide a range of exports of nitrogen export from 76 kg N km^{-2} yr^{-1} to 230 kg N km^{-2} yr^{-1}. This variation may be due to differences in water residence time, precipitation and discharge, non-steady-state behaviors, and other factors discussed by Howarth et al. (1996). The mean value for these reference systems, 133 kg N km^{-2} yr^{-1}, is quite close to the intercept of the regression shown in Figure 3, 103 kg N km^{-2} yr^{-1}.

In comparison with the mean value for nitrogen export from relatively pristine reference systems, Howarth et al. (1996) estimated that human activity has had little or no influence in northern Canada but may have increased nitrogen export to the North Sea by 11-fold and to the northeast coast of the US by 8-fold (Table 3). The estimate of a 3.7-fold increase in riverine inputs to the Baltic Sea agrees remarkably well with an independent assessment by Larsson et al. (1985) of a 4-fold increase due to human activities. For all of the European regions and all of the North American regions considered here, human activity appears to have increased nitrogen inputs to the coast in rivers

Table 3. Estimated percent increase in riverine nitrogen export from the temperate regions of the North Atlantic basin due to human activity. As described in the text, the mean value of nitrogen export from four relatively pristine systems (133 kg N km^{-2} yr^{-1}), is used as the baseline for pristine conditions. For the northern Canadian rivers system, the estimate for current modern flux is less than this assumed pristine baseline, so the percent increase due to human activity is assumed to be zero. Data are from Howarth et al. (1996)

	Percent increase in regional riverine nitrogen export due to human activity
North Canada rivers	0%
St. Lawrence basin	310%
NE coast of US	800%
SE coast of US	510%
Eastern Gulf of Mexico	510%
Mississippi River basin	425%
Total for North American regions	280%
Baltic Sea drainages	370%
North Sea drainages	1100%
NW European coast	980%
SW Eutropean coast	275%
Total for European regions	600%

by 6-fold and 3-fold, respectively (Table 3). There is obviously great uncertainty in setting the baseline for this analysis of change from pristine conditions, but these estimates of change certainly seem reasonable to within a factor of two (Howarth et al., 1996).

Contribution of land-derived nitrogen sources to eutrophication in estuaries and on the continental shelves

Much of the input of nitrogen from rivers to the coastal ocean is funneled through estuaries, and the increased flows due to human activity have undoubtedly increased primary production and eutrophication in many estuaries of the North Atlantic basin. Using data from a variety of marine and estuarine ecosystems, Nixon et al. (1996) found primary productivity to be related to the input of dissolved inorganic nitrogen (DIN) according the following equation ($r^2 = 0.93$):

$$\log \text{Primary Production} = 0.442 \log \text{DIN} + 2.332$$

Assuming that the increases in total nitrogen flux to the coast are proportional to increases in the loading of DIN, this equation and our assessment of how human activity has increased riverine nitrogen fluxes suggests that primary productivity has increased on average by 1.8-fold for the Baltic Sea, by 2.5-fold for the estuaries of the northeastern US, and by 2.8-fold for the estuaries of the North Sea. Of course, the increased loadings to some estuaries within each region have been greater than the average increases for the region.

Much of the nitrogen input to estuaries is consumed by denitrification within the estuaries (Nixon et al., 1996), but some passes through to the continental shelves. For some major river flows, such as the Mississippi River, consumption in the estuary is small and most of the nitrogen is injected directly onto the continental shelves. As part of the analysis of the SCOPE Nitrogen Project, Nixon et al. (1996) estimated how much of the regional river fluxes of nitrogen actually reach the continental shelves; they also estimated direct deposition of nitrogen from the atmosphere onto the waters of the continental shelves (using data from Prospero et al., 1996) and the flux of nitrate from deep North Atlantic waters onto the continental shelves by advection. For most regions, the advection of nitrate from the deep ocean waters is the major source of nitrogen to the continental shelves (Table 4). However, for the Gulf of Mexico, riverine input from the Mississippi River is the major source of nitrogen, and riverine inputs are also an important term for the North Sea and northwestern Europe (Table 4). Direct deposition of nitrogen from the atmosphere onto the continental shelves is a relatively small percentage of nitrogen inputs to the continental shelves for all regions except the North Sea and northwestern Europe.

Table 4. Sources of nitrogen to the continental shelves of the temperate-zone portions of the North Atlantic Ocean. Fluxes are in Tg yr^{-1}. Flux from rivers and estuaries is the direct input of rivers which discharge onto the continental shelf plus the riverine input into estuaries, minus nitrogen consumed in estuaries. Atmospheric deposition estimates in this table are those directly onto the waters of the continental shelf and do not include deposition onto the landscape (which is part of the flux from rivers and estuaries). The flux from the deep ocean represents the advection of nitrate-rich deep Atlantic water onto the continental shelf. Data for modern values are means reported by Nixon et al. (1996). Pristine values (shown in parentheses) are estimated using the same assumptions as outlined by Nixon et al. (1996) for their treatment of modern estimates, but with data for pristine river fluxes from Howarth et al. (1996) and for pristine values of deposition from Prospero et al. (1996). 'Percent increase due to humans' is the comparison of total modern inputs compared to pristine inputs. Fluxes from the deep ocean are assumed not to have been affected by human activities.

	From rivers and estuaries	Direct atmospheric deposition	From deep ocean	Percent increase due to humans
North Canada rivers	0.16 (0.16)	0.10 (0.03)	0.77	7%
St. Lawrence basin	0.34 (0.11)	0.13 (0.01)	1.26	25%
NE coast of US	0.27 (0.03)	0.21 (0.01)	1.54	28%
SE coast of US	0.13 (0.03)	0.06 (0.01)	1.36	11%
Gulf of Mexico	2.10 (0.50)	0.28 (0.03)	0.14	275%
North Sea & NW Europe	0.97 (0.14)	0.64 (0.02)	1.32	98%
SW Eutropean coast	0.11 (0.04)	0.03 (0.001)	0.20	40%

Table 4 also presents estimates for the extent of human influence on total nitrogen inputs to the continental shelves of the temperate North Atlantic ocean. For these estimates, I assume humans have had no effect on advection of nitrate from deep ocean waters. The estimates for inputs from rivers and estuaries are based on values for 'pristine' river fluxes given in Table 3 and the assumptions used by Nixon et al. (1996) for consumption of nitrogen in estuaries and river deltas. Estimates for direct deposition of nitrogen onto the continental shelves (Table 4) are derived from data in Prospero et al. (1996) and Nixon et al. (1996). Not surprisingly, this analysis indicates that human activity has had the greatest influence on nitrogen inputs to the continental shelves in the Gulf of Mexico where advection of nitrate from deep ocean waters is the smallest (Table 4). In the Gulf of Mexico, human activity may have increased nitrogen inputs on average by 2.8-fold, and thereby perhaps increased eutrophication on the continental shelf itself and not merely in estuaries. From the regression of Nixon et al. (1996) which predicts primary production from DIN inputs, it appears that increased nitrogen inputs from human sources may have increased primary production in the entire Gulf of Mexico by an average of 1.6-fold. Human activity has also had a major influence on nitrogen inputs to the continental shelf of the North Sea and northwestern Europe, perhaps doubling total nitrogen inputs. For most other regions, human-derived sources of nitrogen have had relatively little influence on the continental shelves (Table 4), although they may still contribute to eutrophication in the plumes of some estuaries such as that of the Hudson River. In general, for the coastal North Atlantic Ocean, though, human activity has had a major influence on the continental shelves only where circulation restricts inputs of nitrogen from the deep ocean (the Gulf of Mexico) and where human activity has had the greatest effect on increased riverine fluxes and atmospheric deposition (the North Sea and northwestern Europe).

Acknowledgements

This paper summarizes the work of many individuals who contributed to the assessment by the International SCOPE Nitrogen Project of nitrogen cycling in the North Atlantic basin. I particularly wish to thank John Freney, the co-chair of the International SCOPE Nitrogen Project, and Jim Galloway, the co-chair of the SCOPE workshop on nitrogen cycling in the North Atlantic basin. Norb Jaworski, Alan Townsend, Dennis Swaney, Gilles Billen, Kate Lajtha, and Ragnar Elmgren contributed greatly to the portion of that workshop assessing regional nitrogen fluxes from land. This manuscript also relies heavily on materials from working groups chaired by Scott Nixon and Joe Prospero on the fate of nitrogen at the land-sea margin and on nitrogen transfers through the atmosphere. The Mellon Foundation has provided core support for the SCOPE Nitrogen Project and for the preparation of this manuscript. Roxanne Marino and Kristin Kolberg assisted with the preparation of figures and with statistical analyses. Steve Carpenter, Roxanne Marino, and two anonymous reviewers provided valuable criticism of an earlier draft of this manuscript.

References

Berendse F, Aerts R & Bobbink R (1993) Atmospheric nitrogen deposition and its impact on terrestrial ecosystems. In: Vos CC & Opdam P (eds) Landscape Ecology of a Stressed Environment, pp 104–121. Chapman and Hall, London

Bleken MA & Bakken LR (1997) The nitrogen cost of food production: Norwegian society. Ambio 26: 134–142

Boland JJ, Anderson BP, Brooks NH, Eichbaum WM, Goldman LR, Harleman DRG, Howarth RW, Hugget RJ, Keinath TM, Mearns AJ, O'Melia CR, Roesner LA, Rose JB & Schubel JR (1993) Managing Wastewater in Coastal Urban Areas. National Academy Press, Washington, DC

Cole JJ, Peierls BL, Caraco NF & Pace ML (1993) Nitrogen loadings of rivers as a human-driven process. In: McDonnel MJ & Pickett STA (eds) Humans as Components of Ecosystems, pp 141–157. Springer-Verlag, New York

Downing JA (1997) Marine nitrogen:phosphorus stoichiometry and the global N:P cycle. Biogeochem 37: 237–252

Galloway JN, Schlesinger WH, Levy H, Michaels A & Schnorr JL (1995) Nitrogen fixation: Atmospheric enhancement – environmental response. Global Biogeochemical Cycles 9: 235–252

Galloway JN, Howarth RW, Michaels AF, Nixon SW, Prospero JM & Dentener FJ (1996) Nitrogen and phosphorus budgets of the North Atlantic Ocean and its watershed. Biogeochemistry 35: 3–25

Howarth RW (1988) Nutrient limitation of net primary production in marine ecosystems. Ann Rev Ecol & Syst 19: 89–110

Howarth RW (1993) The role of nutrients in coastal waters (Appendix A). In: Boland JJ, Anderson BP, Brooks NH, Eichbaum WM, Goldman LR, Harleman DRG, Howarth RW, Hugget RJ, Keinath TM, Mearns AJ, O'Melia CR, Roesner LA, Rose JB & Schubel JR (eds) Managing Wastewater in Coastal Urban Areas, pp 177–202. National Academy Press, Washington, DC

Howarth RW, Jensen H, Marino R & Postma H (1995) Transport to and processing of P in near-shore and oceanic waters. In: Tiessen H (ed) Phosphorus in the Global Environment: Transfers, Cycles, and Management, pp 323–345. Wiley & Sons, Chichester

Howarth RW (ed) (1996) Nitrogen Cycling in the North Atlantic Ocean and Its Watersheds: Report of the International SCOPE Nitrogen Project. Kluwer, Dordrecht (Reprinted from Biogeochemistry 35: 1–304)

Howarth RW, Billen, G, Swaney D, Townsend A, Jaworski N, Lajtha K, Downing JA, Elmgren R, Caraco N, Jordan T, Berendse F, Freney J, Kudeyarov V, Murdoch P & Zhu Zhao-liang (1996) Regional nitrogen budgets and riverine N & P fluxes for the drainages to the North Atlantic Ocean: Natural and human influences. Biogeochemistry 35: 75–139

Isermann K & Isermann R (1997) Food production and consupption in Germany: N-flows and N-emissions. Nutrien Cycling in Agroecossytems, in press

Jordan TW & Weller DE (1996) Human contributions to terrestrial N flux. BioScience, in press

Justic N, Rabalais NN, Turner R & Dortch Q (1995) Changes in nutrient strucutre of river-dominated coastal waters: Stoichiometric nutrient balance and its consequences. Est Coast Shelf Sci 40: 339–356

Kelly CA, Rudd JWM, Hesslein R H, Schindler DW, Dillon PJ, Driscoll CT, Gherini SA & Hecky RE (1987) Prediction of biological acid neutralization in acid-sensitive lakes. Biogeochemistry 3: 129–141

Larsson U, Elgrem R & Wulff F (1985) Eutrphication and the Baltic Sea: Causes and consequences. Ambio 14: 9–14

Matthews E (1994) Nitrogenous fertilizers: Global distribution of consumption and associated emissions of nitrous oxide and ammonia. Global Biogeochemical Cycles 8: 411–440

Meybeck M, Chapman DV & Helmer R (1989) Global freshwater quality: A first assessment. WHO/UNEP. Blackwell, Cambridge, MA

Nixon SW (1995) Coastal marine eutrophication: A definition, social causes, and future concerns. Ophelia 41: 199–219

Nixon SW, Ammerman JW, Atkinson LP, Berounsky VM, Billen GB, Boichourt WC, Boynton WR, Church TM, DiToro DM, Elmgren R, Garber JH, Giblin AE, Jahnke RA, Owens NJP, Pilson MEQ & Seitzinger SP (1996) The fate of nitrogen and phosphorus and the land-sea margin of the North Atlantic Ocean. Biogeochemistry 35: 141–180

Peierls B, Caraco N, Pace M & Cole J (1991) Human influence on river nitrogen. Nature 350: 386–387

Prospero JM, Barrett K, Church T, Detener F, Duce RA, Galloway J, Levy H, Moody J & Quinn P (1996) Atmospheric deposition of nutrients to the North Atlantic basin. Biogeochemistry 35: 27–73

Tilman D (1987) Secondary succcession and the pattern of plant dominance along experimental nitrogen gradients. Ecol Appl 57: 189–214

Turner RE & Rabalais NN (1991) Changes in Mississippi River water quality this century. BioScience 41: 140–147

Vitousek PM & Howarth RW (1991) Nitrogen limitation on land and in the sea: How can it occur? Biogeochemistry 13: 87–115

Vitousek PM, Aber J, Howarth RW, Likens GE, Matson PA, Schindler DW, Schlesinger WH & Tilman GD (1997) Human alteration of the nitrogen cycle: Causes and consequences. Ecol Appl, in press