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Nitrogen sources to watersheds and estuaries: role of land cover mosaics and losses within watersheds

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"Capsule": *Land cover mosaics on watersheds determine nitrogen loads and eutrophication in receiving estuaries.*

Abstract

Across most of the World's coastal zone there has been a geographic transition from naturally vegetated to human-altered land covers, both agricultural and urban. This transition has increased the nitrogen loads to coastal watersheds, and from watersheds to receiving estuaries. We modeled the nitrogen entering the watershed of Waquoit Bay, Massachusetts, and found that as the transition took place, nitrogen loads to watersheds increased from 1938 to 1990. The relative magnitude of the contribution by wastewater, fertilizers, and atmospheric deposition depends on the land cover mosaics of a watershed. Atmospheric deposition was the major input to the watershed surface during this period, but because of different rates of loss within the watershed, wastewater became the major source of nitrogen flowing from the watershed to the receiving estuaries. Atmospheric deposition prevails in watersheds dominated by natural vegetation such as forests, but wastewater may become a dominant source in watersheds where urbanization increases. Increased nitrogen loads resulting from conversion of natural to human-altered watershed surfaces create eutrophication of receiving waters, with attendant changes in water quality, and marked shifts in the flora and food webs of the affected estuaries. Management efforts for restoration of eutrophied estuaries require maintenance of forested land, and control of wastewater and fertilizer inputs, the major terms in most affected places subject to local management. Wastewater and fertilizer nitrogen derive from within the watershed, which means local measures may effectively be used to control eutrophication of receiving waters. © 2002 Published by Elsevier Science Ltd.

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1. Introduction

It has become evident in recent decades that most terrestrial and aquatic environments are changing under increasing pressure from human activities (Vitousek et al., 1997). The effects of human domination of environments are felt through various mechanisms. Some of these mechanisms involve increased transfer of nutrients from one environment to another, and alterations in the rates of transformations of nutrients within environments. In this paper we center attention on anthropogenic effects on parts of the nitrogen cycle that are critical to the function of the affected watershed and adjoining estuarine systems.

Anthropogenic alterations to the nitrogen cycles of terrestrial environments are important for a plethora of reasons, including perturbation of the species composition of vegetation, alterations of mineralization rates in soils, and changes in leaching rates through nitrogen saturation of forests (Aber et al., 1989, 1995; Nadelhoffer et al., 1995). Similarly, changes in nitrogen cycles lead to significant alterations in aquatic environments. In coastal waters, increased nitrogen supplies stimulate eutrophication in estuaries (Ryther and Dunstan, 1971; Howarth, 1988; Nixon, 1995), lead to loss of valuable seagrass and reef habitats (Bell, 1992; Short and Burdick, 1996; Hauxwell et al., 2001), and affect valuable shell- and fin-fish stocks (Nixon et al., 1986; Heip, 1995). These are by no means an exhaustive list of the consequences of increased nitrogen loadings to natural environments; we cite them merely to provide an idea of the substantive ecological and biogeochemical effects that follow anthropogenic alterations of the nitrogen cycle.

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In response to the recognized importance of nitrogen supplies to natural environments, there has been much effort to prepare budgets of the various nitrogen sources and define transformations and transport in different environments. Increased loading of anthropogenic nitrogen enters specific environments principally through atmospheric deposition, use of fertilizers, and disposal of wastewater. This tri-partite scheme is useful in studies of local sites or watersheds, but it should be evident that in a larger geographical context, nitrogen is ultimately derived from atmospheric sources. Fertilizer nitrogen is fixed industrially from atmospheric nitrogen gas; much of this fixed nitrogen becomes food that people eat and convert to wastewater nitrogen. In practice, however, it has been convenient to separately evaluate the inputs from the three major sources when we deal with specific watersheds. It is useful to know the magnitude of the contributions from each major source for management as well as basic science reasons. For example, we can conceive of managing wastewater and fertilizer use and release to natural environments at a local, single watershed scale, while management of atmospheric nitrogen deliveries has to have a much larger geographical perspective because airsheds are considerably larger in area than watersheds (Dennis, 1995). In this paper we are principally concerned with the dynamics of increased nitrogen loads at the watershed scale, so we consider atmospheric deliveries as the inevitable context in which to assess fertilizer and wastewater inputs.

2. Sources and forms of nitrogen delivery

Atmospheric deposition contributes nitrogen via wet precipitation, and by dry deposition, in approximately equal parts (Voldner et al., 1986; Hinga et al., 1991; Valigura et al., 1996, 1997). Wet deposition includes nitrate, ammonium, dissolved organic, and particulate nitrogen. Dry deposition takes place via direct uptake of NO_x, NH_3, and by impact of particles bearing all forms of nitrogen (Voldner et al., 1986; Russell, 2000).

Fertilizers containing nitrogen are varied, and their use adds nitrate, ammonium, or various forms of organic nitrogen, including urea, to watersheds. Once in soil, microbial transformations convert much of the fertilizer nitrogen to nitrate, which is the form of nitrogen that travels most freely through soils, vadose zones, and aquifers, and is also most readily transported via surface runoff and streams into coastal waters.

Wastewater nitrogen enters natural environments in effluent water from various kinds of disposal systems. These range from the simplest outhouses, to septic systems, and to sewage treatment plants in urbanized areas. Each disposal system has different consequences in terms of interception of nitrogen, magnitude of actual inputs, location of delivery of the wastewater nitrogen, and the array of nitrogen compounds delivered. Wastewater nitrogen is initially in an organic form. Organic nitrogen from wastes can be mineralized to ammonium, which in turn can be nitrified. The effectiveness of the conversion of wastewater-derived organic nitrogen to nitrate differs, depending on the lability of the organic material, and the exposure in the environment into which the organic nitrogen has been released. Assessment of relative lability of DON in different environments is still poorly defined, but it appears that wastewater-derived DON is somewhat more labile than atmospheric- and soil-derived DON (Seitzinger and Sanders, 1997). Duration of exposure in the environment also makes a difference; for example, the deeper the vadose zone under soil that the nitrogen has to traverse, the lower the concentration of dissolved organic carbon (and nitrogen) that survives the passage through the vadose zone (Pabich et al., 2001a; K. Kroeger, unpublished data).

3. Effects of historical changes in land cover mosaics

The relative contribution of nitrogen by atmospheric deposition, fertilizers, and wastewater depends on the specific mosaic of land covers present on a watershed surface. What has been happening world-wide, however, is that there has been a transition within watershed mosaics from naturally vegetated tesserae to human land uses, both agricultural and urbanized. In many areas inland, there has been much transition to agricultural land covers, and hence fertilizer inputs become a major feature of the loading to watersheds and their receiving waters (Correll and Ford, 1982; Jordan and Weller, 1996; Jordan et al., 1997). In coastal areas it is more common to have urban sprawl become increasingly the dominant feature of the land cover mosaic, and for wastewater to become a major nitrogen source. Near the end of the twentieth century, as much as 37% of the worlds population has come to reside within 100 km from shore (Cohen et al., 1997); human populations have increased markedly in the near shore of every estuary around the world (Nixon et al., 1986; Valiela et al., 1992). It necessarily follows that the wastewater released from these increasingly urbanized coastal zones has and will increase. The net result of the geographic land cover transitions, both toward agricultural or urbanized landscapes, has been that, first, nitrogen loads have increased, and that second, the relative contributions from the three major sources—atmospheric deposition, fertilizer use, and wastewater disposal—have changed.

An example of such a geographic transition is evident in work we have done on the historical time course of nitrogen loading to the watershed of Waquoit Bay, Massachusetts, USA. The area of natural vegetation on the watershed of Waquoit Bay diminished about fourfold from 1938 to 1990 (Fig. 1, top). This change was the result of conversion of vegetated land to human uses (Fig. 1, top). In this case the geographic transition was not just an urbanization of the watershed, but of more complex rearrangements of land use categories (Fig. 1, bottom). Turf associated with lawns, parks, and golf courses increased as the number of inhabitants in the area increased. Land devoted to agriculture decreased, while land covered by impervious surfaces (roofs, driveways, roads) associated with urbanization increased.

On the whole, the geographic transition that took place between 1938 and 1990 reduced the land covered by natural vegetation on the watershed of Waquoit Bay from 84 to 68%. The changes in land cover were not uniform: some decades witnessed larger rates of transition. For instance, the conversion of natural vegetation to human used land was particularly marked in the 1940s to 1950s, and again in the 1980s; these were

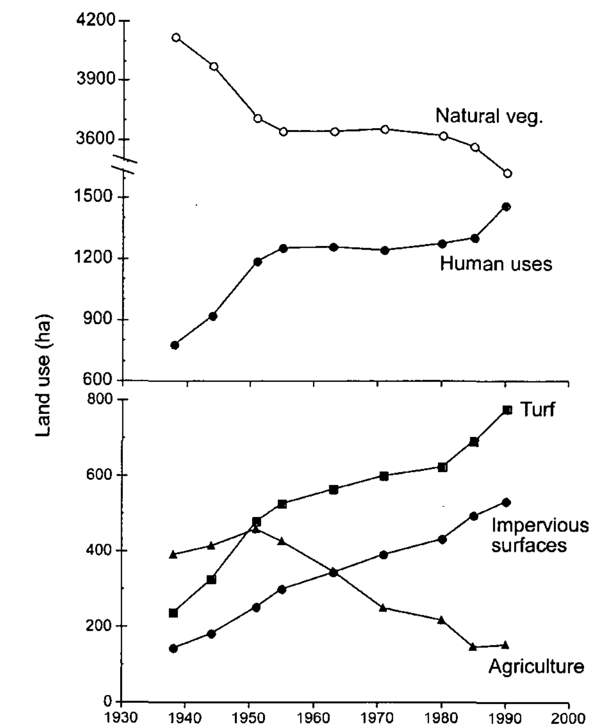

Fig. 1. Changes in the human use of land relative to the changes in natural vegetation (top). Breakdown of human land uses into three major components (bottom): turf (including lawns, parks, and golf courses), impervious surfaces (including roads, roofs, driveways, runways, and parking lots), and agriculture (predominantly horticultural crops and cranberries). We gathered the data for Fig. 1 from aerial photos of the region (our unpublished data), plus a hydrogeological delineation of the watershed (Valiela et al., 1997). The points in the figure show the years for which we found available aerial photography. More detailed descriptions of these data are included in Bowen and Valiela (2001b).

periods when economic and historical trends fostered urban expansion, and therefore increased the area of lawns and other turf associated with additional houses. The time course of agricultural parcels was quite different, with a rise up to the early 1950s, and then a gradual loss as the economy could not sustain the small-farm crops of potatoes and strawberries characteristic of this region. The point to be made about these land cover changes is that land use mosaics show quite different arrays of tesserae, and that, as will be seen below, although no one land cover type was singly responsible, the aggregate result is greater nitrogen loads to receiving waters downgradient.

Knowing the changes in land use in the Waquoit Bay watershed, we set about estimating nitrogen loads across these decades. To calculate the nitrogen loads entering the watershed, we used NLM, a nitrogen loading model we developed (Valiela et al., 1997) and verified (Heberlig et al., 1997; Kroeger et al., 1999; Valiela et al., 2000) to estimate nitrogen contributions via atmospheric deposition, fertilizer use, and by disposal of wastewater by septic systems. We applied the model to each year that we had aerial photographs—and hence land cover data—for the watershed of Waquoit Bay.

NLM (Fig. 2) considers nitrogen inputs from the three major sources into each type of land use (natural vegetation, impervious surfaces, turf, houses, and agriculture), and tracks the fate of the nitrogen from each source as it traverses the various ecosystem components (soil, vadose zone, aquifer). For instance, if in Fig. 2 we follow the fate of fertilizer nitrogen applied to crops, NLM says that 39% of that nitrogen is retained in soils. Of course, atmospheric deposition also contributes to nitrogen entering cropland; NLM says that soils retain 62% of the nitrogen delivered by deposition. NLM then adds the surviving nitrogen from atmospheric deposition and from fertilizer use, and considers that 61% of that sum is intercepted in the unsaturated vadose zone undelying the soils. Then, of the nitrogen that managed to traverse the vadose zone, an additional 35% may be lost during travel through the aquifer. These loss coefficients were arrived at after extensive local research and literature surveys. Valiela et al. (1997, 2000), Lajtha et al. (1995), Seely and Lajtha (1997), Seely et al. (1998), Pabich et al. (2001a, b) provide discussions of the data on which NLM loss coefficients were based, and of the ecological and biogeochemical processes that are involved.

To use NLM to estimate nitrogen loads requires data on atmospheric deposition, fertilizer use, and on land use within the watershed. In previous papers (Valiela et al., 1997, 2000), we used atmospheric deposition data collected during the 1980s and 1990s, and land use data from 1990. For our historical reconstruction of nitrogen loading, however, we needed an estimate of the changes in atmospheric deposition likely to have taken

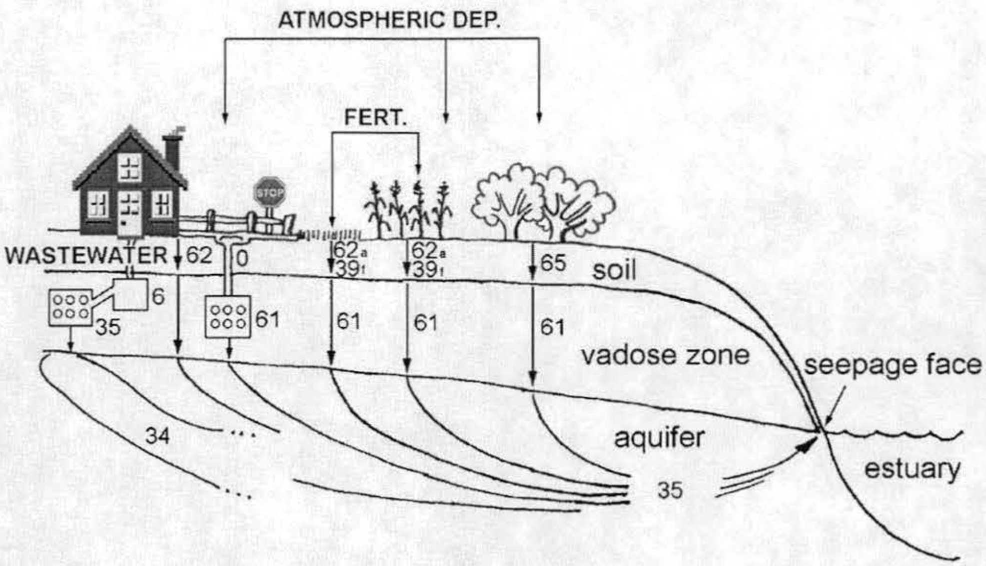

Fig. 2. Schematic of NLM, showing inputs of wastewater-, fertilizer- and atmospheric-derived nitrogen to the watershed, and % losses (shown as numbers) as the nitrogen from each of the three sources is inserted by septic system, or falls on impervious surfaces, turf, agricultural parcels, or vegetated parcels, and then traverses soils, vadose zone, aquifer, and seepage face on its way to receiving estuaries. Taken from Valiela et al. (2000).

place, as well as the changes in land use within the watershed, from 1938 to 1990.

To estimate atmospheric loads to the watershed across the decades of interest we created a spliced record of the deposition of nitrogen (wet and dry, and of nitrate, ammonium, and organic nitrogen), making use of data we collected during earlier studies as well as many records of deposition to a variety of places in the airshed of the Cape Cod region of Massachusetts, including the Northeastern states of the USA, and the Maritime provinces of Canada (Bowen and Valiela, 2001a). This furnished a best estimate of the time course of atmospheric deposition between 1938 and 1990. The literature compilation indicates that NO_3-N in wet deposition to the Massachusetts area increased from 0.9 kg N ha^{-1} $year^{-1}$ in 1925 to approximately 4 kg N ha^{-1} $year^{-1}$ today. During the same period of time NH_4-N in wet deposition decreased from more that 4 kg N ha^{-1} $year^{-1}$ to less than 1.5 kg N ha^{-1} $year^{-1}$. This shift in nitrogen from reduced to oxidized forms could result from a decrease in agriculturally derived NH_3 emissions, and an increase in NO_x emissions from fossil fuel combustion associated with urbanization (Bowen and Valiela, 2001a). After adjusting the wet deposition trend to include dry deposition, and deposition of organic N, the secular trend in total N deposition increased at a rate of 0.26 kg N ha^{-1} per decade over the course of the twentieth century.

To define the changes in land use from 1938 to 1990, we interpreted land covers in aerial photos of the Waquoit Bay watershed taken at intervals during the period of interest (unpublished data). Land covers on watersheds are remarkably complicated; for our purposes, we simplified the land cover classifications into a few major ones (Fig. 2, right to left: natural vegetation, agricultural parcels, turf, impervious surfaces, and also added number of houses). With the simplified compilation of land cover data, plus the atmospheric inputs, NLM could furnish back-estimates of nitrogen loads (Bowen and Valiela, 2001b).

The total nitrogen loads *to the watershed* of Waquoit Bay increased from the 1930s to recent years (Fig. 3, top). The increase in load was particularly marked during the 1960s. Throughout the 50-year period, atmospheric deposition consistently contributed the largest portion of the nitrogen load, with slight increases between 1930 and 1970. The atmospheric supply of nitrogen after 1970 appears to have stabilized, at least in this region. Although the implementation of the Clean Air Act by the US government early in the 1970s did not directly address emissions of nitrogen, the indirect effects of increased fuel efficiency in automobiles and reductions in other pollutants emitted from industrial processes may have prevented further increases in atmospheric nitrogen delivered to the land surface in our area (Fig. 3, top). Fertilizer- and wastewater-derived nitrogen did clearly increase across the 50 years: these sources are mostly responsible for the secular increase in total nitrogen loads to this watershed. In 1938 virtually all the nitrogen delivered to the watershed was by precipitation, but by 1990 (Table 1, first and second columns of numbers), atmospheric sources had dwindled to 56%. Wastewater nitrogen contributions reached 27% of inputs, larger than the 15% contributed by fertilizer use (Table 1; Fig. 3, top), probably owing to reduction of agricultural land, as well as construction of more buildings (Fig. 1, bottom).

4. Losses within watersheds and exports to receiving waters

Nitrogen loads *to estuaries* differ markedly from nitrogen loads to watersheds, owing to significant interception of nitrogen within watersheds. Within-watershed losses of nitrogen delivered by the major sources, and

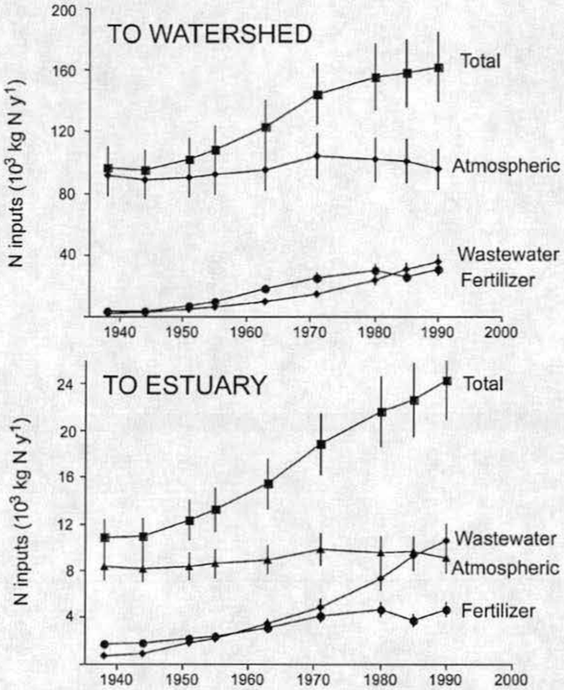

Fig. 3. Modeled historical nitrogen loads to the watershed (top) and estuary (bottom) of Waquoit Bay. The loads are broken down into the three major sources of nitrogen: atmospheric deposition, wastewater, and fertilizer application. Data from Bowen and Valiela (2001b). Note the order of magnitude difference between N inputs to the watershed (top) and to the estuary (bottom). Data are plotted with the 14% standard error that is associated with NLM (Valiela et al., 1997).

during passage through the various land cover types were considerable (Table 1, third column of numbers). Almost 90% of atmospheric nitrogen was intercepted within estuaries, 79% of fertilizer nitrogen, but only 65% of wastewater nitrogen. This differential throughput means that as nitrogen in groundwater is about to seep into receiving estuarine waters, the relative proportions of nitrogen from the different sources and land cover types differ markedly from the proportions that entered the watershed. Contributions to the receiving estuaries by wastewater were a minor part of the nitrogen loads early on, but became the main source of nitrogen to the estuary by the 1990s (Fig. 2, bottom; Table 1, fourth and fifth columns of numbers), surpassing both fertilizer and atmospheric deposition as contributors to the load.

Our estimate that in the 1990s there was interception of almost 90% of the atmospheric-derived nitrogen delivered to forests and other natural vegetation highlights the importance of maintaining green open space within watersheds. Reduction of the area of natural vegetation, by conversion to residential sprawl, will necessarily increase nitrogen loads to receiving waters, for at least two reasons: insertion of more wastewater, and loss of the retentive subsidy of atmospheric nitrogen furnished by natural vegetation. We should note that although the relative contribution by atmospheric nitrogen has diminished to some degree across recent decades, the magnitude of current atmospheric nitrogen loads, which we estimate reach 10–15 kg N ha^{-1} year^{-1} for the Cape Cod area, are at the lower range of loads that are thought to reduce the nitrogen-retentive capacity of forests (Emmett et al., 1993; Dise and Wright, 1995). Thus, even though atmospheric nitrogen inputs are currently largely intercepted within the watershed, atmospheric loads *to forests* of Cape Cod are poised at rates which, if exceeded, may considerably increase delivery of nitrogen *to estuaries* in the future.

We have so far discussed atmospheric contributions to land-derived nitrogen loads. Additional atmospheric nitrogen falls directly on the water surface of the estuaries (Table 2). Taken together, through-watershed and direct atmospheric nitrogen can add up to considerable

Table 1
Contributions to nitrogen loads to watersheds and to estuaries of Waquoit Bay, MA from atmospheric deposition, use of fertilizers, and wastewater disposal[a]

	N load to watershed		N loss within watershed (%)	N load to estuaries	
	kg year^{-1}	%		kg year^{-1}	%
Atmospheric deposition	64,400	56	89	6900	30
Wastewater disposal	16,600	14	79	3400	15
Fertilizer use	31,700	27	65	11,000	48
Total	115,400	100	80	23,100	100

[a] Land use is based on 1990 aerial photographs. Adapted from Valiela et al. (1997).

Table 2
The role of deposition in total nitrogen loading to several Waquoit Bay, MA estuaries[a]

Estuary	Total nitrogen load (kg N $year^{-1}$)	Atmospheric deposition				Total atmospheric contribution	
		Through the watershed		To the estuary			
		kg N $year^{-1}$	%	kg N $year^{-1}$		% kg N $year^{-1}$	% of total load
Childs River	6200	1700	27	200	3	1900	31
Eel Pond	3700	600	16	800	22	1400	38
Quashnet River	10,200	5100	50	500	5	5600	55
Hamblin Pond	2700	400	15	1000	37	1400	52
Jehu Pond	4200	700	17	1600	38	2300	55
Sage Lot Pond	1900	300	2	1200	63	1500	79

[a] Deposition to the watershed is calculated as the total amount of atmospheric N that travels through the watershed and enters the estuary at the seepage face. Deposition to the estuary is the total amount of atmospheric N deposited on the surface of the estuary. Total anthropogenic nitrogen includes land-derived N from wastewater disposal and fertilizer application, as well as deposition to the watershed and the estuary.

fractions (31–79%) of total nitrogen loads (Paerl et al., 1990). The relative importance of through-watershed versus direct deposition of atmospheric nitrogen depends on areas of watersheds relative to estuaries, but in any case, atmospheric deposition is important. We have focused on land-derived loads in our work because of the large changes across decades, but assessments of total loads merit consideration of direct deposition on water. Unfortunately, measurements of direct deposition to seawater are not straight-forward (Valigura et al., 1996). Surface areas for impaction and active uptake of dry deposition are quite different in land versus water bodies, and the dynamics of air movements at the interfaces differ in these two environments. Nonetheless, we made the simplifying assumption that dry deposition on water resembled dry deposition on land, and hence probably overestimated direct deposition to water surfaces.

The multi-decadal pattern of development in the Waquoit estuaries is one of residential land use replacing forests and agricultural uses; "number of houses per watershed" is therefore a reasonable indicator of the geographic transition these watersheds have undergone (Fig. 4). Basically, the trend has been to convert the landscape to more residential land covers, and this transition is associated with increased nitrogen loads to estuaries (Fig. 4, top). In addition, as number of houses increase, the composition of the nitrogen transported by groundwater towards receiving waters differs: more houses are associated with large increases in the nitrate in groundwater (Fig. 4, bottom). In contrast, concentrations of dissolved organic nitrogen decrease as the landscape becomes more urbanized (Fig. 4, bottom); we presume that the relative leaching of atmospherically derived organic nitrogen from forest soils becomes progressively smaller as forest area diminishes. Ammonium concentrations in groundwater seem unaffected by different land use patterns (Fig. 4, bottom).

We know that estuaries receiving the nitrate-dominated loads are eutrophic, and the estuaries receiving the DON-dominated loads are reasonably pristine (Valiela et al., 1992, 2000). This is in spite of the nearly similar total sums of concentrations of nitrate, ammonium, and DON in groundwater delivered from watersheds with different land use (Fig. 4, bottom). This discrepancy must be related to the relative low lability of the land-derived DON supplied by groundwater. Although soils furnish lots of DON to receiving waters, the terrestrially derived DON seems relatively unimportant as a promoter of eutrophic conditions in receiving estuaries.

The inorganic nitrogen derived from wastewater is the major component that has changed with changing land cover mosaics, and that has the potential to alter the aquatic ecosystems receiving inputs from land. That wastewater nitrate was unambiguously involved in the increased loads of ecologically active nitrogen is clearly demonstrated by studies based on stable isotopic data (McClelland et al., 1997; McClelland and Valiela, 1998). These studies showed that the isotopic signatures in fresh groundwater about to enter the estuaries were heavier in proportion to the relative presence of wastewater-derived nitrate, and further, that the heavier signatures could be found in all the producers within the receiving estuaries, and propagated within the estuarine food webs in each of the estuaries. The isotopic data corroborate our conclusions that urbanization of watersheds was associated with greater nitrogen loads, and demonstrate that it was the very nitrogen atoms inserted into the watershed that made their way through the various trophic levels within estuarine ecosystems.

5. Comparison of sources in different systems

We have so far dwelled on the historical changes within one coastal land/estuary system. Differences in land cover on watersheds of different estuaries reveal similar influences on nitrogen loads and contributions from the major sources to the receiving estuaries (Fig. 5).

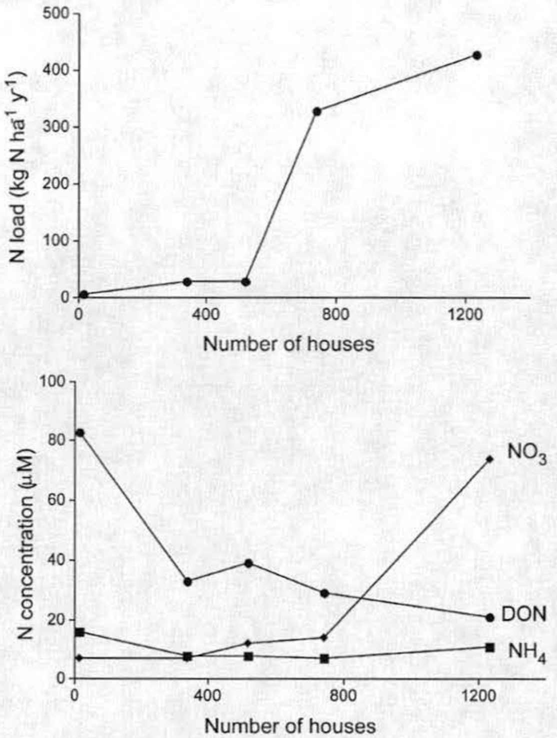

Fig. 4. Changes in N load as the number of houses in the subwatersheds of Waquoit Bay changes (top). Each point represents a different subwatershed. Change in the concentrations of the three dominant nitrogen species in groundwater (NO_3, NH_4, and DON) as a function of the number of houses in the watershed (bottom).

As a proxy for the changing geographic transition we used the ratio of the percentage of watershed area covered by residential and natural land. We then plotted the percentage of total nitrogen loads by wastewater, fertilizers, and atmospheric deposition versus the proxy. The data were compiled from published papers from various locations.

On the left side of Fig. 5 lie values for estuaries with less-developed, largely forested watersheds, and as we move to the right we encounter estuaries with more urbanized watersheds, up to about equal proportions of residential and forested areas. There is quite some scatter, but several trends are clear. Atmospheric sources dominate on the extreme left, but their predominance diminishes as soon as some degree of urbanization takes place. By the time that the ratio of residential to forested areas reaches 0.1, atmospheric sources contribute less than half the nitrogen entering receiving estuaries. Wastewater and fertilizers become dominant above 0.1–0.3. Clearly, soon after humans become established in a watershed, the sources of nitrogen associated with their activities—fertilizers and wastewater—overwhelm the importance of land-derived atmospheric sources. The relative magnitude of nitrogen inputs, and of within-watershed losses (Table 1), by atmospheric versus

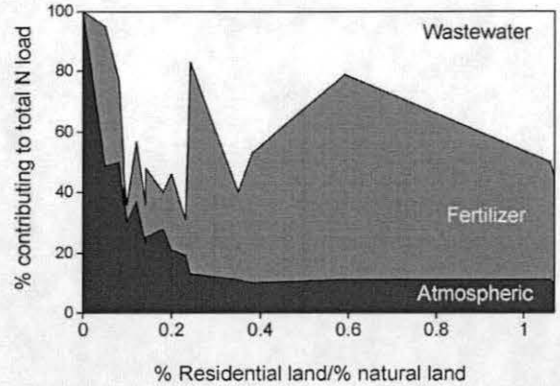

Fig. 5. Change in the % contribution of each of the three sources of nitrogen (atmospheric deposition, fertilizer application, and wastewater disposal) to the total nitrogen load to the estuary as the ratio between the % of residential land and the % of naturally vegetated land changes. Data are from the Waquoit watersheds, Green Pond, MA (Kroeger et al., 1999), West Falmouth Harbor, MA, and Popponesset Bay, MA (unpublished data).

wastewater nitrogen sources is such that nitrogen loads to estuaries become uncoupled from atmospheric inputs in any but the most pristine watersheds.

These results suggest at once the major role of anthropogenic nitrogen contributions, as well as tell us that potentially the added nitrogen that seems most responsible for the increases is also subject to management action at the specific watershed scale. Management of wastewater and fertilizer inputs, although economically and politically challenging are certainly conceivable at the scale of the watershed of the affected estuaries.

6. Effects of land-derived nitrogen loads on receiving waters

Changes in land cover mosaics lead to altered nitrogen delivery to receiving waters, which in turn prompt major alterations of the ecosystems receiving the changing inputs. As already mentioned, increased nitrogen loads stimulate primary production, and create eutrophic waters, particularly in estuaries. The effect of given loads on various producers within the receiving estuaries, however, are not the same (Fig. 6).

The strong coupling between land use mosaics—through the land-derived nitrogen loads delivered to estuaries—and the function and structure of the ecosystem in the receiving estuary can be made evident by considering the relative production carried out by the major types of producers (phytoplankton, macroalgae, and seagrasses) in estuaries subject to different land-derived nitrogen loads (Fig. 6). Here we are using a space-for-time substitution (Pickett, 1989), assuming that estuaries currently subject to different loads can be

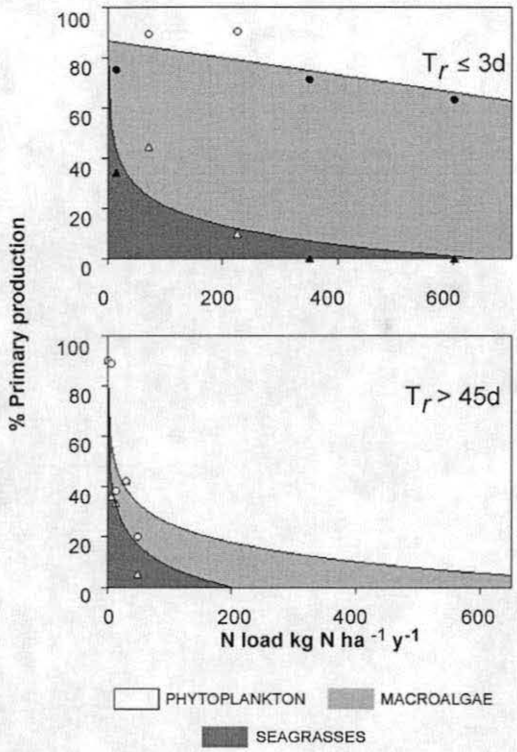

Fig. 6. Partition of total primary production into contributions by phytoplankton, macroalgae, and seagrasses plotted versus measured land-derived N load. Waquoit Bay estuaries: closed symbols, other estuaries: open symbols. The dark shaded area represents the % of production contributed by sea grasses, the light shaded area represents the % of production contributed by macroalgae, and the white area represents the % of production contributed by phytoplankton. Lines are best-fit curves to either the circles (% of total production minus the amount contributed by phytoplankton) or the triangles (% of total production minus the amount contributed by seagrasses. Top panel includes data for estuaries with $T_r < 3$ days (Waquoit Bay estuaries, Buttermilk Bay; Giblin, 1990; Bass Harbor: Kinney and Roman, 1998). Bottom panel includes estuaries with $T_r > 45$ days (Biscayne Bay: Kennish and Lutz, 1984; Corpus Christi Bay: Flint, 1985; Chincoteague Bay: Boynton et al., 1996; Tomales Bay: Smith et al., 1991). Taken from Valiela et al. (2001).

taken to represent a time course during which loads increased.

As nitrogen loads increase, there are major shifts in the relative proportions of production in the ecosystems that are carried out by seagrasses, macroalgae, and phytoplankton. As nitrogen loads rise slightly, the contribution to production by seagrasses decreases steeply, and macroalgae become dominant (Fig. 6, top). The production by phytoplankton rises but slowly in estuaries with short water residence times (Fig. 6, top); in estuaries with longer water residence times, phytoplankton have sufficient time to divide (Tomasky and Valiela, 2001), and they become by far the dominant contributor to production, and respond to increased loads by increasing proportionally. In such estuaries, the relative contributions by seagrasses and macroalgae are generally less prominent. In any case, increases in nitrogen supplies have powerful consequences for the producers in the receiving estuaries.

7. Management implications

The reconstruction of the historical nitrogen loading to the Waquoit Bay watershed makes evident some implications for management or restoration of such loads to estuaries.

Even though atmospheric deposition was the major contributor to loads to watersheds, the larger within-watershed losses of this nitrogen meant that wastewater became the most prominent contributor to loads to estuaries toward the end of the century. One positive aspect of this turnabout is that management practices to lower or control nitrogen inputs to estuaries could be made at the local watershed scale, a less daunting endeavor than management of the emissions from the huge airshed responsible for contributing atmospheric nitrogen deposition. In particular, preservation of green open space in which natural vegetation can be established and maintained in perpetuity will ensure continuing high retention of atmospheric nitrogen.

There is one troubling feature of atmospheric deposition to Cape Cod forests; at the end of the twentieth century, these forests are already exposed to delivery rates that in other sites have begun to undermine the ability of forests to retain nitrogen. Our calculations of nitrogen retention within watersheds have been made with retention coefficients that might not be appropriate in the future. If atmospheric nitrogen deliveries increase, much lower proportions of the largest source of nitrogen to the watersheds of Cape Cod might be retained in the watersheds. Monitoring of atmospheric deposition should be carried out in the long term to make sure that the forests are continuing to provide the retentive subsidy that they have during the past 50 years.

In spite of the importance of atmospheric deposition, in the Waquoit area and elsewhere, it is inputs of wastewater nitrogen (and to a lesser extent, of fertilizer nitrogen) that have increased in past decades. As demonstrated by the loading estimates and the stable isotopic results, wastewater inputs are clearly responsible for the marked environmental changes we have documented. Increased loads were closely tied to complex shifts in land use mosaics, but were particularly linked to urbanization (and particularly to number of buildings), and to the resulting wastewater disposal. If management priorities for nitrogen loads are to be set, it is apparent that the first target might be wastewater inputs. These results also demonstrate that the root cause of the ever-more prevalent eutrophication of such waters is increasing urban sprawl, and that prevention of continuing eutrophication ought to be aimed at control of urbanization of coastal watersheds.

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