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Nitrogen Loads to Estuaries: Using Loading Models to Assess the Effectiveness of Management Options to Restore Estuarine Water Quality

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ABSTRACT: Nitrogen (N) loading to estuaries has become a major concern for coastal planners. As urban development on coastal watershed continues, estuaries and bays are becoming more eutrophic, and cascading effects are being felt at every trophic level. Managers and stakeholders need to have a suite of effective management tools that can be applied to coastal watersheds to minimize the effects of eutrophication. We applied an N loading model and an estuarine loading model to examine the effectiveness of a suite of potential management options that could be implemented in Waquoit Bay, Cape Cod, Massachusetts. This estuarine system is a case study in which we can explore the relative potential effectiveness of decreasing inputs from wastewater and fertilizer-derived N, diverting nitrogenous runoff from impervious surfaces, altering zoning ordinances, preserving forested tracts of land as well as freshwater and saltwater wetlands, harvesting macroalgae, dredging estuary channels, and exterminating waterfowl. From a combination of simulation results, assessment of the magnitude of loads from different sources, and through different land covers, and the additional consideration of feasibility we identified management options with high, intermediate, and low potential effectiveness. Improvement of septic system performance, use of zoning regulations, preservation of forested tracts and freshwater bodies, and conservation of salt marshes emerged as the most promising avenues to manage N loads in our system. Installation of wastewater treatment plants, controlling fertilizer use, and harvesting macroalgae would potentially have intermediate success. Diversion of runoff from impervious surfaces, dredging, and extermination of waterfowl show little promise at reducing N loads. These conclusions potentially set priorities for decision-makers charged with the management of Waquoit Bay. The same procedures applied to another watershed-estuary system with different land covers and different estuarine features may differ. Evaluation studies like this need to be done for any particular site, since the watershed-estuary coupling and the loads delivered to the receiving estuary could differ. The Waquoit Bay case study provides an example of a protocol that leads to identification of the most promising management options.

Introduction

Nonpoint source nitrogen (N) loading to coastal waters is one of the most pressing environmental concerns in management of the coastal zone (Group of Experts on the Scientific Aspects of Marine Pollution 1990; Goldberg 1995). Land-derived N loading to estuaries has increased recently as a result of intensification of land uses on watersheds (Jordan and Weller 1996; Jaworski et al. 1997; Valiela et al. 1997b; Bowen and Valiela 2001a). Increases in the supply of N to estuaries stimulates eutrophication (Nixon 1995), and causes the replacement of submerged sea grasses by blooms of phytoplankton and macroalgae (Sand-Jensen and Borum 1991; Duarte 1995; Valiela et al. 1997a; Hauxwell et al. 2001), and subsequent alterations to estuarine food webs. Over 65% of United States estuaries are moderately to highly affected by eutrophication (Bricker et al. 1999). The increased estuarine N loads occurring throughout the world (Vitousek et al. 1997c; Nicholls and Small 2002) are largely driven by changes in land use on watersheds. In many places, urbanization has become dominant; populations of coastal counties throughout the U.S. have increased three times faster than the U.S. population as a whole (Culliton et al. 1989). Global production of N fertilizers markedly increased in recent decades (Smil 1997, 1999; Galloway 1998), and fertilizers are major sources of N to some estuaries (Lee and Olsen 1985; Hinga et al. 1991; Boynton et al. 1995; Jordan et al. 1997).

The increasing eutrophication of so many coastal waters has aroused widespread interest in lowering, or at least managing, land-derived N loads. We used two recently developed N loading models to provide a quantitative assessment of the options available to manage land-derived N loads to Waquoit Bay, Cape Cod, Massachusetts, where increased urban development has increased N loads and has demonstrably altered the estuarine ecosystem (Valiela et al. 1992, 1997b, 2000b).

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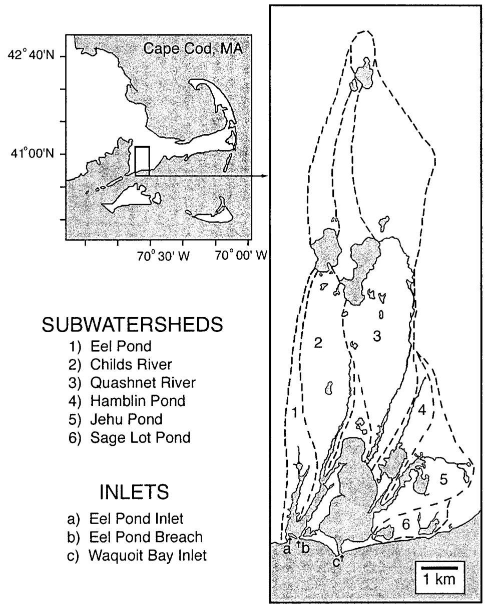

Fig. 1. Location of the Waquoit Bay watershed in Cape Cod, Massachusetts, as well as the various subwatersheds and inlets.

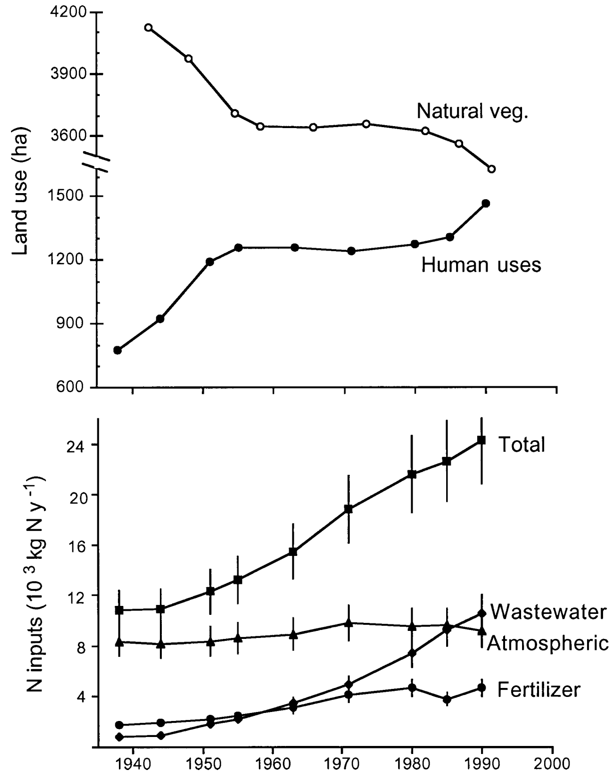

Fig. 2. Changes in the naturally vegetated land cover and the corresponding changes in the human use of land in the Waquoit Bay, Massachusetts, watershed from 1938 to 1990 (top). Taken from Valiela and Bowen (2002). The total area of the Waquoit Bay watershed is 5,366 ha. Changes in the three major sources of nitrogen (wastewater disposal, atmospheric deposition, and fertilizer application) that correspond to the changes in land use in the Waquoit Bay watershed. Taken from Bowen and Valiela (2001a, bottom).

We offer this as a case study of the level of detail that is needed to accurately evaluate both N inputs and options to manage the effects of that N. We emphasize that for other watershed-estuary systems there will be different suites of values for land uses and options, each of which will require use of site-specific information. Our example of Waquoit Bay should serve as a template as to what kind of data might be required to perform this exercise elsewhere.

Site Description

The Watershed

Over the last 60 yr the population of Cape Cod has increased by nearly a factor of 5 (32,000 in 1930 to over 180,000 in 1990 [www.census.gov]). This growth parallels the global trend of steeply increasing human populations in coastal zones (Cohen et al. 1997; Nicholls and Small 2002). Land use in the watershed of Waquoit Bay (Fig. 1) reflects these demographic changes with increases in human uses of land and decreases in vegetated land (Fig. 2). Large increases in human populations carry accompanying increases in the discharge of N from atmospheric deposition, wastewater, and fertilizer application.

In the Waquoit Bay watershed, wastewater disposal, primarily through conventional on-site septic systems (Heufelder and Rask 2001), has become the major source of N entering the estuary (Fig. 2). In the U.S. about 25% of the population disposes of wastewater via septic systems (Cantor and Knox 1985). The remaining population disposes of waste through some form of waste treatment facility ranging in size from small-scale package treatment plants that deal with wastewater from a handful of buildings to regional plants serving larger communities.

Atmospheric deposition is the second dominant form of N delivery to Waquoit Bay (Fig. 2). N from atmospheric deposition falls on every land surface within the watershed, including natural vegetation, freshwater ponds and wetlands, vegetated turf, agricultural land, and impervious surfaces (including roads, roofs, and driveways, and smaller areas of parking lots and runways).

Fertilizers are a third main source of N to the watershed and estuaries of Waquoit Bay (Fig. 2). The watershed of Waquoit Bay has little intensive agriculture, but fertilizers are used on golf courses, residential lawns, and horticultural crops (Valiela et al. 1997b). The major commercially grown crop on Cape Cod is the cranberry (Deubert 1974), and these crops are fertilized at a relatively low rate (Howes and Teal 1995).

The Estuary

The Waquoit Bay estuarine system is a complex of shallow subestuaries and a central Bay, all exchanging water with Vineyard Sound through three relatively small channels (Fig. 1). The flushing time of the various subestuaries of Waquoit Bay range from 1 to 3 d (Valiela et al. 2004). The mean depth of these estuaries is less than 2 m. N loads from land (Fig. 2) move into the Bay and its estuaries through groundwater flow. Substantial areas of salt marsh habitats fringe the estuaries and likely intercept part of the land-derived loads (Valiela and Cole 2002). In spite of the interception of N in watersheds and salt marshes, the increased N loads have prompted blooms of extensive macroalgal canopies, and decreases in the area of *Zostera marina* eelgrass beds (Valiela et al. 1992, 1997b, 2000b). These changes in primary producers have had cascading effects up the food web, resulting in, among other things, a decrease in the commercially important *Argopecten irradians* bay scallop (Bowen and Valiela 2001a). In recent decades, larger populations of resident waterfowl, particularly Canada geese (*Branta canadensis*), double crested cormorants (*Phalacrocorax auritus*), and herring gulls (*Larus argentatus*) have become evident in Waquoit Bay, as they have elsewhere in Cape Cod. Their defecation has been thought to lower water quality (Portnoy 1990).

Models

We used two models in this study. The first is an N loading model (NLM; Valiela et al. 1997b, 2000a) that calculates N loads to estuaries based on land cover data such as areas of freshwater ponds and wetlands, agricultural land, impervious surfaces, and turf, and on the number of houses and occupancy rates within the watershed. NLM tracks the fate of N that enters the watershed from atmospheric deposition, fertilizer use on agriculture, golf courses, and lawns, and wastewater derived from on-site septic systems. NLM then calculates the losses of N during transport through soils, vadose zone, and aquifer, and reports the quantity of N from each source that is about to enter the estuary at the seepage face (Valiela et al. 1997c). All the default terms in NLM can be easily adapted to reflect local conditions if information is available. The estimates of total N load furnished by NLM have annual time steps. A summary of how NLM calculates N loads to receiving waters is provided in Table 1. A more complete description can be found in Valiela et al. (1997b) and verification by comparison with measured values is available in Valiela et al. (2000a).

TABLE 1. Summary of nitrogen loading model, including total dissolved nitrogen inputs to the watershed and resulting TDN loads entering the estuary at the seepage face. Modified from Valiela et al. (1997b).

Nitrogen delivered to watershed surfaces (kg N yr^{-1})
Via atmospheric deposition to:
Natural vegetation [1]: atmospheric deposition (kg N ha^{-1} yr^{-1}) $\times$ area (ha) of naturally vegetated land $\times$ 35% not retained in plants and soil
Turf [2]: atmospheric deposition (kg N ha^{-1} yr^{-1}) $\times$ area (ha) of turf $\times$ 38% not retained in plants and soil
Horticultural land [3]: atmospheric deposition (kg N ha^{-1} yr^{-1}) $\times$ area (ha) of horticultural land $\times$ 38% not retained in plants and soil
Impervious surfaces [4]: {atmospheric deposition (kg N ha^{-1} yr^{-1}) $\times$ [area (ha) of roofs + driveways] $\times$ 38% not retained in plants and soil} + {atmospheric deposition (kg N ha^{-1} yr^{-1}) $\times$ [area (ha) of roads + runways + commercial areas]}
Via fertilizer application to:
Turf [5]: fertilizer application rate (kg N ha^{-1} yr^{-1}) $\times$ area (ha) of lawns $\times$ 34% of houses fertilizing lawns $\times$ 61% not lost as gases
Agricultural land [6]: [crop fertilization rate (kg N ha^{-1} yr^{-1}) $\times$ area (ha) under cultivation $\times$ 61% not lost as gases] $-$ N removed as crop
Nitrogen delivered to and through vadose zone and aquifer (kg N yr^{-1})
Via N percolating diffusely from watershed surface [7]: [sum of items 1 through 6] $\times$ 39% not lost in vadose zone $\times$ 65% not lost in aquifer
Via wastewater from septic systems [8]: N released per person per year $\times$ number of people per house $\times$ number of houses $\times$ 60% not lost in septic tanks and leaching fields $\times$ 66% not lost in plumes $\times$ 65% not lost in aquifer
Nitrogen loading to estuary (kg N yr^{-1}): sum of items 7 and 8

The second model we use to assess management options is an estuarine loading model (ELM; Valiela et al. 2004). ELM takes the land-derived total N load to streams and estuaries and calculates mean annual concentrations of dissolved inorganic nitrogen (DIN) present in the water column of the estuary (Table 2). ELM estimates DIN (NO_3 + NH_4) because these biologically available forms of N drive eutrophication. ELM first partitions land-derived total N loads into organic and inorganic, estimates the fraction of organic N that is biologically labile, and then adds this fraction to the DIN pool. ELM calculations are initially stratified separately per area of freshwater stream reaches, estuarine water column, bare estuarine sediments, salt marshes, and sea grass meadows. For each habitat type, ELM considers inputs from direct atmospheric deposition and N_2 fixation, and losses from denitrification and burial. Then the aggregated estuarine DIN is subject to tidal and freshwater flushing, all adjusted to annual time steps (Table 2).

TABLE 2. Summary of ELM (Valiela et al. 2004). DIN = dissolved inorganic nitrogen, DON = dissolved organic nitrogen, TDN = total dissolved nitrogen.

DIN inputs to the estuary

Via land-derived sources:

Freshwater reaches [1]: [TDN entering freshwater reachs (kg N yr^{-1}) − % of TDN that is DON[a] + labile DON entering freshwater reach[b]] − 13% loss in streams

Saltwater reaches [2]: [TDN entering saltwater reaches (kg N yr^{-1}) − % of TDN that is DON + labile DON entering freshwater reach]

Via N fixation to:

Bare sediments [3]: fixation rate[c] (kg N ha^{-1} yr^{-1}) × area (ha) of bare sediments

Salt marsh sediments [4]: fixation rate (kg N ha^{-1} yr^{-1}) × area (ha) of salt marsh sediments

Sea grass meadows [5]: fixation rate (kg N ha^{-1} yr^{-1}) × area (ha) of sea grass meadows

Water column [6]: fixation rate (kg N ha^{-1} yr^{-1}) × area (ha) of open water

Via atmospheric deposition [7]: [atmospheric DIN deposition rate[d] (kg N ha^{-1} yr^{-1}) + labile atmospheric DON rate[e] (kg N ha^{-1} yr^{-1})] × area (ha) of estuary

DIN losses in the estuary

Via denitrification to:

Bare sediments [8]: denitrification rate[f] (kg N ha^{-1} yr^{-1}) × area (ha) of bare sediments

Salt marsh sediments [9]: denitrification rate (kg N ha^{-1} yr^{-1}) × area (ha) of salt marsh

Via burial to:

Bare sediments [10]: burial rate[h] (kg N ha^{-1} yr^{-1}) × area (ha) of bare sediments × fraction buried that is DIN

Salt marsh sediments [11]: burial rate (kg N ha^{-1} yr^{-1}) × area (ha) of salt marsh sediments × fraction buried that is DIN

DIN regenerated (as NH_4) within the estuary

Via regeneration from:

Bare sediments [12]: regeneration rate (kg N ha^{-1} yr^{-1}) × area (ha) of bare sediments

Salt marsh sediments [13]: regeneration rate (kg N ha^{-1} yr^{-1}) × area (ha) of salt marsh

Water column [14]: regeneration rate (kg N ha^{-1} yr^{-1}) × area (ha) of open water

Net DIN load in estuary (μM) [15]: {[sum (1–7) − sum (8–11) + sum (12–14)] × 10^9}/14

Total DIN available in water column (μM):

Net DIN load/[(estuarine volume × 1000) × Flushing time/365]

[a] % DON = 236.685 − 64.519 × $\log_{10}$ aquifer path length − 4.698 × people ha^{-1}.

[b] % labile DON = 89.322 × Flushing $time^{-0.015}$.

[c] Fixation rates are set in ELM from reviews of published values for each habitat type.

[d] Calculated from mean local wet deposition (Bowen and Valiela 2001b).

[e] % labile atmospheric DON = (73.279 × Flushing $time^{-0.134}$)/100.

[f] Denitrification rates are set in ELM from reviews of published values for each habitat type.

[h] Burial rates are set in ELM from reviews of published values for each habitat type.

Estuary-specific ELM predictions of mean annual DIN were not significantly different from measured DIN concentrations in water columns of several Cape Cod estuaries (Valiela et al. 2004).

We used a combination of NLM and ELM throughout this work. This choice followed a careful comparison of the performance of these models relative to a series of other comparable models developed elsewhere in North America and Europe (Valiela et al. 2002). Detailed justification for the choice, model structure, and data requirements are available in Valiela et al. (1997c, 2000a, 2002). Levins (1966) noted the dilemma that models with reasonable accuracy and predictive power could not be simultaneously general. Our approach to this dilemma was to make NLM and ELM as general as feasible by including all major processes likely to effect N loads. By allowing input data to be site-specific, we also made it possible for NLM and ELM to be reasonably accurate and predictive (Valiela et al. 2002).

We are unaware of previous systematic reviews of the relative effectiveness of the various options in a coastal system. Work has been done that outlines approaches for local estuarine managers (Greening and Elfring 2002) and that describes measures taken to reduce N loads at the national level (Conley et al. 2002). None of these approaches quantitatively assess the actual load reductions that would occur if the management options were in place. We have sufficient information about the watershed and estuaries of the Waquoit Bay estuarine system to do so. We take these traditional assessments further by simulations in which we examine in more detail how a variety of management actions might alter N loads. We use various different approaches made possible by application of NLM and ELM to evaluate potential effectiveness of within-watershed and within-estuary options (Table 3) for managing land-derived N loads to Waquoit Bay and its estuaries. We then synthesize by qualitative comparisons of the different options, and discuss their potential role and implications for development of comprehensive management plans.

Methods

In this section we describe methods to quantify the potential of each management option (Table 3) available to manage the effects of land-derived N loads. We deal with the different options separately as a heuristic device, but in reality the various options are so closely intertwined that, as will become apparent, they resist ready separation. Management of a particular estuary will no doubt involve a mixture of management options. Land-based management options included in Table 3 aim to intercept N before it reaches the receiving

TABLE 3. Management options that are available to reduce land-derived nitrogen loads. Note that protecting salt marshes, dredging of estuary channels, harvesting macroalgae, and exterminating waterfowl are in-estuary management options, other options target land-derived measures (modified from Valiela et al. 2000b).

Management Options	Nitrogen Loads			
	Wastewater	Fertilizer	Atmospheric Deposition	Waterfowl
Within-watershed				
Reducing wastewater inputs				
Improving septic system performance	X			
Constructing waste treatment plants	X			
Altering fertilizer use		X		
Diverting impervious runoff			X	
Altering zoning ordinances	X	X	X	
Preserving forested tracts		X	X	
Protecting freshwater wetlands and ponds	X	X	X	
Within-estuary				
Protecting salt marshes	X	X	X	
Harvesting macroalgae	X	X	X	X
Dredging estuary channels	X	X	X	X
Exterminating waterfowl				X

estuaries; within-estuary options unload N already in the estuaries. The different options target different N sources, and depending on the land use mosaic of the watersheds being considered, may have different potential effectiveness.

A critical aspect of any evaluation of management efforts is to establish whether the proposed action indeed has a detectable effect. The effects of the proposed management option ought, at the very least, to be potentially larger than the uncertainty of the estimates. Throughout the assessments below, we use estimates of uncertainty calculated for NLM and ELM as conservative minimal benchmarks to compare to the magnitude of presumptive effects of management options. In NLM the bootstrap-derived coefficient of variation was based on the standard errors of the terms in the model and was calculated to be 12% (Valiela et al. 1997b). For ELM the coefficient of variation uncertainty, propagated across the entire set of calculations, was 8.1% (Valiela et al. 2004). These uncertainties refer to aggregate uncertainties derived from mean residuals of many points; for specific estuaries, uncertainties are likely larger.

We emphasize that we chose this uncertainty criterion as an almost arbitrary threshold. In reviewing alternative attempts to model N loads we found that most researchers do not attempt such an error assessment (Gaines 1986; Eichner and Cambareri 1992; Cole et al. 1993; Caraco and Cole 1999; Dettmann et al. 2001). Johnes (1996) did so, but used successive simulations to calibrate the model and came to estimations with greatly reduced error. In another comparative work, estimates of uncertainty were so large that intermodel comparisons were unable to clearly distinguish model performance (Alexander et al. 2002).

It may very well be that management of a given N source, say fertilizer use, may in fact lead to a 10% lower N load, and this could be an ecologically significant reduction, even though the lowering would be smaller than our detection threshold. It may also be that implementation of several options, all of which reduce N loads by 10%, would result in improved water quality. We point out that using the model uncertainty described above as a benchmark for the effectiveness of the proposed management option simply indicates that by using our models (which we argue are the most precise available) we would be unable to confirm the effects of these management options.

Within-watershed Options

Increasing Retention of N in Septic Systems

Wastewater is the principal N source to Waquoit Bay (Fig. 2); it seems reasonable then to focus on this term as a management option. We assessed changes in N loads to Waquoit Bay that would result from achieving different degrees of N retention in septic systems. To do this we ran simulations in which we set septic system N retention at a range of values, from the 39% N removal (Valiela et al. 1997b) achieved by conventional septic systems up to complete retention.

We first ran the N retention simulations taking into consideration all buildings on the Waquoit Bay watershed, but replacing or retrofitting septic systems in the entire watershed might be an expensive and politically daunting alternative. A more cost-effective and achievable option may be to improve N retention within areas closer to shore. Septic systems located closer to shore may contribute relatively more N than those located farther away (Westgate et al. 2000). To assess the likely effects of such an option we separately considered those buildings up to 200, 500, and 1,000 m from shore.

Reducing Fertilizer Inputs

To control N inputs from fertilizers, we might opt to regulate either the dosage of fertilizers applied within the watershed or limit the amount of land receiving fertilizers. We used NLM to estimate decreases in N loads that would occur by applying these two alternatives.

We simulated N loads that would result from reduction of fertilizer dosages to total fertilized areas (the sum of golf courses, agriculture, and lawns) by 10%, 20%, 25%, 50%, 75%, 90%, and 100%. We also ran simulations that reduced the area of land receiving fertilizer by 10%, 20%, 25%, 50%, 75%, 90%, and 100%. This second alternative is not equivalent to the first option to control fertilizer inputs, because some other land cover must obligatorily replace formerly fertilized land. In our simulations we assumed that natural vegetation would be allowed to replace the nonfertilized land area, so that atmospheric deposition falling in the now nonfertilized parcels was intercepted as in natural vegetation areas.

Preservation of Vegetated Tracts

As Cape Cod became urbanized across the decades, more and more of the naturally forested areas were converted to residential and other land covers (Fig. 2). We have shown that forested tracts efficiently retain atmospheric N (Valiela et al. 1992, 1997b). The conversion of vegetated land to other land covers implies a loss of the water quality subsidy furnished by forested tracts, a loss that ought to receive more attention in management.

To provide a quantitative idea of the relative value of preserving forested tracts of land (compared to developing residential areas, horticultural land, or golf courses, likely fates of Cape Cod land) we used NLM to calculate N loads from a fictitious 1-ha plot covered by forest, and compared the resulting N load to the load that would result from 1 ha of residential areas with 1, 2, 3, 4, and 10 houses, one hectare of agricultural land, and 1 ha covered by a golf course.

Protecting Freshwater Ponds and Wetlands

Substantial amounts of the N delivered to freshwater ponds and wetlands are intercepted within these aquatic systems (Corredor and Morell 1984; Johnston 1991). Ponds and wetlands also subsidize water quality in estuaries down-gradient, but in the Cape Cod area, these environments are well-protected by municipal and state regulations and are unlikely to change in area or use in foreseeable decades. We assessed their role in N loading of Waquoit Bay simply from NLM estimates of the N load that are retained in ponds and wetlands on the watershed.

Diverting Flow from Impervious Surfaces

Atmospheric deposition falls not only on natural vegetation, but also on other land covers. Impervious surfaces have been thought to alter receiving waters by changing runoff and nutrient deliveries (Arnold and Gibbons 1996; Albanese and Matlack 1998). Diverting that runoff, removing it from the watershed, or treating it through artificial wetlands has often been suggested to help reduce N loading. Because of the popularity of the idea that impervious surfaces may matter to N loads, we used NLM to define the potential role of impervious surfaces in N loading to Waquoit Bay.

To quantify the effect of runoff diversion, we explored how much of the present total N load to Waquoit Bay might be eliminated if 10%, 20%, 25%, 50%, 75%, 90%, and 100% of the N carried by runoff from all impervious surfaces were diverted away from the estuaries. To get a worst-case assessment of what might happen if urban sprawl continues into the 21st century, we ran simulations in which we converted the area of remaining naturally vegetated land on the Waquoit Bay watershed (roughly one third of the watershed) into impervious surfaces.

Altering Zoning Ordinances

One of the most general options to manage N load might be to alter zoning regulations, because changes in zoning alter inputs from the three major sources of N to a watershed (Table 3). We ran two sets of simulations to explore the potential importance of zoning ordinances in altering the N loads to Waquoit Bay.

We explored whether different zoning plans may lead to different rates of N loading to receiving waters. We ran simulations in which we considered the one third of the area of the Waquoit Bay watershed that was still undeveloped in 1990, and asked what N loads might result if these areas were developed under different zoning restrictions with lot sizes of 0.25, 0.5, 0.75, 1.0, 2.0, 2.5, and 5 ha. To define the maximum load under present zoning restrictions, we forecasted the N loads that would occur if all the land in the Waquoit Bay watershed that was already zoned for urbanization were built upon. To do this we used previously collected information on the number of parcels that are left on the watershed of Waquoit Bay and the number of parcels on which it is legal to build a structure under present zoning rules (Brawley unpublished data). We then projected a rate of increase in urbanization based on the mean increase that occurred during the last 20 yr (Brawley et al. 2000; Bowen and Valiela 2001a) and forecasted the number of years until build-out occurs. We assumed that on each buildable parcel there would be only one residential unit, and we simulated the addition of the projected number of parcels to be built per year until build-out was reached.

Within-estuary Options

Preservation of Salt Marshes

Locally and globally there have been marked losses of coastal wetlands (Nixon 1982; Dahl and Johnson 1991; Valiela et al. 2001, 2002); since these habitats attenuate N loads from land (Valiela and Teal 1978; Valiela and Cole 2002), their preservation is one option that should be part of a strategy to prevent further increases in N loading. We assessed the importance of salt marsh interception of N on reducing N loads to estuaries.

To provide a measure of the role of salt marshes in preventing N loads from land to estuary, we compared annual land-derived N loads to Waquoit Bay to estimated annual N interception (at 57 kg N ha^{-1} yr^{-1} [Valiela and Cole 2002], multiplied by area of fringing salt marshes) that might take place within the total area of salt marshes in Waquoit Bay. We then calculated the land-derived N load that would enter the Bay if 10%, 20%, 25%, 50%, 75%, 90%, and 100% of the total fringing marsh area were to be lost from the periphery of Waquoit Bay.

Harvesting Macroalgae

Harvest or removal of the crop of macroalgae has been used to clear what could be an unsightly and often odiferous problem, as well as to remove N stored in the biomass of macroalgae growing in eutrophic estuaries. Even though this alternative has been deployed in several estuaries worldwide, there were no relevant data available on harvests, so we opted to examine this option by simulated scenarios. We asked what might be the lower and upper bounds to the possible annual harvest of algae, and how might these harvest bounds be related to annual N loads?

We calculated the total N that could be contained in the macroalgal biomass of each of three subestuaries of Waquoit Bay where we had information on the crop of marcoalgal biomass (Stieve unpublished manuscript) and their growth rates (Peckol et al. 1994; Hersh 1996). Harvest of the annually averaged crop would be a possible lower bound on the effectiveness of macroalgal harvesting at reducing N loads. We multiplied the N content of the macroalgae (3–4%; Hersh 1996) by the estimated mean biomass of macroalgae in each of the three estuaries (Stieve unpublished manuscript) to estimate N in the standing stock of macroalgae. We could then compare the amount of N in macroalgal biomass to the total N load. An upper bound on algal removal might be the removal of all the biomass that could grow in a year. To do this we used growth rates of macroalgae (0.046–0.063 d^{-1}; Peckol et al. 1994), and estimated the total biomass that could accumulate in the absence of grazing and decomposition and further converted biomass into N content. We then compared the calculated upper bound to the annual N load per estuary.

Dredging Estuary Channels

Decreasing flushing time of the water in an estuary may hasten down-estuary transport of land-derived N and foster replacement of nutrient-rich freshwater with nutrient-poor coastal water and thus unload the estuary (Monsen et al. 2002). Dredging the main channel to decrease flushing time has been proposed as a solution to eutrophication in many shallow coastal estuaries (Mallin et al. 2000).

To assess the potential of dredging as a management option to unload estuaries, we ran ELM simulations in which we changed the possible water exchange in and out of Waquoit Bay and calculated the effect of the altered flushing time on the concentration of DIN in the estuary. To estimate the effectiveness of changing dredging scenarios on the flushing time, we used a previously developed two-dimensional finite element hydrodynamic and mass transport model for Waquoit Bay derived from Isaji and Spaulding (1984). We estimated the changes in flushing time that would occur from increasing the depth of Eel Pond Inlet (Fig. 1) by 50% and 100%, increasing the depth of the Waquoit Inlet by 10%, 25%, 50%, and 100%, and increasing the cross sectional area of both inlets by 50% and 100%. We used ELM to assess the reduction of DIN that would occur as a result of the reduction in residence time.

Exterminating Waterfowl

Another feature that has received considerable attention in Cape Cod and elsewhere is increased abundance of overwintering waterfowl (Valiela and Bowen 2003). N contributions by defecation of waterfowl are mentioned as an agent of eutrophication in a surprising number of conversations with stakeholders and in public meetings. These increases have resulted in the widespread popular belief that the increasing eutrophication of estuaries is linked to the increase in aquatic bird species, and eradication of such birds has been pro-

TABLE 4. The various sources of nitrogen to, and losses of nitrogen in, the watershed and estuary of Waquoit Bay, Massachusetts. Modified from Valiela et al. (1997b). Units are kg yr^{-1}.

Source of N	N Input to Watershed	% of N Load to Watershed	% of N Input Lost Within Watershed	Total N Input to Waquoit Bay	% of N Load to Estuary
Wastewater	31,454	25	67	10,331	44
Fertilizer used on					
Lawns	7,048	6	84	1,099	5
Golf courses	7,730	6	84	1,205	5
Cranberry bogs	1,085	1	54	504	2
Other agricultural land	10,869	9	84	1,695	7
Total fertilizer	26,733	22	78	4,502	19
Atmospheric deposition to					
Natural vegetation	45,637	37		3,936	17
Turf	8,058	6	91	776	3
Cranberry bogs	581	0.5	90	56	0
Other agricultural land	1,191	2	90	115	0.5
Roofs and driveways	1,271	0.5	90	122	0.5
Roads, runways, and			90		
commercial land	4,712	1	75	1,194	5
Ponds and wetlands[a]	2,892	1	56	811	4
Total atmospheric deposition	64,350	51	90	7,124	30
Ponds upgradient[b]	2,661	2	35	1,729	7
Grand total	125,197	100	81	23,687	99

[a] This refers to direct atmospheric deposition on ponds and freshwater wetlands.

[b] This is an import from larger ponds or lakes that are deep enough to intercept the flow through the aquifer. N additions to the watersheds upgradient of the ponds total 25,261 kg yr^{-1} (atmospheric deposition: 15,264 kg yr^{-1}; wastewater: 3,621 kg yr^{-1}; fertilizers: 6,376 kg yr^{-1}). Ninety percent of this N is lost during travel to and within the ponds. The N that passes through ponds is then subject to 35% interception in the downgradient aquifer.

posed more than once as the solution to eutrophication in Cape Cod.

We had no estimates of the number of bird species that reside in Waquoit Bay, so to assess the effectiveness of exterminating waterfowl we opted to work backward. We used literature values on the defecation weights of waterfowl (20 g dry weight of feces d^{-1}, 5% of which is N [Valiela and Costa 1988]), and back-calculated the number of birds that would be necessary to surpass the 12% uncertainty of the loading estimates. We assumed (as a worst-case scenario) that all birds, regardless of their size, made N contributions similar to those by geese, and that all feces entered Waquoit Bay. With these unrealistic and maximal suppositions, we calculated the number of birds that it would take to equal the contributions from the three other dominant sources of N in the watershed.

Results

We first used land cover data to obtain NLM estimates of N contributions and losses from the three main N sources (wastewater, fertilizer, and atmospheric deposition) as the N moves through the major land cover types on the watershed. The results highlight the larger inputs to the watershed surface, and the surprisingly high retention of externally-supplied N within the watershed (Table 4). Most relevant to this paper are the loads derived from each land cover category to Waquoit Bay itself, information that we use throughout the results section below. The N loads of Table 4 describe the situation prevailing in the Waquoit Bay region at the end of the 20th century. We use these results as a point of departure for future evaluation of management options available to control loads.

Within-watershed Options

Increasing Retention of N in Septic Systems

Wastewater N contributed by septic systems added about 44% of the N loads entering Waquoit Bay (Table 4). This is the single largest term in the accounting provided by Table 4, and its magnitude suggests that management of land-derived N loads to Waquoit Bay certainly ought to consider this input.

Septic systems of conventional design retained about 39% of the N supplied by wastewater to the watershed of Waquoit Bay (Fig. 3). Increased retention of N in septic systems decreased total N loads to Waquoit Bay, but this effect was less marked when we included smaller sections of the watershed closer to shore. To make the results of the simulations easier to visualize, we converted the changes in N loads of Fig. 3 (top) to % reductions (Fig. 3 bottom). If we could find a way to increase N retention to 100% (eliminating inputs

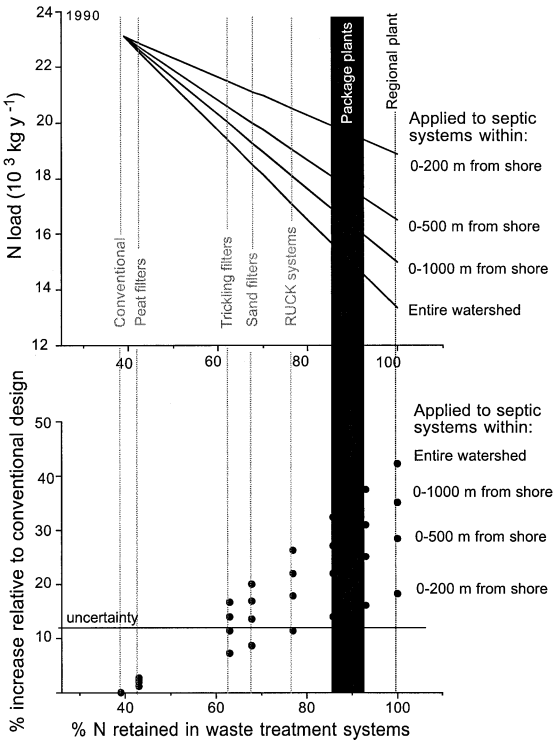

Fig. 3. The reduction in total annual nitrogen loads that would result from increasing the performance of on-site septic systems. Each line represents the reduction in nitrogen loads that would occur if septic systems (top) were improved in different areas of the watershed. The percent reduction in total annual nitrogen loads that would occur within each area of the watershed if increased nitrogen removal were achieved (bottom). The vertical lines indicate a variety of commercially available systems that are designed to lower nitrogen loads.

of wastewater N through complete retention or through disposal of waste outside the watershed), we could expect a range of 44% to 18% reduction in N load to Waquoit Bay, depending on whether we included buildings in the entire watershed or only those within the much smaller area of 200 m from shore (Fig. 3). The relatively larger effect closer to shore was derived from the larger density of buildings near shore (Valiela et al. 1992), as well as the proportionately larger contribution to loads by septic systems closer to shore (Valiela et al. 1997b).

At N retention rates lower than 100%, the % reductions of N loads to Waquoit Bay would, of course, be lower (Fig. 3). If we take the lower bound of projected reductions as the 12% uncertainty of NLM, we can consider a range of possible management alternatives. If we manage only septic systems within 200 m from shore, we need to require that N retention lie between 80–100% to exceed the limit of detectable effects. These restrictions might yield 12–20% lower N loads to the Bay. At the other extreme, we could manage the entire watershed, in which case, it becomes necessary to insist on N retention of 55–100% to show significant reductions, and the likely reduction of N loads to the Bay would be 18–44%. Management of areas between these extremes would lead to intermediate lowerings of N loads. These simulations spell out the possible limits; local conditions will govern the choice of specific values. In any case, improved N retention in septic systems seem large enough to merit inclusion in plans to manage N loads to Waquoit Bay.

The simulations of Fig. 3 suppose that we have some means to increase N retention in on-site septic systems. Certain newer septic designs may be able to do so (Table 5); of the alternative devices available for disposal of wastewater (indicated by the vertical lines in Fig. 3), trickling sand filters, the RUCK system, and package and regional waste treatment plants would work to different degrees.

TABLE 5. On-site septic system retention efficiencies reported for various alternative systems.

Septic System	% N Retention Mean	% N Retention Range	Source	Reference
Conventional system	39	10–90	Various published estimates	Valiela et al. (1997b)
Peat filters[1]	43	30–65	6 in situ systems in Massachusetts	Heufelder and Rask (2001)
Trickling filters[2]	54	22–86	Various systems	Stokes (2000)
Recirculating sand filters[3]	64	59–70	Mean from 4 systems in Maryland	Piluk and Peters (unpublished data)
RUCK[4]	88	66–99	Mean from 6 systems in Massachusetts	Rask (1998)

[1] In peat filters effluent is passed through roughly a meter thick layer of peat before entering the leaching field, providing a carbon-rich source for bacterially-mediated N removal.

[2] In trickling filters effluent leaves the septic tank and enters a filtration unit that contains some form of synthetic medium to promote nitrification. Many trickling filters are available that use different media with varying results.

[3] Recirculating sand filters send effluent through a sand filter, after which a portion of the effluent is sent to the leaching field, and the remainder of the effluent is sent back through the sand filter.

[4] RUCK systems separate black water from septic system waste from the gray water that is the waste from sinks, showers, and other nonseptic wastewater. The black water flows through the RUCK filtration system and is then added to the gray water and pumped to the leaching field.

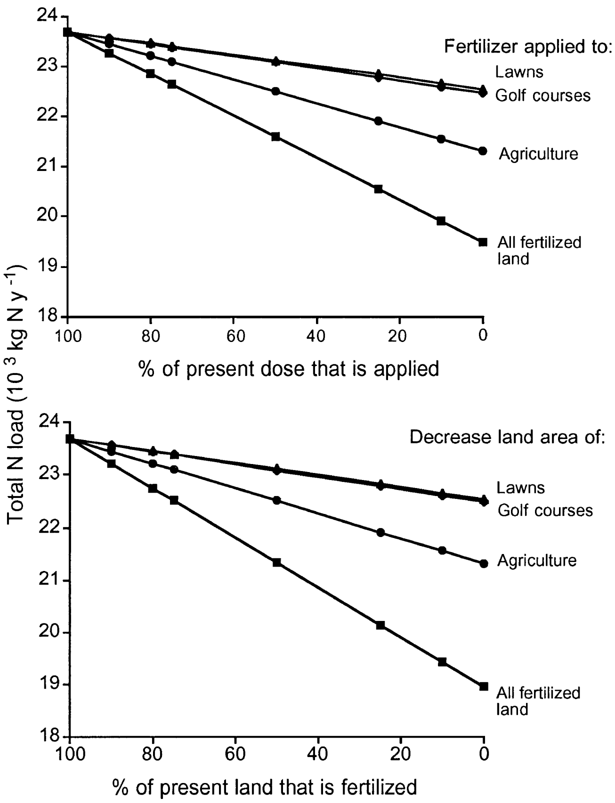

Fig. 4. The reduction in nitrogen loads that would occur as a result of decreasing fertilizer application rates (top) and decreasing the percent of land that receives fertilizer (bottom).

Although mean retention of the various on-site designs differs (Fig. 3), the ranges (Table 5) overlap broadly. We can assess the utility of retrofitting with new designs by using Fig. 3. For example, requiring all buildings on the entire watershed to achieve a retention comparable to that of RUCK systems could lower N loads to the Bay by up to 25%. Doing so only for the band of land between 0–200 m from shore might result in a 12% improvement, an amount that does not exceed the uncertainty in the loading estimates.

Reducing Fertilizer Inputs

Fertilizer N inputs amounted to 19% of the N loads to Waquoit Bay, a modest but significant portion of total loads to the Bay (Table 4). Decreasing the quantity of fertilizer applied would certainly decrease N loads to receiving waters (Fig. 4). To reduce N loads by the 12% that would exceed the uncertainty of the model would require curtailing fertilizer dosages to only 4% of current rates. If no fertilizers were used at all, we could expect a 17% decrease. Significant reductions in use of fertilizer dosages would have only slightly detectable effects on N loads.

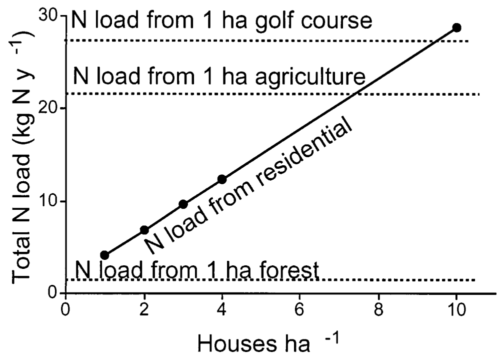

Fig. 5. The total nitrogen load that would result from development of a fictional 1-ha plot of land under different housing densities. These loads are placed in the context of loads that would result from the same 1-ha plot if it were developed as agriculture or as golf courses (dashed lines).

Reducing the area of land that receives fertilizer could also lower N loads, but these reductions would be about the same as those that would result from changing the fertilizer doses (Fig. 4). The results of the two alternatives are not identical, because in the case of lower fertilized areas, these areas have to be replaced by another land cover and its associated N contributions; in our simulations we assumed that natural vegetation replaced fertilized land.

The contribution of fertilizer to the N load of Waquoit Bay is minor, so that managing fertilizer, either by lower dose or a reduction in areas fertilized, does not seem to be a highly promising endeavor. In watersheds covered by more greater areas of agricultural land (Jordan et al. 1997), fertilizer regulation may be an effective approach.

Preservation of Natural Vegetation

As already noted, natural vegetation, which includes all vegetated but nonfertilized land covers, retains about 91% of the atmospherically-derived N arriving on the surface of the watershed (Table 4). Such large interception of N within a watershed is striking evidence that justifies preservation of forest tracts on this watershed. The within-watershed retention is large enough that although the input of atmospheric N to forested areas is quite large, the N coursing through the forested tracts contributes only about 17% of the N load to Waquoit Bay (Table 4).

To make more tangible the subsidy furnished by naturally vegetated tracts, we obtained estimates of N loads produced from a fictitious 1-ha parcel of the Waquoit Bay watershed that receives rates of N deposition comparable to rates in Cape Cod during the 1990s. Were this hectare covered entirely by forest, it would contribute roughly 1.4 kg N yr^{-1} to receiving waters (Fig. 5). If that hectare were converted to agriculture, the N yield to an estuary would be an order of magnitude higher. The same hectare, if covered by a golf course, would yield an even higher N load (27 kg N ha^{-1}).

We can also compare the above loads to a situation where the hectare was converted to residential land. If one house were built on the hectare, loads would be similar to those of forest cover (Fig. 5), but as the number of buildings increases, greater loads result. Seven buildings per hectare would result in loads that are similar to loads likely to result from agricultural uses. Ten buildings per hectare are equivalent to the N loads from a golf course. Lot sizes in coastal areas of Cape Cod can be as small as 0.065–0.093 ha (7,000–10,000 ft^2), so a density of 10 buildings ha^{-1} is comparable to lot sizes in certain areas of the Waquoit Bay watershed. These comparisons should be of interest to decision makers involved in permitting and developing land use plans.

The water quality subsidy furnished by maintenance of naturally vegetated land is evident from our comparisons. Loads contributed by forested land are up to 20× lower than loads from golf courses or intensive residential developments (Fig. 5). Preservation of naturally vegetated land reduces N loads directly through uptake of N by vegetation and indirectly by preventing conversion to land covers that release more N, such as agricultural or residential lands.

There is evidence that the retention of N within forested areas could be compromised in the future as forests becomes saturated with fixed atmospheric N (Aber et al. 1989, 1995; Nadelhoffer et al. 1995). N saturation results when inputs of N exceed the plant and microbial demand for the nutrient and leads to increased release of N from watersheds (Aber et al. 1989). Atmospheric deposition to the Cape Cod area has increased over the last century at a rate of 0.26 kg ha^{-1} per decade, and is presently about 11 kg N ha^{-1} yr^{-1} (Bowen and Valiela 2001b). Future increases in deposition rates, if they occur, could induce saturation in Cape Cod forests and result in much higher rates of N loading to coastal waters.

Protecting Freshwater Ponds and Wetlands

N deposited directly on ponds and wetlands, and N coursing through these habitats by groundwater flow from upgradient watersheds, contributed about 11% of the N load that entered Waquoit Bay (Table 4). This is a small amount, reflecting the retention of atmospherically deposited N in ponds and wetlands. The result of this retention is that only 4% of the total N load to Waquoit Bay can be attributed to atmospheric deposition on ponds and freshwater wetlands (Table 4). Watersheds also retain N transported via groundwater through-flow in ponds (for example in the three large ponds in the upper part of Fig. 1) that were deep enough to capture groundwater flow from their upgradient watersheds. This retention of N in groundwater resulted in a total contribution of only 7% to the total N load to Waquoit Bay from watersheds upgradient of intercepting ponds (Table 4). The interception of N in these freshwater environments furnishes a small, but considerable subsidy toward maintaining water quality in Waquoit Bay, and as in the case of vegetated land, argues for their protection. Since watershed areas upgradient from freshwater ponds will contribute less to the overall N load, managers might choose to focus first on watersheds that are down-gradient from intercepting ponds. There is still much to be learned about groundwater flow capture by wetlands, ponds, and lakes in the Cape Cod Aquifer and elsewhere, so the issue of N interception by water bodies needs more concerted study.

Diverting Flow from Impervious Surfaces

In the Waquoit watershed, the area of impervious surfaces (roads, roofs, driveways, commercial developments) was small at the end of the 20th century, and the total N loads derived from atmospheric deposition that traverse impervious surfaces amounted to 5.5% of the total N load (Table 4). Diversion of all the N carried by runoff from all present-day impervious surfaces in the Waquoit watershed would at most reduce N loads by roughly 5% (Fig. 6); this is not a measurable effect.

This small potential effect follows from the relatively small area of the Waquoit watershed presently covered by impervious surfaces. The magnitude of the effect of impervious surfaces on receiving water could, of course, be much larger as urbanization continues. In the Waquoit Bay watershed there are presently 532 ha of impervious surfaces, and over 3,400 ha of natural vegetation. If the remaining naturally vegetated land parcels were converted to impervious surfaces, the resulting increase in N load to Waquoit Bay would be approximately 5,600 kg N yr^{-1}, or roughly 23.5% above present day loads (Fig. 6). This would result largely because of the loss of N retention of atmospheric N falling on forested land. Perhaps the exhaust from the higher density of vehicles that are characteristic of urban areas might add more N than is considered in this simulation.

Altering Zoning Ordinances

Approximately 35% of the land parcels that are presently (based on 1990 data) zoned for residential land uses in the Waquoit Bay watershed have yet to be built upon. If building does take place on

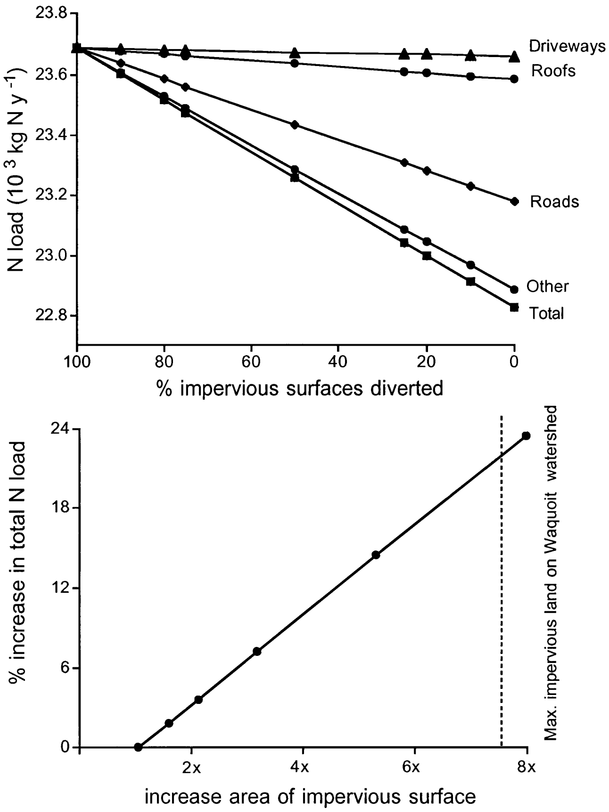

Fig. 6. The reduction in nitrogen loads that would occur as a result of diverting various percentages of impervious surfaces within the watershed (top). The projected nitrogen load that would occur if the area of impervious land were increased from the present area to over 6× the present area (bottom).

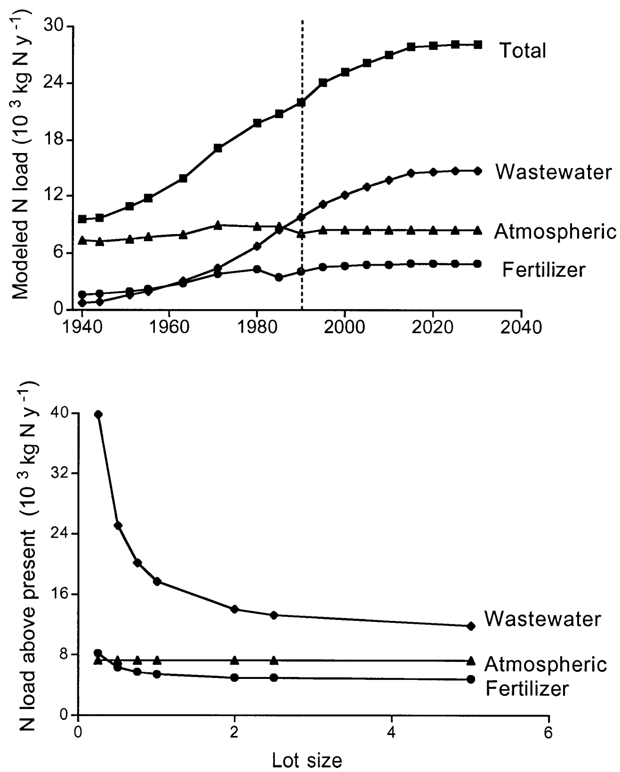

Fig. 7. Simulations of the nitrogen load that would result if all the land parcels that were presently zoned for residential land uses in the Waquoit Bay watershed were built upon (top). Increase above the present nitrogen load that would result from decreasing the area of lot sizes in Waquoit Bay (bottom). The dashed line indicates 1990 upon which zoning restrictions were based. All data to the right of the dashed line are model projections.

these remaining parcels, different N loads might result from setting different limits to the size of lots on which building takes place.

If average lot size on the remaining developable land in the watershed were 5 ha, a rather large mean lot size, N loading that would result from the construction of residences on these parcels would increase somewhat above present loads (Fig. 7). If lot sizes were smaller so that more houses were added to the watershed, the N load would increase far more drastically above present loads. These lot size simulations highlight the importance of regulatory zoning control on future increases in N loads. The simulations also show that the increase in N loads mainly derived from increases in wastewater N that accompanies increases in the number of buildings; N contributions via atmospheric and fertilizer sources are largely unaffected by lot sizes.

If zoning restrictions were held in the present state, when the buildable lots are in fact built upon, N loading to Waquoit Bay would reach up to 29,000 kg N yr^{-1}, an increase of about 20% above 1990 loads (Fig. 7). Based on the watershed-wide growth rate of the past 20 yr, build-out in the entire watershed would be complete by 2030, and some subwatersheds could be complete by 2005 (Table 6). In performing this simulation we assumed no changes in the amount of N delivered

TABLE 6. Number of parcels remaining to be built upon in the Waquoit Bay watershed. For locations of the watersheds see Fig. 1.

Estuary	Maximum Parcel Number	Parcels Remaining to be Built Upon	Mean Number of Houses Built per Year	Anticipated Year of Build-out
Sage Lot Pond	19	5	0.7	2004
Jehu Pond	669	217	22.6	2010
Ashumet Pond	247	81	8.2	2010
Eel Pond	972	244	16.3	2015
Childs River	2,070	633	34.4	2018
Johns Pond	377	146	7.2	2020
Quashnet River	1,374	608	25.4	2024
Hamblin Pond	634	285	8.8	2032
Head of the Bay	143	41	1.3	2032
Snake Pond	18	9	0.3	2034
Total	6,523	2,269	125	2018

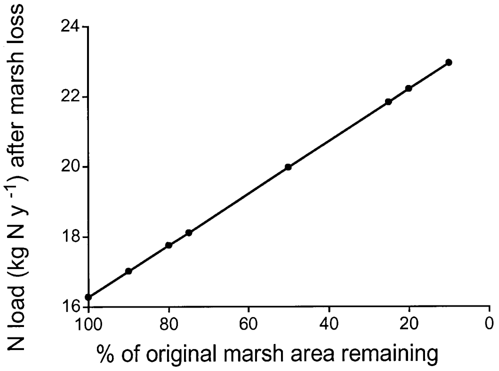

Fig. 8. The nitrogen load that would result from the reduction of salt marsh area in the Waquoit Bay watershed.

via other sources. If there are increases in these sources of N between now and the time build-out is reached, then our simulated N load of 29,000 kg N yr^{-1} will be an underestimate.

Within-estuary Options

Preservation of Salt Marshes

Fringing salt marshes can intercept land-derived N that has traversed the seepage face up-gradient from the marshes. Over 23,500 kg N yr^{-1} arrives at the seepage face around Waquoit Bay. If marshes retain, on average, 57 kg N ha^{-1} yr^{-1} (Valiela and Cole 2002), then the actual amount of N that enters the water column is significantly lower, just over 16,000 kg N yr^{-1} (Fig. 8). If we reduce the area of marshes surrounding Waquoit Bay, the amount of N retained will decrease. If all but 10% of the extant marshes were destroyed, they would retain less than 1,000 kg N yr^{-1}. This makes evident the important subsidy that coastal wetlands provide. Managers can use this knowledge to argue for wetland protection or for wetland reconstruction.

Harvest of Macroalgae

We assessed the possible effects of harvesting macroalgae by examining the upper and lower bounds of effectiveness of harvesting. The lower bound of effectiveness in the three subestuaries of Waquoit Bay depends on the land-derived N load and the ambient N concentrations (Table 7). In Childs River, the most eutrophic of the Waquoit estuaries, the total amount of N incorporated into the standing stock algal biomass is 11% of the total annual land-derived N load. In Quashnet River there is a lower standing stock of macroalgae than in Childs River, and that macroalgae has a lower N content, so macroalgae in Quashnet River contains 9% of the total land-derived load (Table 7). In Sage Lot Pond macroalgal biomass contains about 15 kg N ha^{-1}. Sage Lot Pond is a near-pristine embayment that receives only about 14 kg N ha^{-1} yr^{-1} of land-derived N, so that more than 100% of the total N load is held in macroalgal biomass (Table 7).

The upper bound of effectiveness in the three subestuaries of Waquoit Bay is a function of the growth rates of the two dominant macroalgal species (*Gracilaria tikvahiae* and *Cladophora vagabunda*), as well as ambient N concentrations. Our simulations indicate that the resulting growth of biomass, absent any losses from grazers or decomposition, ranged from 90% to 880% of the annual land-derived N load (Table 7). The 880% figure is from a system that has a very low external N input. The N available to support the growth of the algae would largely be recycled within the system, and on an annual time step, there is enough N to support macroalgal growth.

Assuming that we could find effective mechanical means for macroalgal harvesting, the lower bound harvesting regime could eliminate from 9–

TABLE 7. Variables used and results of simulations to estimate percent of land-derived nitrogen loads that could be removed through the harvesting of macroalgae.

	Estuary			
	Childs River	Quashnet River	Sage Lot Pond	Reference
Lower bound: removal of mean biomass				
Measured N load (kg N ha^{-1} yr^{-1})	601	350	14	Valiela et al. (2000a)
Mean annual biomass of standing stock (kg dw ha^{-1})	1,650	912	500	Stieve unpublished data
% N in biomass of standing stock	4	3.5	3	Hersh (1996)
Total N in standing stock (kg N ha^{-1})	66	32	15	
% annual land-derived N load present in standing stock	11	9	107	
Upper bound: removal of annual crop				
Growth rate (doublings d^{-1})	0.063	0.055	0.046	Peckol et al. (1994)
Potential biomass that could accumulate in a 180 d growing season (kg dw ha^{-1})	18,645	9,030	4,150	
N content of potential biomass (kg N ha^{-1})	745	316	124	
% of annual land-derived N load present in potential biomass	124	90	880	

TABLE 8. Results of simulations to assess increases in tidal volume, flushing time, and reduction in DIN concentration that would occur by dredging Waquoit Bay inlets (Fig. 1, Eel Pond inlet, and Waquoit Bay inlet) by different percentages.

Dredging Scenario		Tidal Volume Increase (%)	Residence Time (h)	Resulting DIN Concentration (μM)	% Decrease in DIN Concentration
Present condition		0.00	45.4	5.0	—
Increase Eel Pond inlet	50%	0.3	45.3	5.0	0.4
	100%	0.4	45.3	5.0	0.4
Increase Waquoit Bay inlet	10%	4.7	43.3	4.7	5
	25%	7.7	41.9	4.6	8
	50%	9.9	40.9	4.5	12
	100%	10.9	40.5	4.4	13
Increase both inlets	50%	10	40.9	4.5	12
	100%	10.9	40.5	4.4	13

107% of annual N loads, and the upper bound harvesting regime could eliminate 90–880% of the annual loads (Table 7). These simulations suggest that harvest, if feasible, could remove considerable amounts of land-derived N from Waquoit Bay. The amount of macroalgal biomass that could realistically be removed from these systems probably lies between the lower and upper bounds presented above.

Dredging Estuary Channels

Increasing the cross sectional area of the inlets increased tidal volume exchange up to 10.9% (Table 8). This increase in tidal volume would reduce the residence time by only 5 h, as indicated by the hydrodynamic model simulations. The results of the ELM simulations suggest that the maximum reduction in DIN concentrations that would result from the 5 h reduction in flushing time was a 13% decrease of present concentrations (Table 8). This difference is only slightly larger than the 8% uncertainty of ELM.

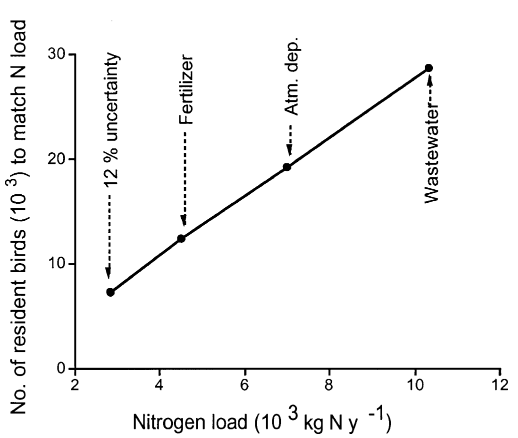

Fig. 9. The bird density that would be required to produce nitrogen loads of the same magnitude as the 12% uncertainty of the model and the loads presently received from fertilizer, atmospheric deposition, and wastewater.

Exterminating Waterfowl

On an annual basis, a single bird would contribute 1 g of N d^{-1}, for a total of 365 g N yr^{-1} (Valiela and Costa 1988). For bird defecation to have a measurable effect on the N loads to Waquoit Bay there must be a sufficient quantity of birds to surpass the 12% uncertainty associated with NLM predictions (roughly 2,850 kg N yr^{-1}). This means that to surpass the error in the model, there would need to be 7,800 birds that were year-round residents contributing daily to the N load of Waquoit Bay (Fig. 9). In Waquoit Bay this is equivalent to roughly 15 birds ha^{-1} over every hectare of estuary surface, every day of the year. This is an unrealistically large number for year-round bird populations. Although numbers of nesting birds can intermittently reach that high in some areas (McColl and Burger 1976), there are few reports of permanent bird populations of that magnitude.

As another comparison, we calculated that for defecation from birds to be equivalent to the contribution from wastewater would require nearly 30,000 birds, or roughly 60 birds ha^{-1}. N contamination from birds, even with unrealistic assumptions, does not seem able to reach the N loads that match those of other sources.

Discussion

The previous sections show examples of how N loading models can be useful tools to investigate a series of different management scenarios for a watershed. A second level of synthesis would be to compare the various options to establish what priorities are most likely to be effective (Table 9). We could not calculate a percent of load attributable to each management option so we rated each option on a scale from 1–5 based on the relative effectiveness of each option at reducing N loads, with a rate of 1 indicating the lowest effectiveness. These ratings were quantitatively assigned in two ways. For management options that would result in a reduction below present N loads (options 1–3

TABLE 9. Summary of effectiveness of proposed management options on the reduction of nitrogen loads and concentrations to Waquoit Bay. Ratings are based on a scale of 1–5 (1 = lowest, 5 = highest). The ranks are based on the sum of the rates, with L = low (sums of 1–4), I = intermediate (sums of 5–7), and H = high (sums of 8–10).

Management Options	Relative Effectiveness of Decreasing N Loads	Feasibility	Sum	Rank
Within-watershed				
1. Decreasing wastewater inputs				
Improving septic system performance	5	5	10	H
Constructing package treatment plants	5	3	8	I
Constructing regional waste treatment plants	5	1	6	I
2. Altering fertilizer use				
Decreasing dose	2	4	6	I
Decreasing area	2	3	5	I
3. Diverting impervious surface runoff	1	2	3	L
4. Altering zoning ordinances	5	4	9	H
5. Preserving forested tracts	5	5	10	H
6. Protecting wetlands				
Lakes and ponds	5	5	10	H
Freshwater wetlands	2	5	7	I
Within-estuary				
7. Protecting salt marshes	4	5	9	H
8. Harvesting macroalgae	5	2	7	I
9. Dredging estuary channels	2	2	4	L
10. Exterminating waterfowl	1	1	2	L

and 7–10 in Table 9) the rating was based on the relative magnitude of reduction in the total N load that each option could have were it to be implemented. If a management option had the ability to substantially reduce N loads below current levels, then it was assigned the highest ranking. For those options that could potentially prevent future increases in loads (options 4–6 in Table 9) the rating was based on the degree to which each option prevents loads from increasing, so that if a management option maintained N loads close to extant loads, it received the highest ranking. We then assessed each option for its perceived feasibility. The feasibility rating (also on a scale of 1–5) was based on the technological difficulty of implementing the option and on our judgement as to the likely socio-political-economic ramifications of each option. We summed the two ratings and from the sum assigned a rank of high, intermediate, or low to each option (Table 9).

Within-watershed Options

Among the within-watershed management options that could lower present day loads (options 1–3 in Table 9) improving septic system performance was given the highest ranking, altering fertilizer use was intermediate, and diverting impervious surface runoff was ranked the lowest. Decreasing wastewater inputs would result in the greatest reduction of present N loads, as it is the largest source of N entering the Bay. Improving the performance of on-site septic systems in extant homes, especially those closer to shore, seems the most feasible way to lower loads.

As urbanization proceeds, it may become necessary to find alternatives to septic systems. Options include a regional plant that services larger areas or the use of smaller structures, referred to as package treatment plants, that can serve smaller neighborhoods. The option for regional treatment facilities is inevitably a costly and politically problematic solution. In the Waquoit Bay watersheds, there would have to be cooperation from three separately constituted municipalities as well as the Federal and State governments, and sites and funds would have to be found. We only mention these additional issues here because these are particularly complicated in this option.

In view of the problems with regional plants, it is becoming increasingly common in Cape Cod to plan for small-scale package treatment plants that are designed to treat effluent volumes of 200–50,000 $m^3\ yr^{-1}$ from local neighborhoods (Environmental Protection Agency [EPA] 2000). Several different types of package plants are commercially available. There are a number of different types of package plants that treat effluent in different ways. The range of reported effectiveness of these plants is from 86–93% when they are properly functioning, but there are frequent reports of systems that fail as a result of storm water pulses and microbial contamination. A properly functioning package plant is capable of N retention that exceeds that of on-site systems, and might be appropriate to manage subareas of watersheds. The funding, legal, and other complications so evident in the case of regional treatment plants are much less problematic in the case of package treatment plants, since only a small and local group of dwellings are serviced. Package plants seem like a good option for new neighborhoods to be constructed in coming years.

N derived from fertilizers is the smallest, though appreciable, source of N to Waquoit Bay. Altering fertilizer use patterns, though relatively feasible, would not be as effective as decreasing wastewater inputs. Diverting runoff from impervious surfaces would not significantly reduce N loads, and it would be costly to reroute water from impervious areas.

For those within-watershed management options that could prevent future increases in N loads (options 4–6 in Table 9), altering zoning ordinances, preserving forested tracts of land, and protecting ponds and freshwater wetlands all ranked in the highest category. All of these regulatory controls can be implemented through legislation, and many of them already are in place. Preventing decreases in lot sizes in zoning legislation will help maintain low loads by limiting the number of houses and the amount of wastewater that could enter the estuary. Preserving forested tracts of land will keep N loads low because of the high retention efficiency of forests, and because it prevents the land from being converted to land uses that would produce more N, such as houses or agricultural crops.

Within-estuary Options

As with ponds and freshwater wetlands, salt marshes remove land-derived N before it enters the estuary and act as a natural filter to protect estuarine water. Preservation of these habitats is on-going through wetlands legislation, and it is important that managers and planners support these efforts on a local scale.

Harvesting macroalgae merits an intermediate rank for the within-estuary management options. This intermediate ranking derives from the large removal of N that is potentially possible, weighted versus some drawbacks. It is necessary to find a method to practically remove algal biomass. Removal of the maximum annual macroalgal crop seems unrealistic, as mechanical harvesters are imperfect, there will be active regrowth, and there are bound to be losses from grazers and decomposition. Removal of macroalgae would probably amount to significantly less than the upper bound reported above. The harvested biomass also needs disposal, which is usually done through composting. Salt contained in the macroalgae may reach the groundwater if the macroalgae is composted, and if the compost is reapplied within the watershed, then the removal by harvest merely relocates, rather than reduces, the amount of N in the watershed-estuary system. There is very little information on the resulting by-catch of benthic animals during macroalgal harvest, and of the ecological effects of habitat alteration that results from macroalgal removal. More research is needed to fully understand these ancillary effects of macroalgal harvesting before it may be implemented.

Dredging estuary channels and exterminating waterfowl received the lowest rankings among the within-estuary management options (Table 9). In view of the considerable cost and habitat disturbance caused by dredging, it seems that, at least for Waquoit Bay, the reduction in N concentrations would be less effective at unloading the system than harvesting macroalgae.

The potential utility of exterminating waterfowl is far less than is usually thought. Many of the waterfowl in fact recycle N already within the water body; such is the case with ducks, coots, rails, gallinules, herons, egrets, and many other bird groups that feed within the water bodies on benthic biota. They merely eat and defecate old N within the system. They do not furnish new N and cannot be considered as sources of N in eutrophic waters. Some birds do bring in new N to a water body, particularly Canada geese in our area. Geese feed elsewhere on turf and agricultural fields, and return to roost in the water body at night. Considering that geese defecate every 20 min or so, the loads they might bring back to the water body are smaller that their daily intake of N contained in grass. In terms of N contributions, waterfowl seems unlikely, on the basis of first principles, to be a significant transport mechanism in most cases. Of course in water bodies where transient birds accumulate at extraordinary densities, their contributions of N may reach considerable magnitudes, but these densities, judging from our calculations, seem unusual.

On the whole, the results of the simulations summarized in Table 9, suggest that improvement of septic system performance, using zoning regulations, preserving forested tracts of land, as well as ponds and salt marshes, appear to offer the highest potential for effective and feasible management of land-derived N loads to estuaries such as Waquoit Bay. A second tier of management options includes consideration of regional or package sewage treatment plants, controls on the use of fertilizers, preservation of freshwater wetlands, and harvest of macroalgae. The final group of options (diverting runoff from impervious surfaces, dredging estuary channels, and exterminating waterfowl) seems less useful or less feasible.

These conclusions refer to our case study in Waquoit Bay. Elsewhere, different land use patterns, population densities, and so on, may lead to other conclusions. The example we provide here is intended to illustrate how the use of models, tied to sufficient land use and ecological information, can form a basis from which to inform management options. The level of detail that was required here to do the evaluations of the various management options should furnish a good template for the kind of information that is necessary to quantitatively assess management options.

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