Eelgrass in Estuarine Research Reserves Along the East Coast, U.S.A.,

Part II: Management of Eelgrass Meadows

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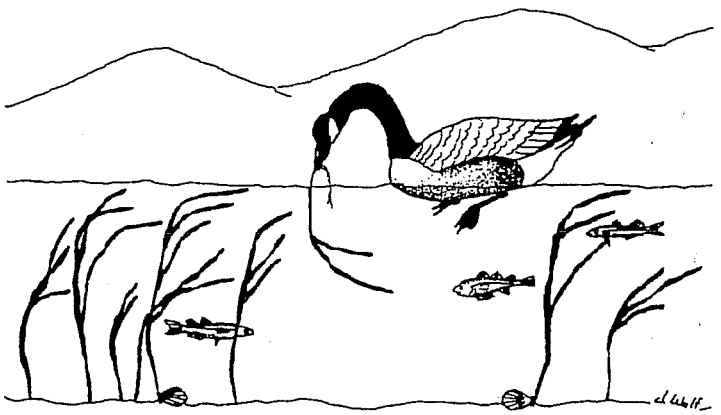

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Management of Eelgrass Meadows in East Coast Research Reserves

ABSTRACT

Eelgrass along the East Coast of the United States is threatened by both pollution and disease, which together are diminishing eelgrass populations in many estuaries. The pollution, mainly wastewater discharge ultimately resulting from intense development of coastal areas, reduces water quality and thereby affects the success of eelgrass growth. The disease affecting eelgrass is a recurrence of the 1930s wasting disease, which at the time destroyed 90% of the eelgrass along the East Coast. Both disease and pollution impact eelgrass health, and each has destroyed eelgrass populations in some locations. Evidence suggests that these two stresses interact, causing eelgrass to die off rapidly. Of the disturbances to eelgrass caused by human activities, the effects of pollution stress appear to have the greatest potential for reducing population size and distribution below naturally recoverable levels if another disease epidemic occurs.

Reduced available light resulting from eutrophication is by far the greatest pollution-related threat to seagrass populations. Other problems include mechanical damage, like dredging and boat traffic, which dig up the beds and suspend sediments, thus contributing significantly to the decline of seagrass. Eelgrass acts as a filter of estuarine waters. Eelgrass stabilizes sediments and provides habitat for scallops, crabs, and other marine organisms; therefore its condition must be a concern to those seeking to protect or restore the health of tidal rivers and estuaries. Since reduced water clarity limits eelgrass production and distribution, loss of water clarity must be rectified before eelgrass can recolonize or be restored to an estuarine area where eelgrass habitat has been destroyed by disease or by marine-related human activities. In cases where water quality is improved, mitigation of environmental damage through the establishment or restoration of eelgrass habitat can be very successful and should be encouraged. Establishment of beds will further improve water quality, habitat value and conditions in potential eelgrass habitats. Estuaries can be managed successfully to sustain eelgrass, the marine habitat it supports, and its complex ecosystem which forms a valuable component of the coastal zone.

INTRODUCTION

Eelgrass, *Zostera marina*, is a marine underwater plant of coastal and estuarine waters that contributes significantly to the ocean's health and productivity. Eelgrass is not a seaweed or algae, but a seagrass. It is a true flowering plant, with roots and rhizomes growing into the muddy sediments of bays and estuaries. The rhizomes send up shoots with leaves from six inches to over a yard long. The

thin, strap-like green eelgrass leaves that float and wave in the tidal currents form extensive underwater meadows. While alive, the leaves are bright green, sometimes with algae and other marine organisms (termed epiphytes) growing on them. When dead, eelgrass blackens and forms a predominant part of the wrack, the lines of dead material along the beach that are washed up by the tides. During the summer, eelgrass flowers pollinate under water and produce seeds which sink to the muddy bottom or are carried away by currents to other sites where they may create new eelgrass beds.

Eelgrass and the ecosystem it fosters are an important part of our coastal environment. Eelgrass is appreciated by shellfish enthusiasts, fishermen, and duck hunters because of its important role in the life cycle of scallops, crabs, finfish, geese, and ducks. The three-dimensional structure of an eelgrass bed provides a breeding area and nursery for young finfish and shellfish such as flounder, scallops, and crabs (Thayer et al. 1984). These dense underwater meadows provide a vertical substrate, or place of attachment, in the water column as well as a haven from predators. In addition, birds such as Canada geese, brant geese, and ducks consume the leaves and seeds of eelgrass as a principal food source. As a result, eelgrass areas are frequent stopping points for migrating waterfowl (Buchsbaum 1987).

In the normal life cycle of eelgrass, many of the leaves break away from the base of the shoots, especially in the fall. Some float away, carried by the currents; others fall to the bottom where they decompose (Phillips 1984). Detritivores begin to break down the leaves into smaller particles, which are consumed by bacteria and fungi. In this detrital process, many invertebrates also consume the decaying eelgrass. The adult and larval forms of these invertebrates become food for larger life forms such as fish and crabs.

Eelgrass communities are valuable sediment traps and help stabilize bottom sediments (Thayer et al. 1975). Because their leaves form a three-dimensional baffle in the water, they act as dampers, reducing water motion. Eelgrass meadows act as a filter of estuarine waters, removing both suspended sediments and dissolved nutrients (Short and Short 1984). Suspended materials carried by currents move into eelgrass beds and are rapidly settled to the bottom. Polluting levels of nutrients entering the estuary from coastal development are taken up by eelgrass leaves for their growth (see review by Short 1987). However, too many nutrients from wastewater effluent and fertilizers can produce algal blooms which then shade and destroy eelgrass ecosystems. For these reasons, eelgrass health is an indicator of the overall health of bays and estuaries.

The value of eelgrass was first noted by Danish biologists in the late 1800s, who recognized its importance to coastal fisheries (Petersen 1891). But the crucial role of eelgrass in coastal ecology was revealed dramatically in the 1930s when a serious disease threatened to eliminate eelgrass (Rasmussen 1977). This catastrophic decline, which became known as the wasting disease, killed over 90% of the North Atlantic eelgrass population (Milne and Milne 1951). As a result, scallops, clams, crabs, and

many fish species suffered from the loss of protective habitat and from the sedimentation and erosion that occurred because eelgrass no longer anchored the bottom sediments. The commercial scallop fishery in North Carolina declined in the early 1930s and completely crashed as a result of the loss of eelgrass (Thayer et al. 1984). In addition, many species of ducks and geese were severely affected; the American brant nearly vanished from the North American flyway (Buchsbaum 1987).

In most areas along the North Atlantic coast, eelgrass recovered from the wasting disease by the 1960s, although in some locations the eelgrass never grew back (Thayer et al. 1984). Now a new outbreak of the disease on both sides of the Atlantic is threatening eelgrass populations (Short et al. 1986). The recurrence of the disease was first noticed in 1984 in New Hampshire's primary estuary, Great Bay (Short et al. 1986). Now diseased plants have been found from Nova Scotia to North Carolina, on the west coast of the United States, and on the coast of Europe (Short et al. 1988).

As with the 1930s wasting disease, plants growing in high salinity waters are most susceptible, while those growing in lower salinities further up the estuaries are more resistant to infection (Short et al. 1987). The symptoms of the current disease are similar to those in the 1930s: first, pinhead-sized black dots appear on the leaves (Short et al. 1988). The dots spread, forming large black stripes and patches. Eventually the whole leaf blackens, dies, breaks off and floats away. If conditions of salinity and temperature are right, then the disease transfers easily from plant to plant within a dense eelgrass meadow. Detrital eelgrass leaves and ocean currents also spread the disease.

A species of *Labyrinthula*, a marine slime mold, was suspected but never proven to be the cause of the 1930s wasting disease. *Labyrinthula zosterae* has now been shown to be the organism responsible for the present outbreak (Short et al. 1987; Muehlstein et al. 1988 and 1991). Localized die-offs have occurred along the East Coast of the United States in upper Casco Bay, Maine; Great Bay, New Hampshire; Stage Harbor, Massachusetts; and Niantic River, Connecticut. Today, *Labyrinthula* and the wasting disease symptoms can be found throughout most of the eelgrass populations on the East Coast. Whether the current outbreak of the wasting disease will prove to be as serious as that of the 1930s remains to be seen.

Besides the wasting disease, the other major factor that limits the production and survival of eelgrass in coastal areas is any pollution resulting in decreased water clarity. Decreased water clarity reduces the amount of light reaching the bottom, shading the eelgrass and reducing its growth (Dennison 1987). The two main factors contributing to water clarity reduction are suspended sediments and increased phytoplankton growth from nutrient loading. Suspended sediments shade the plants directly; nutrient loading shades the plants by promoting planktonic and algal growth (e.g. Dennison et al. 1989).

Suspended sediments result primarily from upland run-off in deep estuaries, and also from boat traffic, wind mixing, and clam digging in shallow estuaries and coastal ponds. Sand, silt, and

clay from disturbed upland areas wash into streams which carry the suspended material into the estuary. Residential and commercial development and rapid rates of clearing and building in estuarine watersheds also contribute suspended sediments. The ultimate effect of suspended sediments in an estuary is a decrease in the light reaching eelgrass and reduction in plant growth, sometimes to the point of elimination.

Nutrient loading results from effluents which reach the estuary from wastewater treatment plants, inadequate septic systems, boat discharge of human and fish wastes, and storm drain run-off carrying animal waste and fertilizers from lawns and farms. Additionally, it has been shown that even successfully functioning septic systems in coastal areas with sandy soils transmit nutrients through ground water directly into estuarine waters (Nixon and Pilson 1983). Nutrient loading is a particular problem in embayments with reduced tidal flushing. Ultimately, the cause of pollution to an estuary is people; increased population density increases the problem. Nutrient loading can cause decreased water clarity through increased phytoplankton growth or through a shift in community dominance to algal growth.

Eutrophication and suspended sediments are the two water quality problems which have the greatest impact on seagrass decline in our coastal zone. Though both restrict seagrass production and distribution by reducing light, eutrophication has the greatest long-term impact on seagrass health and survival. Under low to moderate nutrient loading conditions, seagrass can effectively filter large amounts of nitrogen and phosphorus from the water column (Short and Short 1984). However, the excessive continual loading of nitrogen and phosphorus into the coastal environment eliminates seagrass beds and prevents their reestablishment. The direct impact of eutrophication is the stimulation of competing plant forms which reduce the light available to seagrass (Twilley et al. 1985, Orth and van Montfrans 1983, Short et al. 1989). The plants that compete with seagrasses for light are: 1) phytoplankton (free-floating diatoms and dinoflagellates), 2) macroalgae, and 3) epiphytes (diatoms and algae that are attached to seagrass blades). Excessive nutrient loading can result in a shift to any of the three algal forms (Fig. 1). When these other plant forms thrive, light reaching the eelgrass is greatly reduced, thereby reducing overall eelgrass production and plant density, and ultimately reducing the distribution of seagrass populations. Areas having identifiable seagrass declines resulting from pollution include Chesapeake Bay (Orth and Moore 1983 and 1988, Kemp et al. 1983, Twilley et al. 1985); Indian River, Florida (Kenworthy et al. 1989); Cockburn Sound, Australia (Cambridge and McComb 1984); San Francisco Bay (Wyllie-Echeverria et al. 1989); Waquoit Bay, Massachusetts (Short et al. 1991); and Aburatsubo Bay, Japan (F. T. Short, unpublished data).

After the 1930s wasting disease, eelgrass grew back from the plants in low-salinity areas where the population survived. It is these very up-estuary areas that are now so frequently affected by pollution from septic systems, fertilizing, and other human activities. The complete elimination of eelgrass from an estuary due to pollution, disease, or their combined effects can mean the removal of

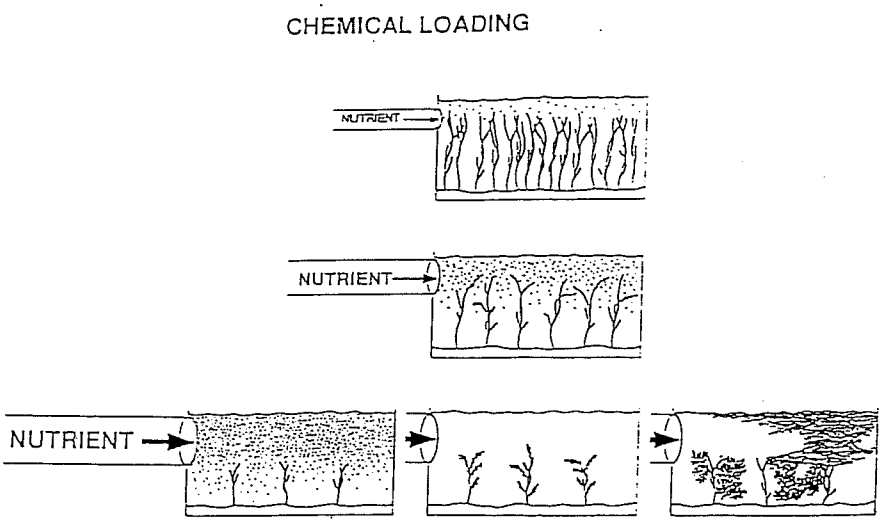

Figure 1. Diagram showing the effects of eutrophication on the seagrass community. Increased nutrient loading negatively impacts seagrasses and promotes a shift to phytoplankton, epiphyte, or macroalgal dominance.

any chance for reestablishment of the eelgrass habitat by natural mechanisms. The only alternative becomes replanting.

Although the wasting disease is currently causing serious losses of eelgrass, the long-term survival and success of eelgrass in our coastal waters will depend largely on water quality in the estuaries. The situation is at the point where estuarine management is necessary to insure the survival of eelgrass and the ecosystem it supports. Factors that are currently decreasing water quality need to be addressed and corrected in order to create a coastal environment that will sustain healthy eelgrass, not to mention other marine organisms. In many embayments along the East Coast, the shallow eelgrass habitats are already in trouble.

The management of estuarine and coastal waters to promote the survival and proliferation of eelgrass populations and to ensure the longevity of eelgrass habitats requires an initial knowledge of the distribution of eelgrass and the seasonal and year-to-year variation in eelgrass abundance. Once the present, and if possible the past, status of eelgrass in an estuary have been established then the ongoing health and survivorship of the existing eelgrass communities can be ascertained. To do this, the factors that contribute to or cause the demise of eelgrass populations must be evaluated. These factors include water clarity, algal competition, the eelgrass wasting disease, sedimentation, and mechanical disruption.

The information presented here includes the results of our work in the field and mesocosms, and the scientific literature pertinent to estuarine management decision making. We discuss how a manager can acquire the necessary information about eelgrass environments and the factors that are currently threatening eelgrass population survival, some of which, at least, are alterable through management practices.

METHODS

We investigated factors responsible for the distribution, loss, or elimination of eelgrass in estuarine environments, specifically researching those factors implicated in the success or failure of eelgrass in an estuary. Aerial photography, a series of field measurements, and mesocosm manipulations were used. The aerial surveys and field studies were conducted within National Estuarine Research Reserves along the East Coast of the United States at the following sites: Beaufort, North Carolina within Middle Marsh in the Rachel Carson Site; the Narragansett Bay Estuarine Research Reserve in the middle of Narragansett Bay, Rhode Island, including the eelgrass populations around Prudence Island; and the Waquoit Bay National Estuarine Research Reserve at Waquoit Bay on Cape Cod, Massachusetts. Additionally, studies were done of the eelgrass populations in the Great Bay Estuary (designated a National Estuarine Research Reserve in 1990), on the New Hampshire-Maine border and in the tidal Niantic River, Connecticut.

The first step in assessing the eelgrass in these bay and estuarine systems was to determine the occurrence and distribution of eelgrass within the estuary. No assessment of impact on eelgrass habitats or on the survival of eelgrass populations can be adequately made without prior documentation of eelgrass distribution. Therefore, maps of eelgrass distribution were made for each of the research sites. Wherever possible, aerial surveys were flown over the bays, and low altitude color photographs were taken of the eelgrass beds using Kodachrome 64 color slide film. Aerial surveys were conducted from aircraft with a special port for vertically mounting a camera in the bottom of the plane. When aerial surveys were not possible, suitable recent historic photographs were acquired from the National Ocean Service, NOAA. The aerial imagery was cataloged by recording the date, location, and elevation on each to provide a permanent record of the distribution of benthic plants and the morphometry of the estuary. Careful analysis of the photographs, combined with ground truth assessments, enabled detailed mapping of eelgrass distribution within the estuaries.

In order to acquire reliable aerial photographs, the photos were taken at low tide or just prior to low tide at a time of day when reflection from the surface of the water is at a minimum. The best combination of conditions often occurred at early morning low tides. The vertical photographic images were projected onto a scaled map and the distribution of eelgrass beds transferred directly. The eelgrass distribution data were then transferred onto a computer map which provided a permanent record of eelgrass distribution patterns within the estuary.

Ground truth observations were, as always, an essential adjunct to the aerial photography. Even experienced analyzers of aerial imagery need ground truth assessment to determine if the submerged features are indeed eelgrass. Under different light, depth, and tide conditions, features like seaweed patches and mussel beds can look like eelgrass beds. Ground truthing surveys are conducted

from small boats at low tide or by SCUBA diving to observe the bottom vegetation at close range. The most efficient method is to do ground truth surveys after photographs have been taken and can be used to guide the observations.

The second step in assessing eelgrass was to use field studies to examine light levels in relation to plant growth. Maintaining sustainable eelgrass habitat in an estuary requires an adequate level of water quality to insure sufficient eelgrass productivity. The lack of water clarity in an estuary strongly affects the eelgrass growth rate and provides a measure of comparability between different estuarine systems. During the peak of production at each of the estuarine study sites, eelgrass growth was measured in conjunction with detailed measurement of water temperature, salinity, and the amount of light reaching the plant surface within the eelgrass bed. The measurement of subsurface light levels is important because it provides information on whether the water clarity is suitable for the sustained growth of eelgrass.

Eelgrass growth was measured by quantifying leaf elongation. An eelgrass shoot was marked with a needle, poking a hole through all the leaves within the bundle sheath just below the top of the sheath. Marking in this way provides a permanent indication of a given elevation on the older leaves that are no longer growing and a measure of new leaf growth over time. The hole on the growing leaf moves up and away from the original marked site as the leaf elongates from the basal meristem. The shoots were collected after one week and the distance between marks was measured. Using this relatively simple marking technique, a large number of leaves can be marked at any particular location, giving an overall average leaf growth rate of a plant community.

Third, a set of manipulative studies of eelgrass were performed in eelgrass mesocosms at the Jackson Estuarine Laboratory. Eelgrass populations were grown in tanks under culture conditions where environmental factors including light and salinity were manipulated in order to assess the response of eelgrass to various environmental stresses (Short 1987). The experiments described here assess the growth and development of eelgrass populations under light conditions which simulate different degrees of water clarity. Environmental parameters including temperature, salinity, and irradiance were measured within each tank throughout the study. The response of eelgrass plant size and growth to the various light levels was investigated. Additionally, we measured the possible response of the eelgrass wasting disease to the various reduced light levels simulating environmental light stress from reduced water clarity.

Eelgrass was planted in the mesocosms in June and light shades made of neutral density screen were placed over the tanks as soon as the "eelgrass beds" were established. The light levels included 94% (no shading), 61%, 41%, 22% and 11% of the surface light conditions. These tanks were initially maintained under reduced salinity conditions (<12 ppt), which prevented the wasting disease from infecting the eelgrass. After the eelgrass had grown for two months and had stabilized in terms of its development relative to the ambient light levels within each tank, growth was measured.

Eelgrass growth in the tanks was monitored periodically and, at the beginning of September, the salinity was allowed to increase to ambient levels and diseased eelgrass plants were introduced into each tank as an inoculum. The spread rate of the wasting disease and degree of eelgrass mortality within the tanks was monitored weekly for the next two months. Growth of eelgrass leaves was monitored by the marking technique described above. The extent of the eelgrass wasting disease was measured by the index method (Burdick et al., in review).

RESULTS

Eelgrass Status

The status of eelgrass in an estuary, coastal pond, lagoon or other coastal area can best be established by assessment of the spatial distribution and some knowledge of the magnitude of the standing biomass in the area in question. For example, the spatial distribution of eelgrass in Niantic River, Connecticut (Fig. 2) was mapped from available aerial photographs. Such photographs show the extent of area cover but do not quantify the density or biomass of eelgrass.

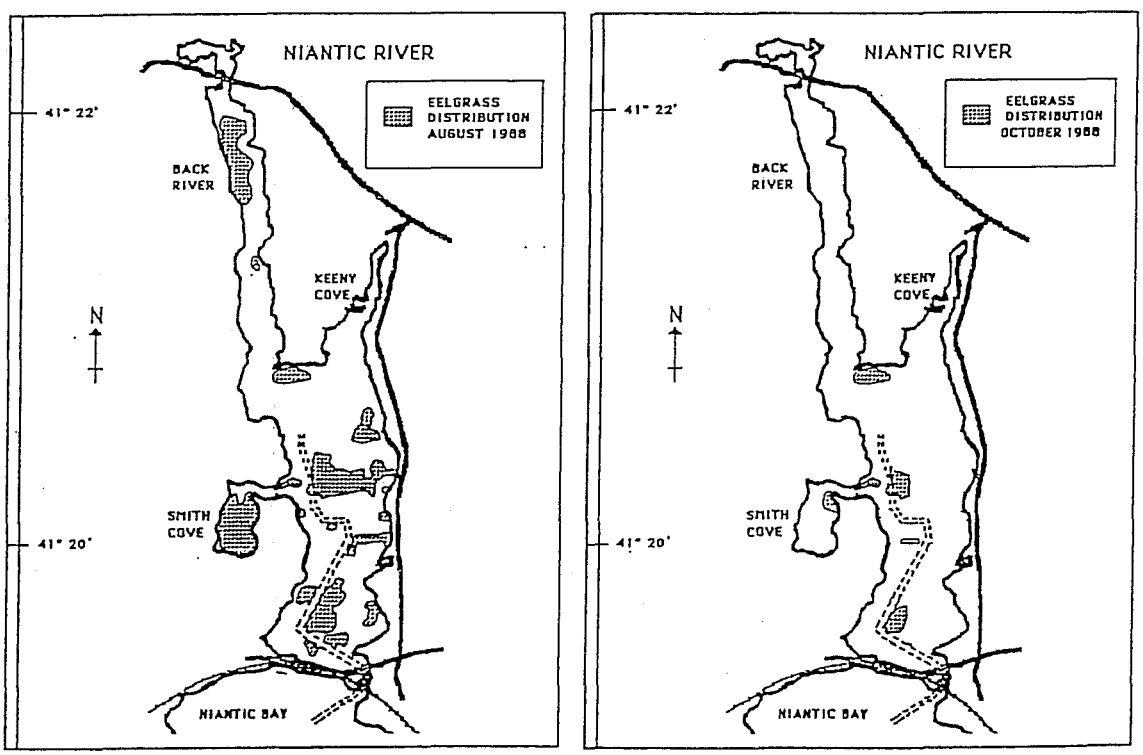

Figure 2. Eelgrass distribution in the Niantic River, Connecticut, on August 5 and September 21, 1988 showing a large decline in eelgrass in the estuary in less than two months.

The standing stock of eelgrass is often highly variable, making quantification of density and biomass a major project. For example, eelgrass density in any particular location can vary from a few plants per square meter to over 2000. Measurements of abundance can have a large seasonal variation as well. For comparison of different estuarine locations, eelgrass biomass in analogous environments was measured at Research Reserves along the East Coast of the United States. Eelgrass biomass vs. latitude is plotted, showing a general decrease in biomass farther south (Fig. 3). A latitudinal variation in eelgrass biomass is evident in literature data (Fig. 4). In general, the annual peak in eelgrass biomass occurs later in the north. More specifically, the time of the greatest biomass increase (a steeper slope of line) shows a distinct shift from June-July for Nova Scotia and New Hampshire in the north to May-June for New Jersey, Virginia, and North Carolina in the south.

In order to understand these phenomena and to manage estuaries in a way that will sustain eelgrass, it is important to examine the factors contributing to these population die-offs and assess their impacts on eelgrass separately and collectively.

Water Clarity

Reduced water clarity is a major problem affecting estuarine and coastal benthic plant communities. Suspended sediments in the water effectively reduce water clarity by increasing turbidity, a process that reduces the depth to which light can penetrate into the water (Dennison 1987, Kenworthy and Haunert 1991). Nutrient loading also reduces water clarity by increasing phytoplankton growth. Thus, increases in turbidity and/or nutrient loading limit how deep benthic plants, like eelgrass, can grow in an estuary.

The question is, in shallow estuaries and coastal ponds, can decreased water clarity from increased turbidity eliminate eelgrass completely? Previous research has shown that the depth limit of eelgrass growth is determined by the amount and duration of light reaching the bottom (Bulthuis 1983; Dennison 1987). However, these results are not directly applicable to the situation of poor water clarity in shallow water, since in deep water the duration of the daylight period changes as well as intensity of light reaching the bottom.

An example of the effect of turbidity on seagrass beds can be found in seagrass beds in Hobe Sound, Florida. The beds have declined rapidly, leading to an investigation that focused on changes in the estuarine environment (Kenworthy et al. 1989). The resuspension of sediments, resulting in part from increased boating activity in the intracoastal waterway, was found to limit light penetration into

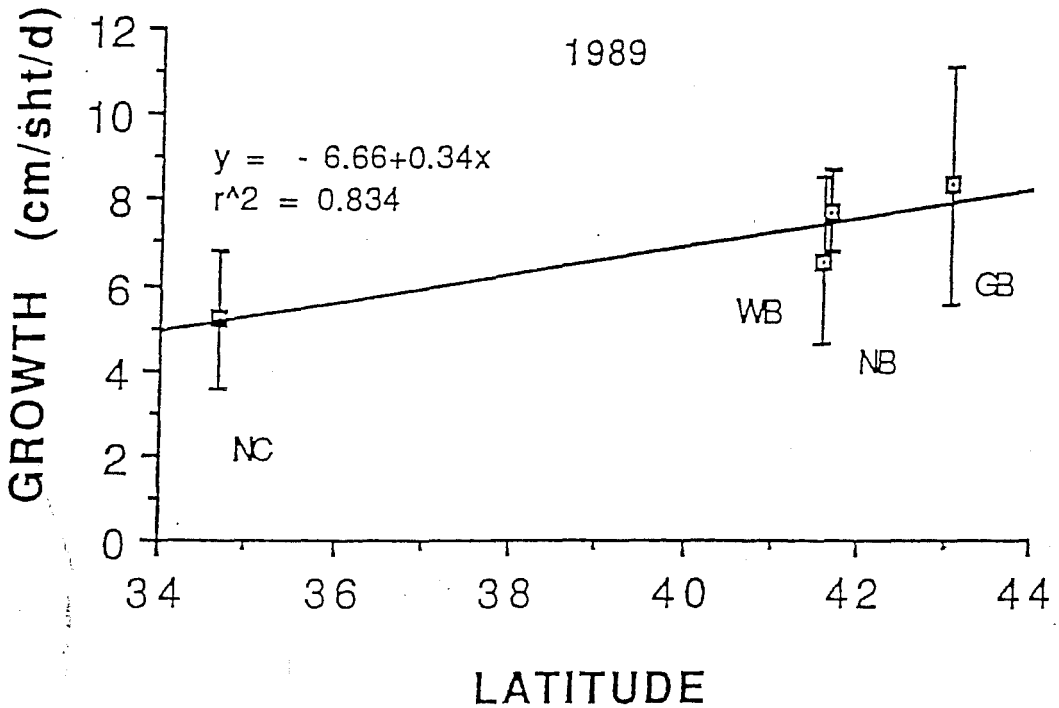

Figure 3. Eelgrass leaf growth vs. latitude for NERR sites. Mean ±1 sd of leaf elongation rate for NC: North Carolina, NB: Narragansett Bay (RI), WB: Waquoit Bay (MA), and GB: Great Bay (NH).

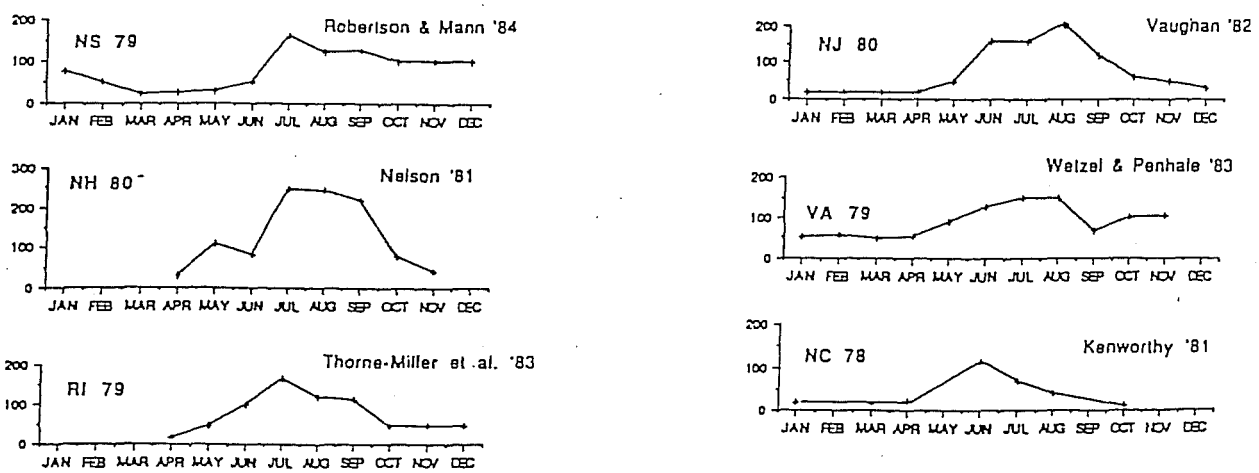

Figure 4. Eelgrass leaf biomass for six sites from north to south. Data from NS: Nova Scotia, NH: New Hampshire, RI: Rhode Island, NJ: New Jersey, VA: Virginia, and NC: North Carolina.

these waters, significantly reducing the depth to which the seagrasses could survive (Kenworthy et al. 1989).

Another cause of reduced water clarity is increased phytoplankton growth resulting from increased nutrient loading. The ultimate impact of eutrophication on the seagrass community is the loss or degradation of the seagrasses themselves and increased primary production causing decreased water clarity. Under conditions of elevated nutrient loading, phytoplankton may bloom (reproduce rapidly) so that their abundance in the water column is great enough that it effectively shades the seagrass canopy, significantly shading the plants. Our experiments with eelgrass have shown that reduction in light decreases growth, promotes a reduction in plant density (Fig. 5), and ultimately can eliminate an eelgrass population altogether.

We investigated the impact of reduced water clarity on eelgrass in shallow waters by testing the effect of reduced light intensity through the use of experimental eelgrass mesocosms (Short 1987). Using the mesocosm approach, light levels can be decreased to simulate various water clarity conditions while other environmental parameters remain the same. Experimental studies of eelgrass in

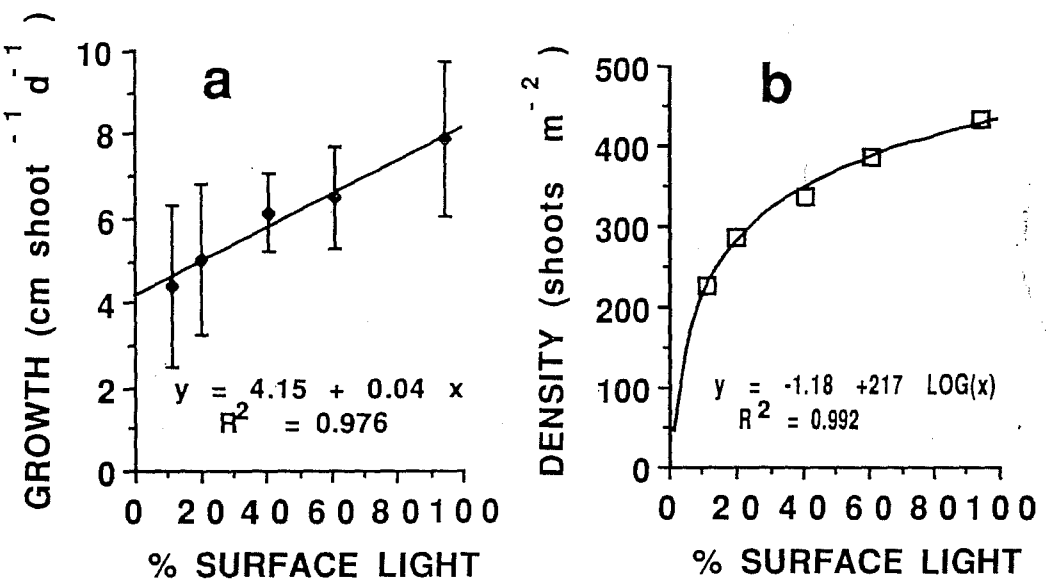

Figure 5. Eelgrass shoot growth (a) and density (b) vs. percent light for plants grown under shaded conditions in the 1988 mesocosm (1.5 m^2 tanks) experiment. Regression analysis of these data demonstrates the influence of reduced light.

shaded shallow mesocosm tanks show that over the short term eelgrass will grow down to very low light levels (approximately 10% surface light, Fig. 5), the compensation depth for eelgrass (Dennison 1987). The light manipulation mesocosm experiments show how dramatically reduced light levels decrease the growth of eelgrass plants (Fig. 5). By any measure, such reduced growth rates stress eelgrass populations. The importance of water clarity to sustaining viable eelgrass beds is evident. Additionally, any increase in water clarity will increase eelgrass growth and improve the overall health of the estuary.

Algal Competition

Two other effects of nutrient loading include: 1) a shift in the community toward domination by green or red macroalgae and 2) the growth of epiphytes on eelgrass blades. Macroalgal domination is typically seen following rapid growth of either small plants initiated as epiphytes attached to seagrass blades, or free-floating algal mats (Fig. 6). Growing rapidly when stimulated by excess nutrient loading, seaweeds become thick mats that overcome and weigh down the eelgrass blades, causing shading stress. In addition, algae take up nutrients more rapidly than seagrass leaves under eutrophic conditions and outcompete the seagrass (Harlin and Thorne-Miller 1981). The excessive production increases the organic flux to the bottom, where decomposing algal material creates anoxic conditions. Such an absence of oxygen negatively affects the entire plant and animal community normally sustained by seagrass.

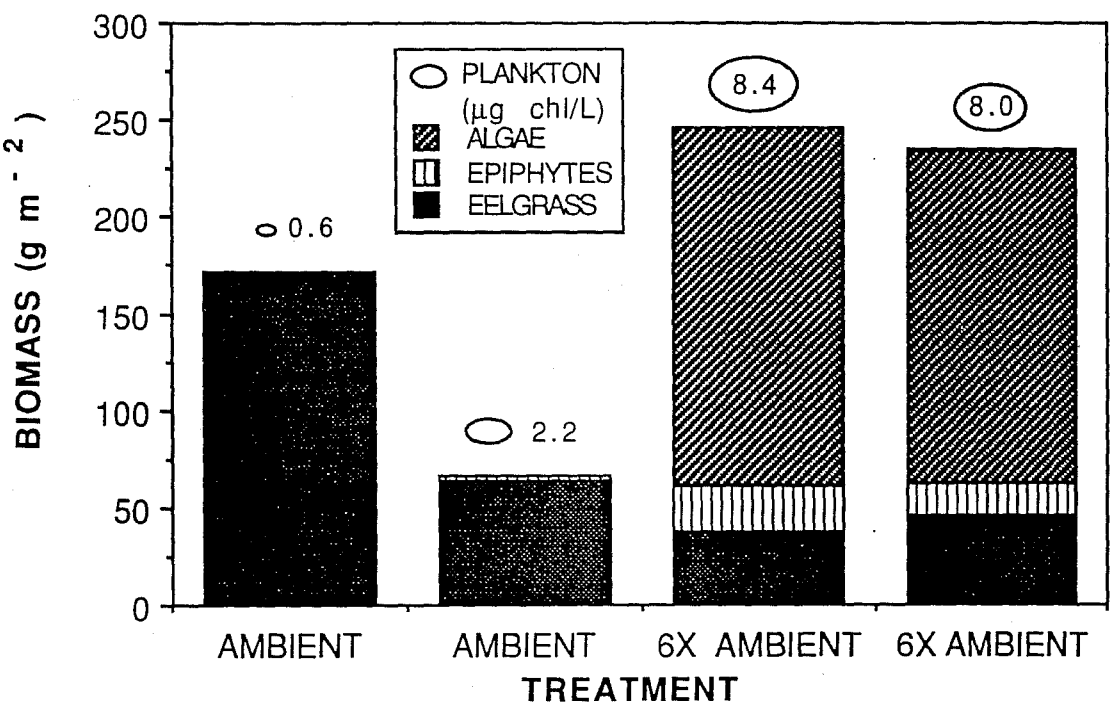

Figure 6. Shifts in the plant community of replicate experimental mesocosms in 1990 following eight weeks of nitrogen and phosphorus enrichment that was six-fold greater than ambient.

The growth of epiphytic diatoms and algae on the eelgrass blades brought on by excess nutrient loading limits both light and nutrients reaching the eelgrass leaves (Fig. 6). As one might suspect, dense epiphytic growth also becomes a detriment to the long-term success of the eelgrass population, primarily through light reduction (Sand-Jensen 1977).

With respect to excess nutrient loading, the factors determining the type of primary producer that proliferates as seagrass declines in dominance are complex and as yet not clearly understood. Evidence from our experimental mesocosms suggests that the type of nutrient entering the system, the availability of various algal propagules to initiate growth, the presence of herbivorous snails and amphipods, as well as the presence of carnivorous fish which regulate amphipod populations, all play a role in determining the plant community resulting from eutrophication (Table 1). Whatever the pathway, the ultimate result of community changes in response to eutrophication is the decline of seagrass and the highly productive habitat it sustains.

Table 1. Outcomes of mesocosm enrichment experiment, 1989, based on descriptive observations. Eelgrass remained dominant in the three replicate control tanks, but was replaced by other plant forms in the three enriched (six-fold ambient N and P) tanks.

PLANT DOMINANCE	CONTROL	NUTRIENTS	NUTRIENTS & AMPHIPODS	NUTRIENTS, AMPHIPODS & FISH
Eelgrass	X X X			
Plankton		X		
Macroalgae			X	
Epiphytes				X

Wasting Disease

The recent recurrence of the eelgrass wasting disease (Short et al. 1986) adds a complicating factor to the investigation of eelgrass declines, as the disease accelerates and intensifies the demise of eelgrass populations in many estuarine and coastal environments. Losses of eelgrass due to the wasting disease may eliminate eelgrass from any environment where conditions favor the pathogen or where eelgrass populations are stressed, producing changes in the habitat that will decrease water quality, thereby creating conditions that are inhospitable for the natural revegetation of eelgrass. Currently, the prospects for combating the wasting disease are poor.

The extent and intensity of the current wasting disease will likely be determined by global climatic conditions (Short et al. 1988). However, present-day problems of diminishing water quality in the coastal zone will also impact the severity of the wasting disease (see below). The causal organism is a slime-mold-like protozoan of the genus *Labyrinthula* (Muehlstein et al. 1988) which infects and kills eelgrass. The wasting index is a quantitative measure of the extent of this infection. The spread of the wasting disease followed in outdoor mesocosms showed that decreases in seawater salinity improved eelgrass survival (Short et al. 1989). As available light is decreased, eelgrass becomes more susceptible to infection by wasting disease which in turn can kill plants and eliminate whole populations (Fig. 7).

Sedimentation

The effect of sediment load on the eelgrass, aside from the impact on water clarity, has received little or no attention. In many areas, suspended sediments in the water column drastically reduce the depth to which seagrasses can grow and in some areas may eliminate seagrass populations altogether. Our field studies and those of others have observed populations of eelgrass that have suffered from heavy deposition of sediments on seagrass leaves (Short and Short 1984). In some cases the deposit

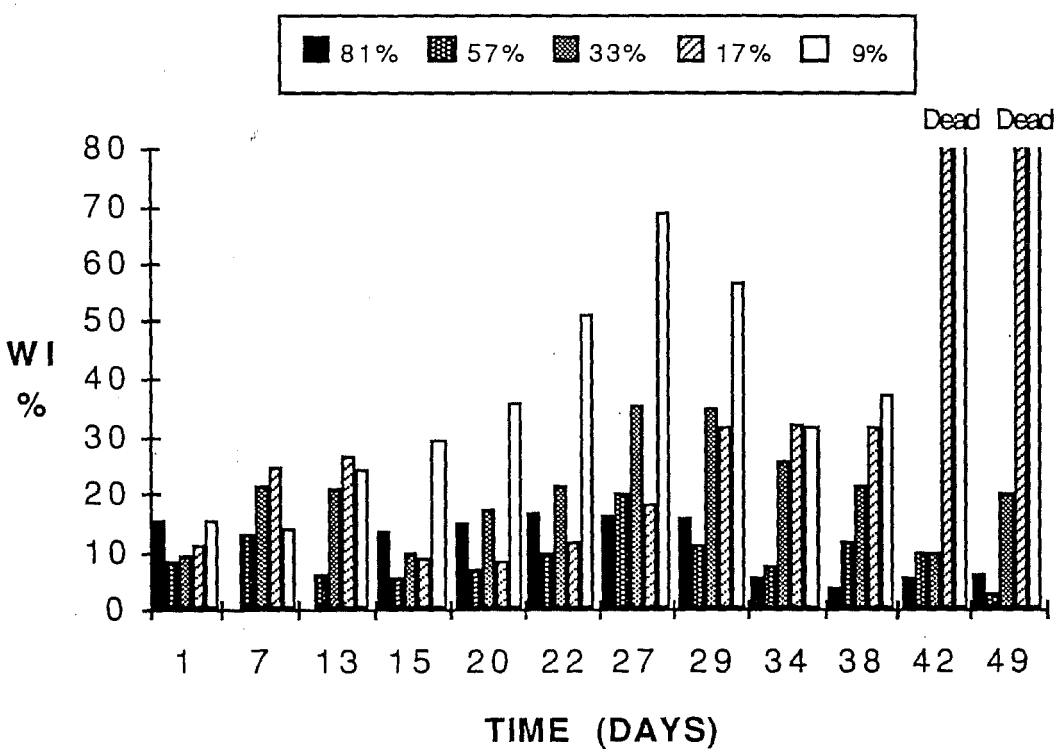

Figure 7. Wasting Index (WI) as percent surface area for eelgrass shoots at five light levels (81, 57, 33, 17, 9%) in a mesocosm shading experiment, starting October 11, 1988. Shoots at the lowest light levels were dead after 42 days.

of sediments is sufficient to prevent the plants from maintaining their upright floating position in the water. The impact of sedimentation is often increased where epiphytes are abundant on eelgrass blades, because epiphitized blades collect a greater quantity of sediment. The blades and the epiphytes appear dull brown when coated with a fine layer of sediment, and they often sink to the bottom. When eelgrass in this condition is disturbed, a cloud of sediment is released into the water. The magnitude of smothering by sediments in an estuarine environment is difficult to predict, although it has the potential for eliminating eelgrass from heavily impacted areas. This is an area of research that requires study.

Mechanical Disruption

Another less well known aspect involving the destruction of eelgrass beds is mechanical damage. We define mechanical disruption of eelgrass as activities in the coastal zone that cause eelgrass leaves to be broken off or entire eelgrass plants to be uprooted. Some mechanical disruptions causing eelgrass loss include: motorboat propellers cutting through eelgrass beds or digging into the mud, clam diggers collecting from eelgrass covered areas, and bottom draggers pulling nets and trawls through eelgrass beds.

Information on mechanical disruption is mostly limited to casual observation and anecdotal reports. The absence of eelgrass beds at the mouth of the Moonakis River in Waquoit Bay, MA may be due, in part, to intense shellfishing activity in this area. In some estuaries, shellfish harvest is restricted in eelgrass beds. The magnitude of this impact on eelgrass beds can be large and the effect long lived, as seen in damaged tropical seagrass areas where long ditches dug by propellers remained unvegetated for years (Zieman 1976). Dock facilities for boats also have detrimental effects on seagrass by concentrating boating activity and shading beds that were able to survive or recolonize following dock construction. Mooring chains swinging around their mooring blocks create circular bare patches within seagrass meadows (Fig. 8). Other activities like fin and shellfishing using trawls and nets also disrupt eelgrass beds. Overall, the impact of mechanical disruption may be substantial and research in this area is necessary.

GUIDELINES FOR SUSTAINING HEALTHY EELGRASS BEDS

The overall goal of this research project has been to develop a comprehensive understanding of the interactions of eelgrass with various environmental situations that threaten eelgrass populations. A large part of our effort has focused on investigation of the threats to eelgrass habitats so we can provide information useful in the management of estuarine areas. Our experimental research as well as our field studies have focused on developing quantitative relationships between characteristics

Figure 8. Aerial photograph showing the damage to eelgrass beds from a boat mooring in Waquoit Bay, MA.

of eelgrass success and environmental influences. In completion of this report, we have collected the scientific information and presented the documentation that supports that information, and constructed a management guideline that will be useful for Estuarine Research Reserve managers and managers of other estuaries in their efforts to maintain the health of estuarine systems. Successful management strategies will promote a suitable environment for the survival and expansion of eelgrass populations.

Eelgrass Distribution

A fundamental requirement for such an undertaking is an understanding of the current distribution of eelgrass populations. The status of eelgrass populations within each of the Research Reserves has been carefully documented through the use of aerial photography. Ground truth verification and assessment has been performed to insure the accuracy of aerial photographic interpretation. The information from these initial evaluations has been combined to construct maps of eelgrass distribution for each of the Research Reserves. Because the assessment of eelgrass status is critically important in determining the rate of change in eelgrass populations over time, we recommend that surveys of eelgrass populations be done annually during the mid to late summer season.

Once the status of eelgrass populations has been established for several consecutive years, it is then possible to determine from these maps the overall population size of eelgrass in the Reserves and determine the increase or decrease in population over time within these systems. In estuaries that have been shown to have stable eelgrass populations, assessments are necessary only every two or three years. Overlay maps of year to year change in eelgrass populations provide a graphic documentation of problems of population loss within each Reserve. To correct such problems, these eelgrass

distribution maps are useful in establishing restricted areas for human activities, such as boating and fin or shell fish collection that may be necessary for preservation of the eelgrass population. Further, these maps illustrate to managers and to the general public that extensive submerged wetland environments exist or once existed within estuarine waters of the estuary, and that care must be taken to protect and enhance these wetlands in addition to the other wetlands within the estuary.

Threats to Eelgrass Habitats

A large part of our research project was the investigation of conditions threatening eelgrass populations within the Research Reserves on the East Coast of the United States. A list of symptoms of deteriorating eelgrass populations with associated causes has been developed that includes suggestions for management to improve estuarine health (Table 2). The following paragraphs discuss possible reasons for declining estuarine health, followed by a section of recommendations, both of which are outlined in Table 2.

The primary factor responsible for the reduction in eelgrass populations in these Estuarine Reserves has been identified as a decrease in water clarity within an estuary. Reduced water clarity is caused by an increase in the quantity of suspended particles in the water column and may result from increased turbidity or increased phytoplankton populations. Increased turbidity in the estuary is caused by suspended sediments within the water column (either resuspended by natural and man-induced processes, or entering the estuary through riverine systems).

Large suspended sediment loads of riverine inputs resulting from upland development within the watershed are fast becoming a chronic disturbance to seagrass populations. Increased phytoplankton populations result directly from increased nutrient loading or from eutrophication of the estuary, as discussed below. The minimum water clarity required to sustain eelgrass populations in an estuary is determined to be between 10 to 20 percent of ambient surface water light levels. Below 10% surface light, eelgrass does not survive. Data from our mesocosm experiments and field studies demonstrate that the growth rate of eelgrass increases directly with the amount of light available. Thus as estuarine water becomes clearer, the productivity of eelgrass populations will increase, and in turn the overall health of the estuary will improve. A clear knowledge of this response is very important to managers because it shows that efforts to increase the water clarity of an estuary will have a direct impact on the productivity of eelgrass populations and indirect effects on water quality, living resources, and recreational/aesthetic qualities of the estuary.

Eutrophication resulting from increased nutrient loading into upper estuaries is the greatest single process occurring in estuarine systems that threatens eelgrass populations and the health and survival of our present estuarine ecosystems. As discussed above, eutrophication is a main contributor to reduction in water clarity in coastal and estuarine waters, and by definition, stimulates algal growth which changes the plant community and further degrades the estuarine environment. These algae

include attached algal forms on the blades of eelgrass (epiphytes), as well as excessive growth of seaweeds. From the original community dominated by eelgrass, eutrophication leads to an algal dominated community which ultimately decreases the productivity of the estuary as physical characteristics are changed (e.g., anoxic events) and important resources are altered or eliminated (e.g., shellfish kills).

At low levels of nutrient loading in an estuary, eelgrass populations can absorb a large portion of the nutrients available from the water column through their leaves. In doing so, eelgrass acts as a filter in the estuary, cleaning the water. As nutrient loading increases, a point is reached at which eelgrass can no longer absorb all the nutrients and algal growth is stimulated. Once this begins to happen, the eelgrass is negatively impacted in a way that results in the algal domination characteristic of eutrophication. Determining the level of nutrient loading that an estuarine system can withstand is a difficult prospect and one that is the current focus of our ongoing research funded by NOAA's Coastal Ocean Program. Research to date has shown that eelgrass populations exposed to six times ambient nutrient loading rates (which translated to approximately 12 μMolar ammonia and 4 μMolar phosphate concentrations in the water during active removal of these nutrients by the entire primary producer community) can be severely degraded by excessive growth of phytoplankton, epiphyte, and seaweed populations. Our field work also demonstrates that plants growing in the ambient nutrient conditions of Great Bay are impacted to some degree by increasing nutrient levels in the water column promoting the growth of algal competitors.

The major challenge to estuarine managers is to begin the process of reversing eutrophication. This is most effectively begun by an aggressive program of education to increase public awareness of the threat to our estuaries. Much of the problem results from inadequately treated wastewater discharge. Although upgrading wastewater treatment facilities is expensive, maintaining a healthy estuary has its own economic value. The second most important source of eutrophication is non-point source pollution, including a number of sources that all require specific attention. Given an awareness of these problems, managers can immediately do a great deal to decrease the loading from non-point sources. A specific example would be to coordinate volunteer groups to identify non-point sources from old or failed septic systems and work with local health officials to reduce this problem. Agriculturally based inputs of nutrients can be reduced by managers working with farmers and the U. S. Soil Conservation Service to improve land use practices, and to develop a fertilizer application program that will save money and reduce nutrient inputs to the estuary. Another volunteer group could identify poor land use practices occurring adjacent to the estuary and work with managers and landowners to reduce non-point sources (e.g., planting or expanding buffer strips of natural, unmanaged vegetation that will intercept nutrients in runoff waters). Managers can work with local officials, including the conservation commissions (or similar groups that regulate development adjacent to wetlands), to strictly enforce conditions set forth in development permits in sensitive areas, and create an area of special concern surrounding the estuary and its water sources (where stricter guidelines for resource protection would apply).

Table 2. Signs of deteriorating eelgrass habitats that indicate decline of estuarine health.

HEALTH PROBLEMS	POSSIBLE CAUSES	MANAGEMENT ACTION
Lack of eelgrass in areas where there are historical records of beds, or in a shallow estuary	Reduced water clarity, algal competition, wasting disease, lack of seed source	Initiate studies of estuarine health and enforce water quality regulations
Loss of eelgrass from deep sites or upper areas of an estuary	Increased sediment load Eutrophication	Curb upland runnoff into estuary Investigate and set up a manage ment plan to reduce N & P loading (from point and/or non-point sources), or increase flushing
Abundant black spots on young eelgrass leaves	Wasting disease	Monitor wasting disease using the wasting index; notify the Wasting Disease Hotline: 603-862-1170
Heavy algal epiphyte covering on eelgrass leaves	Eutrophication	Investigate and set up a management plan to reduce N & P loading or increase estuarine flushing.
Replacement or invasion of eelgrass beds by seaweeds	Eutrophication	Reduce N & P loading or increase flushing, as above
Reductions in fish populations or bird use	Decreased water quality, loss of eelgrass/trophic disturbances	Initiate study of estuarine ecology (water quality, eelgrass, fish, and bird populations)
Ditches or cuts through shallow eelgrass beds	Boat or other human activity	Regulate boat speed, mark safe channels, restrict access to areas with vulnerable beds

The eelgrass wasting disease is the other major factor contributing to the decline of eelgrass populations in Estuarine Research Reserves on the East Coast. The disease has been measured using a quantitative assessment of infected tissue relative to uninfected tissue in eelgrass populations. High wasting indices have been closely associated with mass mortality in eelgrass from disease. The contributing factors to the death of eelgrass populations from the disease are first, the presence of *Labyrinthula zosterae*, the pathogenic slime mold that causes the disease, and second, environmental variation and disturbances that stress eelgrass populations and increase their susceptibility to the disease. We have found no mechanisms for dealing with the pathogen attack of the host. At this point, the best mechanism to reduce the spread of disease within the eelgrass populations is reduction in the levels of disturbance that produce stress in these populations, particularly the elimination of pollution problems within the estuary (see above). One of the methods for recouping losses of eelgrass from either pollution or disease is restoration or creation of new grass beds through transplanting. The methods and mechanisms for achieving adequate transplant success are currently under investigation.

Other factors that contribute to the decline of eelgrass populations include the deposit of sediments on eelgrass blades from increases in sediment loading to an estuary, or change in the structure of the estuary such that sediments are resuspended more easily. Eelgrass acts as a filter to remove a large portion of this sediment material, thus improving water clarity. The relative importance of this process is also currently under investigation. Methodology and technology to reduce the upland inputs of sediments to an estuary is readily available. Managers must make it a priority to eliminate these sediment sources by ensuring the use of erosion control structures, replacing drainpipes with settlement basins, and implementing the construction of sediment filtering mechanisms at the upland/water interface.

Mechanical disruption of eelgrass populations is also a factor that leads to eelgrass population loss. Little is known about the extent and magnitude of physical disruption in different systems. Future research needs to assess impacts quantitatively, evaluate these effects in different environments, and develop management criteria for dealing with these problems. As a first step, a conservative position must be taken by managers to oppose construction of docks, moorings, or channels in eelgrass beds. In addition, boat speed limitations should be regulated and enforced in eelgrass areas.

RECOMMENDATIONS

What follows are our recommendations for achieving healthy eelgrass habitat and encouraging a recovery of marine life by improving water quality over the long term. These recommendations are arranged roughly in order of their value for rapid water quality improvement. The order of importance may be different for shallow and deep estuaries.

Improve Wastewater Treatment

The problem of septic leachate entering the river through groundwater flow, as well as that of inadequate or overused septic systems, must be resolved if water quality is to improve in the long term. Nutrient input from septic systems represents the largest problem affecting water quality in many coastal areas. Unfortunately, it is also probably the most expensive problem to correct. We strongly recommend that cities and towns place a high priority on the installation of sewers around the periphery of rivers and estuaries. Otherwise, water quality will continue to deteriorate in these coastal areas as development pressure increases. We recommend upgrading wastewater treatment plants to include tertiary treatment that eliminates the discharge of nutrients into estuarine watersheds. More effort must be put into the development of innovative methods for treatment of wastewaters.

Control Surface Run-off

The problem of run-off and the pollutants that it carries is difficult to control. A large combination of sources contribute to run-off which carries sediments, nutrients, and other pollutants such as oil, fecal bacteria, and heavy metals into the estuary. Current practice discharges these materials into our rivers and bays through storm drains and road ditches, as well as through direct inputs from surrounding dwellings and farms. Problems of run-off from drains and ditches can be regulated by local government installation of settlement ponds and dry wells that collect and filter run-off before it reaches the estuary. Direct inputs are more difficult to control. In many cases they can be handled by enforcement of federal regulation. Alternatively, education of coastal dwellers can have a major positive impact. Because run-off has so many non-point sources, its management may require a substantial effort involving much planning, time, and money to achieve real change necessary for improved water quality in many of our bays and estuary.

Regulate Boat Traffic

Boat speeds should be restricted within shallow bays and estuaries to avoid resuspension of sediments, and boat channels should be clearly marked and their use enforced, especially for low-tide boating so that the shallow flats are avoided. Boat mooring and docking facilities should be limited to control boat density and the shading of the estuary bottom. Federal laws should be enforced to eliminate overboard discharge of wastes from boats. These changes will require regulatory and enforcement action. However, they represent relatively low cost efforts that will contribute substantially to improved water clarity and decrease mechanical disruption.

Restore Eelgrass Beds

Methods for successful transplanting of eelgrass have been experimentally worked out (Fonseca et al. 1982a). These methods have been tested in North Carolina (Fonseca et al. 1982b), Chesapeake Bay (Orth and Moore 1988), and Connecticut (Short 1988). In Connecticut, specific methods for planting in areas destroyed by the wasting disease were developed (Short 1988).

Establishing the transplant units with adequate space between them insures that plant-to-plant transmission of the wasting disease will not eliminate the bed in the first few years, thus reestablishing valuable habitat. Given the value of eelgrass habitat, in many areas it is cost effective to undertake repeated annual eelgrass transplant efforts in order to maintain habitat necessary to sustaining marine resources like scallop fisheries.

Restrict Fish and Shellfish Harvest

In areas where fish or shellfish dragging is mechanically damaging to the eelgrass bed or where shellfish collection creates sediment plumes that decrease water clarity, regulations should be implemented that restrict the time or area of harvest. Such laws and their enforcement are particularly important while the threat of the eelgrass wasting disease is present because of the interaction of disease and environmental stress.

OPPORTUNITY FOR MANAGEMENT ACTION

The future of our estuarine environments is now in question and managers are in a position to make a major difference. We now understand that our land-based natural resources must be managed to maintain air and water quality and to preserve these irreplaceable resources; the challenge now is to educate the public and local governments to understand that underwater estuarine resources are of equal value and require the same degree of management.

This management document describes the results and conclusions of our scientific investigations so that managers can apply our recommendations directly to problems within the Research Reserves. Factors like the cost and availability of eelgrass restoration and creation efforts still need further investigation. However, it is clear that eelgrass can be used as an indicator in the estuarine system to show whether the system is in balance, or if changing conditions (such as eutrophication) are leading to degradation of the estuarine environment. We now know that environmental impacts of upland change and development in near shore areas have a major impact on coastal and estuarine waters. This impact is translated directly into the health and productivity of eelgrass, which, because of its unique combination of roles, can be used as a barometer to indicate when the problems of pollution and human development will begin to dramatically change the character of the estuarine environment. With our current understanding of eelgrass populations, managers are in a good position to press for the implementation of regulations, or in many cases the enforcement of existing regulations, that will begin to turn conditions around to favor eelgrass survival and to promote estuarine health.

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