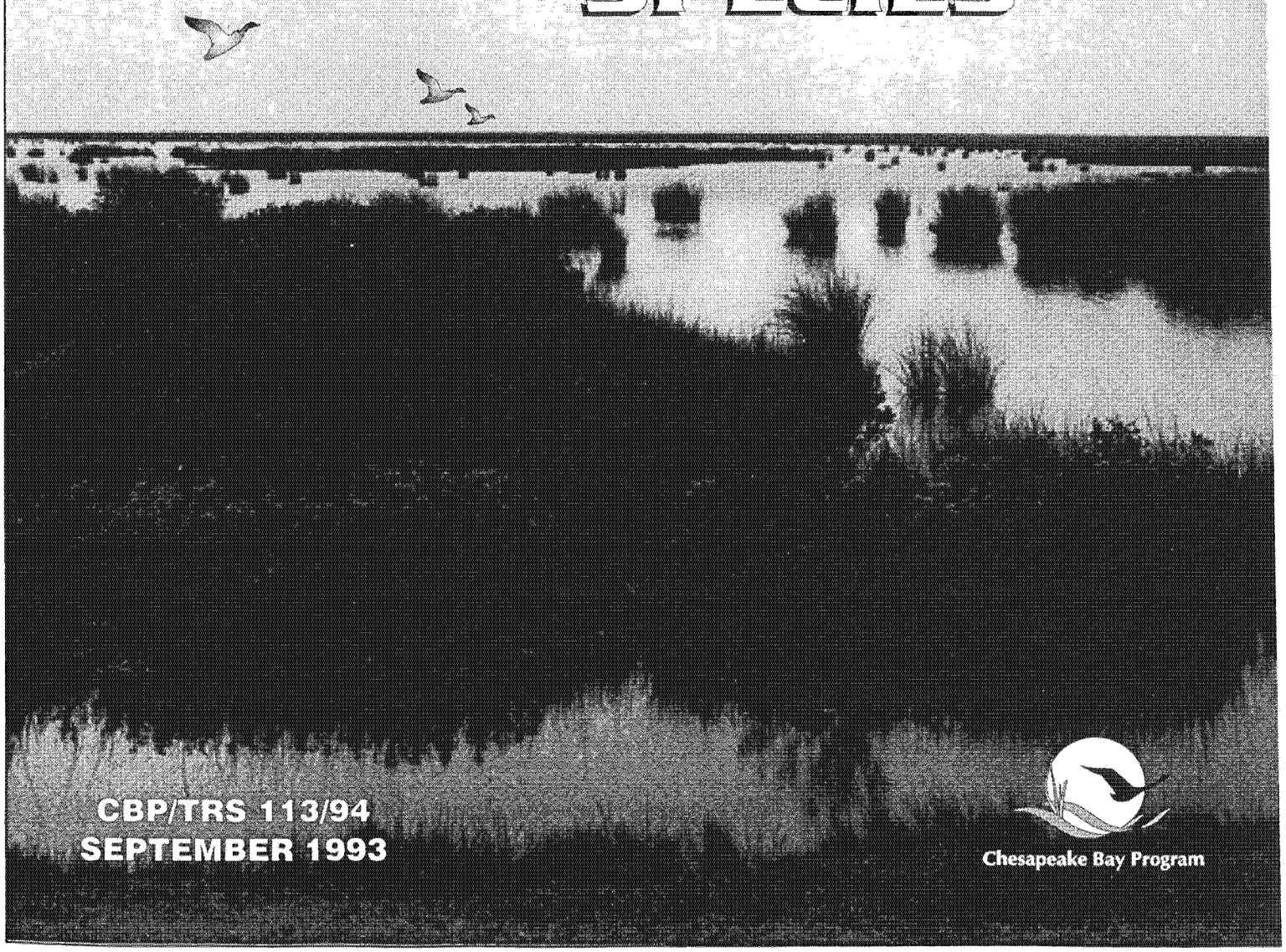
CHESAPEAKE BAY STRATEGY FOR THE RESTORATION AND PROTECTION OF

ECOLOGICALLY VALUABLE SPECIES



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Chesapeake Bay Program

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FOR
THE CHESAPEAKE BAY PROGRAM

Chesapeake Bay Strategy for the Restoration and Protection of Ecologically Valuable Species

Prepared by
the Ecologically Valuable Species Workgroup
of the Living Resources Subcommittee

September 1993
CBP/TRS 113/94

ADOPTION STATEMENT

We, the undersigned, adopt the Chesapeake Bay Strategy for the Restoration and Protection of Ecologically Valuable Species, in fulfillment of the commitments of the Living Resources section of the 1987 Chesapeake Bay Agreement:

> *"to develop, adopt, and begin to implement a Bay-wide plan for ... ecologically valuable species," and "the development of Bay-wide resource management strategies for ... ecologically valuable species."*

We agree to accept the Strategy as a guide in the restoration and protection of ecologically valuable species and their functional roles in the Chesapeake ecosystem. We agree to support this Strategy as a mechanism for cross-program integration of the various fishery management plans, waterfowl management plans, habitat restoration plans, and other Chesapeake Bay Program plans. We further agree to work together to implement the major recommendations of the Strategy: (1) provision of educational and informational aids to understanding the Bay as an ecosystem, (2) pursuit of a program to develop simulation models of the Chesapeake ecosystem, (3) development of a comprehensive habitat restoration and management plan for Chesapeake Bay, (4) development and implementation of a consistent system of biological indicators of ecosystem integrity, (5) continuing long-term support for key living resources monitoring programs, (6) expand the utility of the Chesapeake Bay living resources database as outlined in the Strategy, and (7) promote directed research on ecologically valuable species.

We recognize the need to commit long-term, stable financial support and human resources to the task of protecting the indigenous species, habitats and biological diversity of the Chesapeake region.

Date September 1993

For the Commonwealth of Virginia

For the State of Maryland

For the Commonwealth of Pennsylvania

For the United States of America

For the District of Columbia

For the Chesapeake Bay Commission

ACKNOWLEDGEMENTS

We want to thank all the members of the Ecologically Valuable Species Workgroup for their valuable input. This work could not have been completed without the help of a grant from the Maryland Coastal Zone Management Program and staff support of the Maryland Department of Natural Resources. We also want to thank the members of the Living Resources and Monitoring Subcommittees, and the contributing authors (see Appendix B).

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EXECUTIVE SUMMARY

Overview

In 1987, executives of the Chesapeake Bay Commission, the District of Columbia, Maryland, Pennsylvania, Virginia and the U.S. Environmental Protection Agency signed the Chesapeake Bay Agreement, pledging to initiate management plans for "commercially, recreationally, and ecologically valuable species." To meet the last part of this commitment, the Ecologically Valuable Species Workgroup was organized by the Living Resources Subcommittee of the Chesapeake Bay Program, and charged with development of a plan for ecologically valuable species. The concept developed by the Work Group, in consultation with a group of scientific experts, is not a management plan in the traditional sense, but rather a strategic plan: to view the Bay as an ecosystem, composed of biological communities that interact with the physical and chemical factors of their surroundings to function as a single unit; and to build management recommendations around this holistic view of the Chesapeake ecosystem. The ecologically valuable species in the Bay connect management in all domains (e.g., fisheries, water quality, and habitat) to ecosystem responses, but usually cannot be managed directly. Therefore, this Strategy has provided an opportunity to explore and make more explicit the connections within the spectrum of management efforts to restore and protect the Chesapeake.

The better-known Chesapeake Bay species, the oysters, crabs, striped bass, and wildlife, depend on ecologically valuable species for survival: for nutrients and energy, habitat structure, and relief from predators and competitors. Many ecologically valuable species, though most people would recognize neither their names or appearances, are the balancing elements in the Bay ecosystem. No matter what is done to control nutrients and improve habitat conditions, there must be an adequate base of zooplankton, forage fish and benthic animals for healthy and productive populations of recreational and commercial finfish to be supported.

Ecologically valuable species are defined in the Strategy as those species or groups of species that have significant functions in the ecosystem, by:

1) regulating populations of other species (prey and predators);
2) regulating the quantity and quality of habitat for other species (e.g., oysters and submersed aquatic vegetation);
3) processing large amounts of material (nutrients, organic and inorganic matter) by both physical and chemical means (phytoplankton, bacteria, filter feeders); or
4) producing organic matter (phytoplankton, SAV, plants of marshes and shorelines).

This definition does not exclude species of commercial and recreational importance, but rather puts them in context as members of biological communities where they are valuable for their ecological functions rather than for their value to humans.

Vision of the Chesapeake ecosystem

The vision of the Chesapeake Bay ecosystem developed in the Strategy derives directly from the 1987 Bay Agreement. The framers of the Agreement realized that "...the entire system must be balanced, healthy, and productive." The Strategy offers working definitions of "balanced," "healthy," and "productive," and explores the implications of this vision for management, monitoring, and research.

Balanced
having sufficient populations of prey species to support the species at the top of the food chain, and to limit overabundance at the bottom of the food chain; no major function of the ecosystem dominates the others;

Healthy
having diverse populations that fluctuate within acceptable bounds; free from serious impacts of toxic contaminants, parasites, and pathogens; having sufficient habitat to support a diversity of species;

Productive
providing sufficient production of harvestable products to serve human needs without depleting predator and grazer populations to the point where internal, functional balance is disrupted.

Management
Because most of the ecologically valuable species cannot be managed directly, the Work Group had to ask "what are the control points where management can help to achieve the vision of a balanced, healthy and productive ecosystem?" For example, the concepts of top-down and bottom-up ecosystem control are discussed in the context of the Chesapeake system. In the Chesapeake, bottom-up control is represented principally by nutrient management, a central focus of the Bay Program since its inception. Top-down control includes protection and restoration of fisheries populations and their habitats, a more recent and less certain aspect of Bay management. The interaction of bottom-up and top-down controls needed to attain a balanced and productive ecosystem is not known for the Chesapeake. The Strategy recommends filling this knowledge gap by developing simulation models of the ecosystem, so that the results of various mixes of controls can be predicted.

The Strategy also recommends the development of educational materials to better inform both managers and the public about ecologically valuable species and their vital roles in the ecosytem.

Monitoring
Effective management depends on up-to-date feedback from the ecosystem. Traditionally, the Chesapeake Bay Program has relied largely on measures of water quality (dissolved oxygen, nutrients, and chlorophyll), supplemented by the status of a few major fishery resources, to measure the integrity of the Chesapeake ecosystem. Ecosystem indicators (including both biological and habitat indicators) can be more directly reflective of balance, health and productivity than chemical or physical monitoring, and are readily available or can be developed with relative ease. These community-based indicators are more reflective of the balance, health, and productivity of ecologically valuable species than, for example, fishery statistics or other abundance indices for commerical fishery species. The Strategy advocates the further development and consistent use of ecosystem indicators.

Research
Many of the most important ecologically valuable species in the Bay are also some of the least known, in terms of life histories, habitat requirements, and interactions with other species. These species seldom receive priority in research programs, although recent studies of small reef fishes, gelatinous predators (sea nettles and comb jellies), zooplankton, and planktonic bacteria have added greatly to our understanding of some important ecosystem processes. The Strategy recommmends the development of a research plan for ecologically valuable species to help fill the many remaining gaps in our knowledge of these species and their functions.

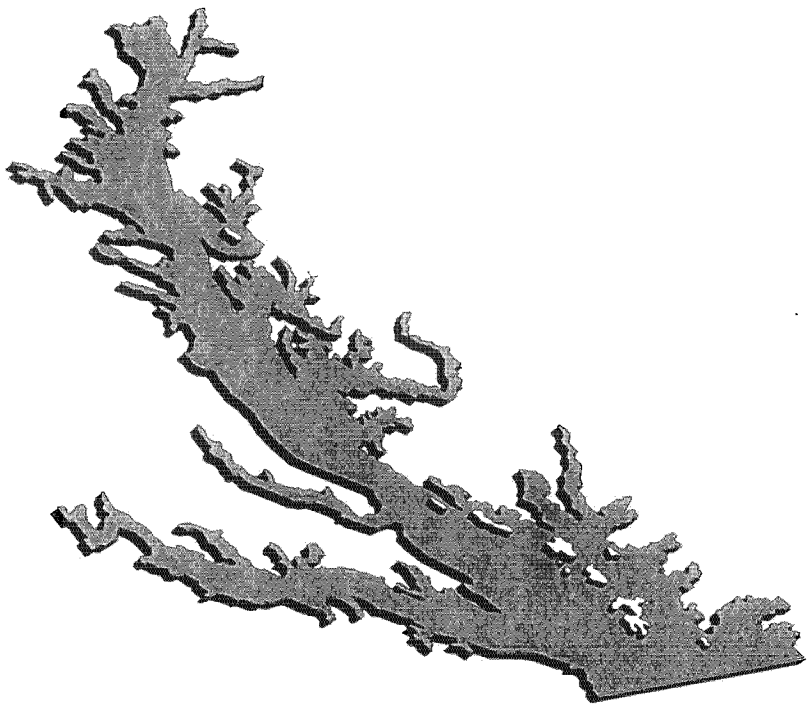
Specific recommendations
The principal recommendations of the Strategy are summarized below.

- Apply available information on species interactions and habitat requirements in the development and revision of fishery management plans.
- Incorporate habitat goals for living resources into tributary-specific nutrient reduction strategies.
- Provide information to management and to the public to support and reinforce recognition of the importance of ecologically valuable species.
- Publish and continually update a handbook of ecosystem indicators for Chesapeake Bay. This handbook will include information on measurements and their interpretation.
- Use information gathered directly from the Bay ecosystem for effective management. This approach will require continued monitoring of ecologically valuable species, and the development of a consistent program for ecosystem indicators of biological integrity.
- Coordinate ecosystem modeling efforts, and update models used by management with state-of-the-art ecological knowledge. Computer simula-

tions of the ecosystem have demonstrated their effectiveness in the diagnosis of prevailing conditions. Simulation will be useful to Bay managers for prediction of future outcomes given certain changes in nutrient and toxic levels, area available for habitat, and other factors important to living resources.

- Develop a comprehensive habitat restoration and management plan to achieve the goals of the 1987 Bay Agreement and the 1992 Amendments which would benefit the maximum number of species: commercial, recreational, and ecologically valuable ones alike.

- Develop a list of priority research topics directed at ecologically valuable species and communities. This will notify research institutions of particular needs, and should stimulate researchers to explore these subjects.



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INTRODUCTION

Background

This strategy was developed by the Ecologically Valuable Species Work Group of the Chesapeake Bay Program Living Resources Subcommittee to fulfill one of the commitments of the Living Resources section of the 1987 Chesapeake Bay Agreement: "to develop, adopt, and begin to implement Bay-wide management plans . . . for ecologically valuable species." The work group developed the concept that the best approach to a strategy for ecologically valuable species would be one which viewed the Bay as an ecosystem comprised of communities, structural groups of species, abiotic (physical and chemical) factors, and their interactions. Besides affording a feasible method for developing the strategy, the ecosystem concept provides the basis for exploring the relationships between the many separate plans for management of Chesapeake Bay species, habitats, and water quality. The preamble of the Bay Agreement commits the signatories to "managing the Bay as an integrated ecosystem"; in the Living Resources section of the Agreement, the signatories agreed that "the entire system must be healthy and productive." A balanced, healthy, and productive ecosystem depends upon the integrity of communities of ecologically valuable species and the maintenance of their functional roles.

In considering the possibilities for management plans for ecologically valuable species, it became clear that, in the traditional sense, there were few, if any, realistic options for "managing" many critically important Chesapeake Bay species such as the bay anchovy, hogchoker, sea nettle, or numerous species of planktonic and benthic organisms. For the majority of ecologically valuable species the focus must be on the environmental conditions and habitats necessary to support their populations and maintain their functional roles, rather than the usual focus of management plans for fish and shellfish, i.e. regulating harvests.

There are a variety of habitat issues for these species, and the work group considered the idea of recommending a series of management plans based upon restoring and protecting habitats. Various attempts to describe critical habitats are well intended efforts to direct limited resources. However, the implication that there are less critical or non-essential habitats is counter to the primary goal of restoring a balanced ecosystem. The habitats and habitat problems of ecologically valuable species are shared with many other, often commercially valuable species. For example, the distribution of bay anchovy is thought to be restricted by low dissolved oxygen in deeper waters of the Bay (Houde and Zastrow 1991), but this problem exists for many other species as well, and already is a central focus of the Chesapeake Bay restoration. Several of the most important habitat issues for Bay species have been addressed by specific plans, e.g., the Wetlands Policy and Implementation Plan (CEC 1988a; PSC 1990), the Submerged Aquatic Vegetation Policy and Implementation Plan (CEC 1989; CEC 1990), and the Strategy for Removing Barriers to Fish Migration (CEC 1988c). Therefore, habitat-based plans for individual ecologically valuable species would, to a large extent, be redundant with existing plans. A need was recognized, however, to coordinate various habitat management plans and initiatives within a common framework. A long-term commitment to the goals of the 1987 Chesapeake Bay Agreement will require long-term monitoring, the use of ecosystem indicators, data management and analysis, ecosystem simulation and analysis, research and habitat management.

Selected ecologically valuable species and species groups are shown in Table 1. It is possible to describe the roles of these species groups in the larger ecosystem, to estimate their status with respect to baseline conditions, and to define some of the stresses which may have compromised biotic communities and their functions.

Goal

The primary goal of this strategy is identical to a principal goal of the Chesapeake Bay Agreement:

- *to restore a more balanced ecosystem in Chesapeake Bay.*

The strategy proposes that this goal demands special attention to ecologically valuable species, coupled with actions directed toward achieving "a more balanced ecosystem," measuring its properties, and predicting results of management actions on the ecosystem and its constituent communities.

Objectives

- *to focus management and research attention on the importance of non-harvested species and functional groups of species;*
- *to protect and restore the functions of subsystems of the Bay ecosystem, e.g., reef communities, pelagic, soft bottom, areas of submerged aquatic vegetation (SAV beds), and wetlands communities;*
- *to find common ground, in an ecosystem context, for the development and implementation of species-specific and habitat management plans, and to foster an overall, ecosystem- and community-oriented view of management activities;*

Table 1. Ecologically valuable species occur within communities. These communities are often subdivided based on the functional roles of species, their habitat preferences, or sampling considerations. Examples are: chemical activity (bacteria); size fractions (plankton); feeding method or diet (macrofauna); or growth habit (vegetation). In general, moderate abundances of many diverse species indicate a healthy ecosystem.

Community	Category
Bacteria	heterotrophic aerobic group sulfate reduction community
Phytoplankton	<3 µm 3-10 µm >10 µm
Zooplankton	44-202 µm 202-505 µm >505 µm
Benthic Infauna	obligate suspension feeders facultative suspension feeders surface deposit feeders subsurface deposit feeders predators
Benthic Epifauna	filter feeders opportunistic omnivores parasites
Fish	planktivores benthivores carnivores
Waterbirds	planktivores herbivores omnivores predators
Vegetation	submerged aquatic vegetation (SAV) emergent vegetation

- *to propose measures of ecosystem and community integrity that will be practical, responsive, and informative to management programs;*
- *to guide the improvement and use of analysis tools, including ecosystem simulation.*

Definitions

Ecologically valuable species

Ecologically valuable species are defined as those species or groups of species which have significant functions in the ecosystem by:

1) regulating populations of other species; for example: gelatinous zooplankton may exert significant control over their prey, primarily crustacean zooplankton; also forage fish, including bay anchovy, silversides and other species, may exert significant control over the abundance of both their prey (largely consisting of crustacean zooplankton) and their predators (especially larger fish like striped bass);

2) regulating the quantity and quality of physical habitat for other species; these roles are fulfilled by submerged vascular plants, marsh grasses, burrowing animals and numerous species of hard-shelled molluscs and crustaceans;

3) physical and chemical processing of large amounts of material (nutrients, organic and inorganic matter); the form and distribution of large quantities of these materials are controlled by complex communities of benthic and planktonic organisms;

4) producing organic matter; phytoplankton, macroalgae, and vascular plants provide the living and detrital matter upon which the Bay's food chains depend.

Ecological importance of a species does not preclude economic importance and vice versa. For example, spot (*Leiostomus xanthurus*) are important in commercial and recreational fisheries, but also are important regulators of benthic communities through heavy predation on the benthic fauna (Homer and Mihursky 1991). Oysters and blue crabs are species of prime economic importance, but also have tremendous ecological importance because of their functional roles as consumers, recyclers, prey, and (in the case of oysters) as physical habitat for many other species. This strategy does not exclude these species because of their commercial and recreational importance, but rather puts them in context as members of ecological communities and functional groups.

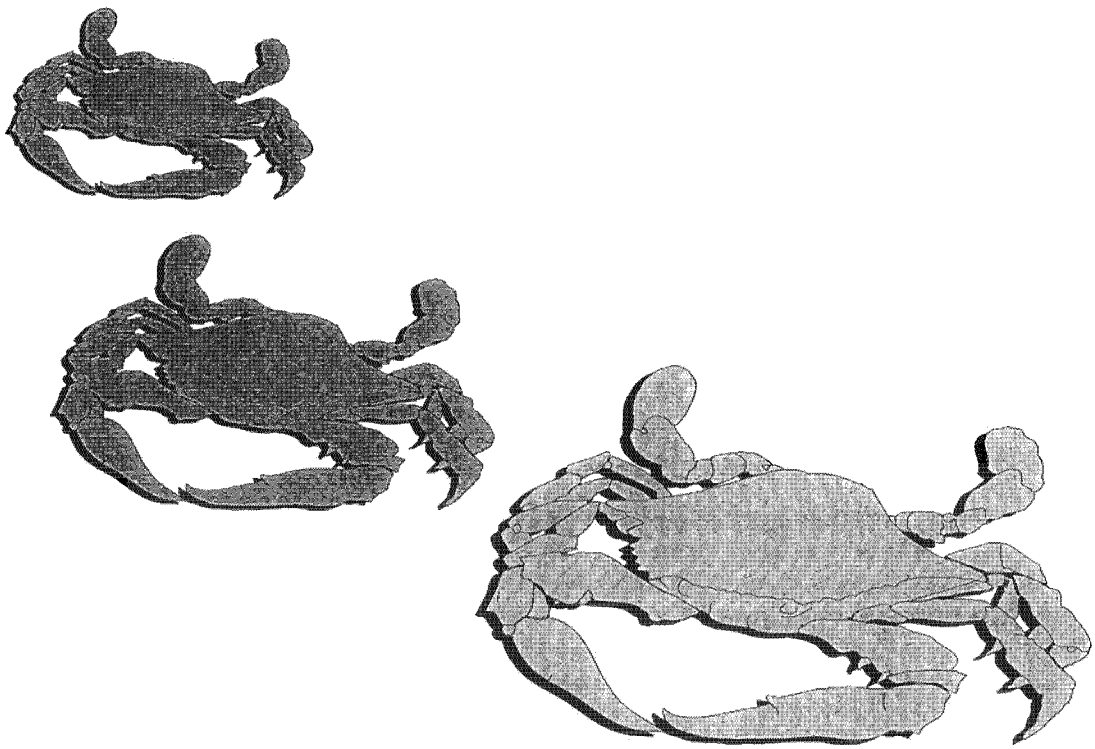
Ecosystem

The Chesapeake Bay ecosystem is defined for the purposes of this strategy as the tidal waters and tidal wetlands of Chesapeake Bay, along with adjacent upland margins, and includes the physical and chemical environment, the biota, and the watershed inputs to the tidal system. Non-tidal waters, wetlands, and uplands of the Chesapeake watershed are excluded from this definition in order to set reasonable boundaries and to avoid an unworkable degree of complexity, although it is recognized that substantial energy flows and other effects originate from these sources.

Structure of the Strategy

In the following sections, we present 1) a vision of a balanced, healthy, and productive ecosystem; 2) an assessment of the current status of available ecosystem

indicators with respect to the baseline vision; 3) general recommendations and a proposed set of tools for accomplishing the goals of the strategy; and 4) specific recommendations for implementation of the strategy.



VISION - TOWARD A BALANCED ECOSYSTEM

What is a "balanced, healthy, and productive" ecosystem? Because there is not, as yet, a complete quantitative understanding of this idea, qualitative and aesthetic views prevail. A Bay teeming with game fish, blue crabs, oysters, and waterfowl, with clear water and a minimum of "nuisance" organisms (algae, sea nettles, bacteria, too-dense SAV beds) is a pleasant, if perhaps unrealistic vision (each of these "nuisance groups" has a vital role to play in a balanced and healthy system).

There is a tendency to think of natural systems as unchanging or static, but in reality they are dynamic, governed by internal processes, stressed by external forces, and characterized more by change than by stasis. The terms "stable" and "stability" as applied to ecological systems do not mean that they are permanently invariable, but rather that they exhibit dynamic equilibrium over relatively long periods of time; permanent changes in function and the structure of populations and communities take place slowly over time, not suddenly. Populations in stable systems may fluctuate dramatically in abundance over seasons or decades, but nevertheless maintain constant baselines, or long term average abundances. All ecosystems change drastically over climatic, evolutionary, and geologic time scales.

Ecological balance may best be defined in functional terms, i.e., as a balance between producers, consumers, and detritivores such that material (e.g., organic carbon) is produced in rough proportion to consumption, and does not accumulate or dissipate in excessive amounts. Balanced ecosystems tend to remain relatively stable in productivity, species diversity, and population structure over long periods of time.

The problem of eutrophication in Chesapeake Bay appears to be reflected in an imbalance between primary producers (phytoplankton) and higher order consumers (e.g., fish). The consumption of excess production by bacteria depletes dissolved oxygen, and makes portions of the Bay unsuitable habitat for higher order consumers, while bacteria continue to thrive. The system has been shifted "out of balance" by the introduction of excess nutrients and waste products from human activities. In addition, fisheries have contributed to the depletion of populations of some consumer organisms (e.g., oysters), probably further shifting the balance towards algae (producers) and detritivores, especially bacteria.

"Health" is a very loose term to apply to an ecosystem; it would be awkward to describe an "unhealthy" or "sick" ecosystem. More accurate terms are *stress* (a response to stressors, e.g., nutrients, toxic contaminants, pathogens) and *disturbance* (e.g., destruction of wetlands and other habitats). Stressed and disturbed ecosystems may show imbalances or departures from stable conditions, as well as reduced productivity of some or all components. Stress and disturbance also can favor the proliferation of tolerant, opportunistic ("weedy"), and exotic species, some of which are nuisances to human activities or outcompete more desirable species.

Productivity is an important element to consider in developing this vision of the ecosystem. The Bay is, by most accounts, *too* productive of phytoplankton and bacteria because of an overabundance of nutrients. But what is a suitable level of productivity? Could the Bay be engineered so as to convert existing nutrient loads into biomass useful to humans (fish, shellfish, and other wildlife) instead of bacteria and biochemical oxygen demand? It is plausible that the Bay could be managed to produce much greater quantities of edible fish and shellfish than under pristine conditions. Would this scenario be compatible with our qualitative and aesthetic vision? Do we want a wild Bay or a cultivated one? Overly stringent nutrient reductions, without compensatory changes in the way we use and manage the Bay's resources, might lead to a system less productive of harvestable resources than we would wish.

The Chesapeake Bay Program has used a "bottom-up" approach in its attempt to restore the biological integrity of the Bay, i.e., a 40% reduction in nutrient input, along with habitat protection and restoration. But the "top-down" approach also needs to be considered. A top-down strategy recognizes that sizeable populations of top predators such as striped bass, bluefish, and predatory birds are as necessary to a balanced ecosystem as is nutrient reduction. Removing top predators by heavy harvesting can increase the size and abundance of their prey (forage fish), which in turn puts severe predation pressure on the primary consumers (zooplankton), and thereby lessens grazing pressure on the phytoplankton. Depletion of benthic filter-feeding organisms (oysters, clams, and many species that primarily inhabit oyster shells) through harvest, disease, loss of habitat, and low dissolved oxygen also acts to favor an overabundance of phytoplankton. The filter-feeders are equivalent in importance to zooplankton as consumers of phytoplankton in shallow reaches of the Bay and its tributaries.

Phytoplankton are the main source of organic matter in large areas of the Bay; if they are not consumed (mostly by zooplankton and other filter feeders), they die and either are consumed by bacteria, or accumulate in bottom sediments, where they may be buried or consumed by bacteria

at a later season. Bacterial respiration (biological burning of organic fuel) is the major cause of dissolved oxygen depletion in the Bay. Recent modeling exercises indicate that bacterioplankton oxygen consumption is most important in the spring, whereas sediment sulfide production and subsequent sulfide oxidation (a bacterial and chemical process that depletes dissolved oxygen) becomes dominant during the summer. Nutrient management (bottom-up control) seeks to alleviate the problems of low dissolved oxygen and excessive turbidity by limiting the production of phytoplankton. Strategies to increase grazing by larger, longer-lived organisms (top-down control) could help to achieve these ends while allowing higher overall productivity, by channeling primary productivity to fish and shellfish rather than to oxygen-consuming bacteria. A combination of top-down and bottom-up approaches probably needs to be employed to restore the biological integrity of the Bay.

Whether one takes a top-down or bottom-up perspective on the Bay restoration, it is largely the species in the middle (primary and intermediate consumers) that link management actions to the intended results. No matter what is done to control nutrients and improve habitat conditions, there must be an adequate base of zooplankton, forage fish and macrobenthos to support healthy and productive populations of recreational and commercial finfish. Many ecologically valuable species, although most people would recognize neither their names nor their appearances, are the "species in the middle" - balancing elements in the Bay ecosystem.

Our vision therefore can be summarized as a Chesapeake Bay ecosystem which is:

Balanced
having sufficient populations of prey species to support the species at the top of the food chain, and to limit overabundance at the bottom of the food chain; no major function of the ecosystem dominates the others;

Healthy
having diverse populations that fluctuate within acceptable bounds; free from serious impacts of toxic contaminants, parasites, and pathogens; having sufficient habitat to support a diversity of species;

Productive
providing sufficient production of harvestable products to serve human needs without depleting predator and grazer populations to the point where internal, functional balance is disrupted.

This vision implies that human uses should be planned so as to balance inputs of nutrients and organic matter (wastes) with removal (harvests), while taking into account internal sources (carbon and nitrogen fixation) and sinks (burial and denitrification). Management actions should be taken to reduce stress factors (contaminants, diseases) and disturbance (habitat destruction and alteration, introduction of exotic species) wherever possible. Specific recommendations relating to these and other issues for ecologically valuable species are contained in the MANAGEMENT RECOMMENDATIONS AND TOOLS section.

STATUS OF ECOSYSTEM INDICATORS

General considerations

How can the integrity of the Chesapeake ecosystem best be measured? To date, the Bay Program has relied largely on measures of water quality (e.g., dissolved oxygen, nutrients, and chlorophyll) supplemented by the status of a few major fishery resources, to assess the "State of the Bay." Other indicators, including biological community and habitat measures, with broader ecological relevance, are readily available or could be developed with relative ease.

The use of ecosystem indicators in management programs is entirely dependent on monitoring programs to generate the necessary data on biological communities and their habitats. Biological monitoring can be more directly reflective of balance, health and productivity than chemical or physical monitoring.

Several existing or planned monitoring programs provide information on biological communities and habitat conditions for the Bay's living resources. The Bay-wide water quality monitoring program includes extensive measurements of important habitat variables, including dissolved oxygen, nutrients, light attenuation, and total suspended solids. Biological communities - phytoplankton, zooplankton, and benthic infauna - are monitored as a part of this program. In addition to the presence or absence of specific organisms, the diversity of species and habitat are important indicators. Many ecologically valuable species of fish are monitored as by-catch in surveys directed at commercial species. Although sampling methods may not be ideal for most non-commercial species, valuable data are obtained at little extra cost. Areas of submerged aquatic vegetation beds are measured regularly, using both aerial and ground surveying techniques. Oyster reefs are monitored by fisheries management agencies in Maryland and Virginia, not just for oysters, but also for selected predators and fouling organisms that share this habitat. Wetland monitoring is part of the Chesapeake Bay Wetlands Policy Implementation Plan. A workshop was held in April 1992 to develop consensus on a wetlands monitoring program.

Below, we list general criteria for ecosystem indicators, describe indicators that can be generated from existing monitoring programs, their recent status, if available, and recommend additional steps for their development and use. Single-species indicators (e.g., juvenile fish indices, harvest statistics) often have large sources of variation and biases that cause difficulty in relating them to the health of the ecosystem. Mobile or migratory species can be components of indicators if acute changes occur while the population resides in the region of interest, as for example fish kills, blocks to migration due to low oxygen, avian cholera, eggshell thinning, etc. Biological measures may be used as indicators of ecosystem status and integrity if they possess the following attributes:

- indicator increases or decreases can be tied to issues of management concern;
- temporal and spatial variabilities in the measures can be reasonably well documented, predicted, and understood;
- variance in statistically valid indices is not so great so as to preclude practical and affordable sampling;
- indicator changes due to management can be separated from changes due to natural environmental factors causing variability;
- indicator responses are rapid enough to be detectable;
- indicators are not overly sensitive to effects outside the region of interest.

Indicators usually are most informative and robust if they integrate important attributes of the structures and functions of biological communities.

Description and status of ecosystem indicators

A synopsis of ecologically valuable groups and habitat considerations is given below. All major groups have been included, even though, for practical reasons, some have little potential as indicators. Table 2 presents an overview of potentially useful indicators.

Submerged aquatic vegetation

The distribution and coverage of submerged aquatic vegetation (SAV) are recognized as important ecosystem indicators, and the relationship of SAV status to nutrients, chlorophyll, and turbidity are fairly well understood (Dennison *et al.* 1993). Also, SAV beds are understood to have important functions as 1) physical and biological filters that remove nutrients and suspended sediments from the water; 2) as physical habitat and centers of abundance for fish, crabs, and other invertebrates; 3) as important primary producers; and 4) as food for waterfowl (Hurley 1991).

Bay-wide monitoring of SAV has been conducted almost annually since 1984. The Baywide acreage of SAV has become an accepted statistic for assessing the health of the Bay, and for following trends in the improvement of water quality. The geographical distribution of SAV also is important; for example, the reappearance of SAV in the upper tidal Potomac River has been correlated with regional

Table 2. Description, status, and trends of ecosystem indicators. Specific references should be consulted for more complete information.

HABITAT INDICATORS	USES	STATUS	TRENDS
Seagrass beds	fish spawning, crab nursery, waterfowl food source	variable by region	improving
Water quality	all ecologically valuable species except birds	variable	improving in some aspects
Reefs	oysters, other benthic epifauna species, microorganisms	generally poor	declining
Wetlands/ shorelines	many species	generally fair	declining

BIOLOGICAL INDICATORS	CONSUMERS	INDICATIONS
Seagrasses	waterfowl, snails, turtles	water clarity, suspended particles, chlorophyll a, dissolved inorganic nitrogen and phosphorus
Phytoplankton	zooplankton, benthic species (especially oysters and clams)	water quality, quality of food for consumers, short term changes
Zooplankton	forage fish, benthic species including oysters	water quality, quality and quantity of food for consumers, short term changes
Benthos		
Infauna	benthic-feeding fish (e.g. flounder), humans	environmental impacts, water and sediment quality
Epifauna	benthic-feeding fish (e.g. drum), humans	not established; data available
Fish	other fish, birds, marine mammals, humans	trends in seasonal distribution, health and balance of tributaries
Bacteria	microzooplankton	biological oxygen demand, carbon and nutrient cycling

improvements in water quality and fisheries (Carter *et al.* 1988; Fewlass 1991). Management has made extensive efforts to set targets for SAV restoration in all dimensions: distribution, density and species diversity.

Because SAV so well integrates ecological function with water quality, it is recommended that annual monitoring continue, and that annual acreage statistics should be generated for all major segments of the Bay and Baywide. Because SAV abundance and distribution can fluctuate considerably from year to year in response to hydrologic conditions, it is suggested that multi-year running means of acreage would be more indicative of trends than year-to-year changes. The possibility of predictive relationships between SAV occurrence and abundance, and recruitment of juvenile fish, crabs, and molluscs should be explored.

Phytoplankton

Chesapeake Bay is presently a plankton-dominated system (Baird and Ulanowicz 1989). Phytoplankton are microscopic plants found throughout aquatic systems and form the base of the food web. Phytoplankton abundances, growth rates, and species composition respond directly to changes in nutrient concentrations, turbidity, and contaminants. Phytoplankton production, accumulation and subsequent decomposition translate into changes in the quality and quantity of food available at the base of the food chain, thereby affecting the livelihood of many consumer species as well as nutrients and dissolved oxygen. Phytoplankton assemblages (abundance and species composition) have been monitored on a Bay-wide basis for several years, but there has been insufficient effort to interpret these data in an ecosystem context. Given appropriate analytical attention, these groups have considerable promise for 1) reflecting changes in the system over fairly short time spans, because most generation times are short; and 2) providing information on functional aspects of the system that are important to higher trophic levels.

Indices of species composition, ratios of green to blue-green algal cells or diatoms to dinoflagellates, size spectra, and

diversity indices are potential indicators both of water quality and of the quality of food for higher organisms. For example, diatoms are considered to be more suitable food for oysters and other bivalves than blue-green algae or dinoflagellates. These community indicators have not been widely used or evaluated for Chesapeake Bay until recently. It is recommended that candidate indicators should be calculated from the existing data to determine their variability and potential for routine use in reporting monitoring data.

Zooplankton

Zooplankton are a link between water quality and living resources. The populations in this group respond quickly to habitat conditions and, therefore, are good indicators of both short-term and long-term shifts in the Chesapeake Bay environment. They are critical connectors between primary producers (phytoplankton) and higher consumers, providing the bulk of the forage prey for most larval and juvenile fishes. In addition, many other estuarine organisms and adult fish of species such as anchovies or silversides rely on them for prey. They have a key role in models being developed to track the movement of toxic compounds through food chain pathways.

Zooplankton have been monitored Bay-wide for several years, and, with an accumulation of 5-7 years of data, are beginning to show significant trends. Unfortunately, budgetary problems have forced reductions in monitoring effort, and threatened the overall program. This is an example of ecologically valuable species "falling through the cracks" of management and monitoring programs because they are not perceived to have direct relevance either to water quality or to commercial and recreational species. The great importance of the zooplankton component of the ecosystem argues for continued monitoring and greater efforts to interpret existing data in terms of ecological function and integrity. A zooplankton monitoring workshop held in September 1991 addressed these questions (Buchanan 1992). The focus was on use of the monitoring data in a more integrated context, and the development of indicator statistics which would be responsive to system integrity.

Benthos

Benthic infaunal assemblages have been monitored extensively in Chesapeake Bay, both as part of the Bay-wide monitoring program and to evaluate environmental impacts (e.g., of power plant operations and dredged material disposal sites). Therefore, there is a large database of information on the abundance, distribution, species composition, and environmental associations of benthic infauna. Estimates of the macrobenthic infaunal community are used to indicate environmental health because benthic animals 1) are relatively sedentary (cannot avoid water quality problems), 2) consist of species that exhibit different tolerances to stress, and 3) have relatively long life spans (indicate and integrate water quality problems over time). A significant amount of effort has been applied to interpreting the ecological relationships of the benthos both to water and sediment quality and to consumer organisms. Species richness and overall abundance (biomass per unit area) are used routinely to describe these assemblages. It is generally recognized that with proper interpretation (e.g., accounting for sediment type and salinity) these statistics are indicative of habitat integrity and the quantity of forage available for the many species of fish that feed on benthic fauna. More integrative measures of benthic community integrity have been developed (Luckenbach 1988; Maxted 1990) for portions of the Bay, but have not come into widespread use.

Benthic epifauna are largely dependent on hard surfaces for attachment. Oyster reefs, in particular, are habitats for a diverse assemblage of epifauna, including mussels, barnacles, anemones, worms, small crabs, sponges and tunicates (CEC 1988b). They are monitored as part of annual oyster surveys. Up to the present, however, little use has been made of this data.

Fish

Long term, geographically extensive monitoring of fish assemblages in the Bay and its tributaries has provided invaluable data sets for the development of ecosystem indicators. Recently, these data have been used to identify species which appear to respond in rather predictable ways to long term changes in the Chesapeake ecosystem (Vaas and Jordan 1991). The data also have been used in the development and calibration of an Index of Biotic Integrity for tidal tributaries of Maryland. Although this work is unfinished, trial IBI's have shown the capacity for discriminating both temporal and spatial trends in the diversity, abundance, and pollution tolerance of these fish assemblages (Jordan *et al.* 1991). Several non-fishery species are fairly well-represented in these data sets.

Birds

The Chesapeake Bay is home to over 48 species of common or abundant migratory waterbirds, including 26 species of waterfowl, two species of loons, two species of grebes, cormorants, gannets, six species of gulls, four species of terns, osprey, and bald eagles. These species are only those which are dependent on the water itself (Table 3). Many other species of migratory birds are dependent on the Bay's adjacent wetlands and shorelines.

The geese and half of the ducks are chiefly herbivores. Other ducks eat mollusks, insects, and small fish. Some

Table 3. Number of species, season of abundance, approximate numbers, and foods of waterbirds common or abundant in the Chesapeake Bay during at least two seasons of the year.

Birds	# of Species	Season	Abundance	Foods
Loons	2	WSpF	> 16,000	Fish
Grebes	3	WSpSF	> 3,000	Fish, invertebrates
Gannet	1	WSpF	5,000	Fish
Cormorant	1	SpSF	13,000	Fish
Herons and Egrets	5	SpSF	> 25,000	Fish, invertebrates
Swans and Geese	2	WSpF	>350,000	Crops, SAV
Dabbling Ducks	6	WSpSF	>210,000	SAV, crops, invertebrates
Diving Ducks	8	WSpF	>230,000	SAV, clams, invertebrates
Mergansers	2	WSpF	> 46,000	Fish
Sea Ducks	4	WSpF	>260,000	Clams, invertebrates
Eagle and Osprey	2	SpSF	> 5,000	Fish, waterfowl
Gulls	6	WSpSF	>250,000	Fish, invertebrates
Terns	4	SpSF	> 14,000	Fish

species which were largely herbivores historically have changed their diets with the decrease in sea grasses. The species which persisted in their dependence on seagrasses have been the most affected by the decline of SAV. It is hoped that their populations will recover as SAV is reestablished. Waterfowl are a symbol of the Bay region to many people, and a return to former population levels would be welcomed by all.

The Bay is well known for its abundant wintering waterfowl but less well known are the thousands of loons, grebes, and gulls which also depend on its rich waters for their winter survival. After the wintering populations depart for northern breeding grounds there are still large numbers of waterfowl such as wood ducks, black ducks, and mallards which breed and raise their young in the Bay.

Also, many thousands of colonial waterbirds such as herons, egrets, cormorants, gulls and terns depend on the rich fishery and secluded nest sites to raise their young. Other species such as bald eagles and osprey are also ecologically valuable.

It is difficult to assess the ecological role of such a diverse assemblage of birds. Food habits are known for only a few species and accurate population figures are difficult to obtain due to the migratory nature of the birds and their widespread distributions. Most fish and invertebrates inhabiting the Bay are preyed on by some birds, but their role in limiting prey populations, including competitors of commercial fish species, or controlling less fit individual fish, is unknown.

Colonial waterbirds may exert less of an effect on their environment than their environment exerts on them. However, colony sizes, numbers, and locations may be worth tracking as rough indicators of environmental quality. Although waders tolerate relatively poor water quality in terms of contaminants (Erwin and Spendelow 1991), they may prove useful in evaluating changing contaminant loads in the Bay.

Most waterbirds of the Chesapeake Bay are migratory, thus their populations and survival may not be indicators of the health of the Bay. Rather the populations of waterbirds must be viewed as a whole because populations of individual species may be limited by factors outside the Bay region. Only with a thorough knowledge of the birds' food habits, life history, and conditions in other areas can we understand the meaning of fluctuations in waterbird populations of the Chesapeake Bay.

The baselines of waterfowl and raptor population indices have changed over the years in relation to degradation of the Bay. The potential for a multi-species bird index, analogous to indicators of other groups, should be examined. Adequate data to support such an index may already exist.

Other groups

The following groups are components of the Bay ecosystem which have not yet been monitored sufficiently well in the past to play the parts of ecosystem indicators.

BACTERIA

Bacteria largely control cycling of important biological elements including carbon, nitrogen, phosphorus and sulfur. The sheer magnitude of organic carbon flow needed to support the metabolism of aerobic heterotrophic bacteria and sulfate-reducers as well as their demonstrated role as key players in oxygen consuming processes indicate that these groups should be targeted. Bacteria have been studied

enough, in a research context, to provide an extensive database which could be applied to questions of ecosystem status for some areas of the Bay, but it has not yet been used for this purpose.

Studies in central Chesapeake Bay have shown that bacteria comprise a large percentage of the standing stock of carbon during summer (Malone *et al.* 1986). These high bacterial densities are associated with high water column oxygen consumption rates. When coupled with sediment oxygen demand, observed water column respiration rates are sufficient to maintain hypoxic and anoxic conditions in the deep areas of the central Chesapeake during the summer months (CEC 1988b). For example, deep water dissolved oxygen levels in the vicinity of Cove Point, Maryland show statistically significant decreased dissolved oxygen concentrations over time (Cargo *et al.* 1986). Recent evidence from examination of mid-Bay sediments indicates increased sulfur cycling since colonial times (Cooper and Brush 1991). There is growing evidence that overenrichment by nutrients is causing changes in the plankton which negatively affect the supply of food to fish and shellfish.

The microbial food web (bacteria provide food for single celled animals, especially flagellates and possibly ciliates) is composed of a greater number of energy transfers than the classic phytoplankton - zooplankton - higher animal scheme. Thus its efficiency is lower and a smaller fraction of production ultimately reaches higher, economically important levels.

Macroalgae

Macroalgae, generally known as seaweed, are important primary producers of the Bay. Some are very abundant, for example sea lettuce (*Ulva* sp.), and may have significance both as food resources and as physical habitat. Macroalgae are important sources of nutrients at times when dense windrows accumulate along shallow shorelines. Decomposition of accumulated biomass may affect dissolved oxygen and nutrient concentrations significantly in some areas (CEC 1988b).

Meiofauna

Meiofauna are very small animals that inhabit sediments and submerged surfaces. They include nematode worms and a variety of single-celled animals. Meiofaunal communities have been monitored in some aquatic systems as indicators of pollution, but have not been monitored extensively in Chesapeake Bay.

Mobile Epifauna

Mobile epifauna (crabs, snails, nudibranchs, reef fishes, and other species) tend to concentrate around with oyster reefs and other submerged structures. Because of their habitat preferences and mobility, they often are poorly represented in general biological surveys. This makes it difficult to predict population trends and effectively plan for management, even for those species which are commercially important such as the blue crab. Reef fishes can be sensitive indicators of hypoxia (Houde and Breitburg, unpublished data 1991); other members of this group may have promise as indicators, but monitoring techniques have not been fully developed.

Gelatinous Zooplankton

All species of gelatinous zooplankton are carnivorous, feeding on the primary consumers of the zooplankton such as copepods and pelagic polychaetes. They also feed on fish eggs and newly hatched fish larvae. In addition, sea walnuts eat bivalve larvae, something the sea nettle is unable to digest. The gelatinous zooplankton themselves have very few predators. The sea nettle is the only significant predator known on the sea walnut and hydromedusae, and the sea nettle is not known to have any significant predators, although certain fish are known to prey on other species of scyphomedusae. Gelatinous zooplankton have an important function as regulators of planktonic food chains in the mesohaline portion of the Bay (Baird and Ulanowicz 1989).

Gelatinous zooplankton have been monitored on the Patuxent River for many years, and monitored Bay-wide from 1987 to 1990, but budgetary reductions have been reflected by reductions in the monitoring effort. Current research indicates that their overall impact in the Bay mainstem on zooplankton is relatively small in comparison to the volume of the predators.

MANAGEMENT RECOMMENDATIONS AND TOOLS

The recommendations that follow are grouped into the following major categories:

- General recommendations
- Ecosystem simulation and analysis
- Habitat Restoration and Maintenance
- Ecosystem indicators
- Monitoring
- Data management and analysis
- Research

1. General recommendations

1.1. Develop the mechanism to make this Strategy a framework for coordination of the various fisheries management plans, waterfowl management plans, habitat restoration plans, and other Chesapeake Bay Program plans, promoting cross-program integration throughout the Chesapeake Bay Program.

With the increasing number of Chesapeake Bay Program management plans, there is a growing need for communication between managers and coordination and consistency between plans. This Strategy is laying the groundwork for integration of plans.

Important management decisions should not be based entirely upon considerations of individual system components or their interactions in isolation from the larger system and other domains of management. For the most part, the direction of ecosystem responses to management controls can be predicted (e.g., nutrient reductions will result in less severe hypoxia, and hence improved habitat quality for fish, zooplankton, and benthos), but the magnitudes of the responses are less clear, and the ramifications for other structural and functional aspects of the system usually are not fully considered. The interrelationships between nutrient controls, fisheries management, and restoration of habitats, for example, may be critical to the future of the Bay. Only recently have pilot efforts been undertaken to simulate these interactions; comprehensive, quantitative predictions are not yet available. In the future, using the tools being developed now, the Bay Program should be able to apply a conceptual ecosystem model in all major decision making, and to exercise caution in implementing large scale modifications that ultimately could have unintended results.

1.1.1. Incorporate an ecosystem component into fishery management plans and programs.

The various methods of fishery management (harvest levels, open seasons, fish passage, etc.), will have differing effects on the surrounding environment for other living resources. In the future as more is learned, the effects of top-down control and impacts of specific fisheries on the ecosystem as a whole will become clear. Many of the best-known Chesapeake Bay fishes are migratory – having life cycles where the young mature in one habitat, and then migrate seasonally to other areas as adults for spawning – effectively transporting nutrients from one region to another. For example, shad, river herrings and striped bass transport nutrients into the Bay from both freshwater and marine habitats. Adult menhaden transport nutrients out of the Bay. Fishes are not the only living resources important to nutrient cycling in the Bay. Zooplankton and oysters process large amounts of suspended material, using some of it for growth and reproduction and packaging the rest in a form which other organisms find readily available. The significant ecological processes sustained by these animals need to be considered when managers are determining priorities and making decisions.

ACTION ITEM: PURSUANT TO THE SCHEDULE OF FISHERY MANAGEMENT PLAN RE-EVALUATIONS, REVISE OR AMEND SELECTED FISHERY MANAGEMENT PLANS TO INCLUDE ALL AVAILABLE INFORMATION ON THE EFFECTS OF FISHERIES ON THE ECOSYSTEM.

1.1.2. Apply living resources habitat goals in analysis and reporting of water quality information.

As habitat requirements have been defined and compiled for many living resources (Funderburk *et al.* 1991, Jordan *et al.* 1992, Batiuk *et al.* 1992), the ability to incorporate them into reports should be used. By reporting not only the dissolved oxygen, nutrient and contaminant levels but where the values fall in relation to the needs of living resources (i.e., for SAV in polyhaline waters: DIN <0.15, DIP <0.02) the ecological value of changes in these levels will be made clear. Managers will be made aware of the effects of their actions in a direct and timely way.

ACTION ITEM: BY AUGUST 1993, INCORPORATE LIVING RESOURCES HABITAT GOALS INTO TRIBUTARY-SPECIFIC NUTRIENT REDUCTION STRATEGIES.

1.2. Provide educational and informational aids to support and reinforce the ecosystem-based approach, as well as recognition and understanding of the importance of ecologically valuable species.

Much is yet to be learned about the structure and functions of the Chesapeake ecosystem. Implementation of recommendation 1.1. will be facilitated by ensuring that sound concepts of the structure and functions of the Bay ecosystem are shared by those who plan, make, and implement Bay Program decisions. This Strategy is a first step toward this goal. More compact and accessible tools are needed, however. First, to communicate these ideas to the public; second, to sustain the use of these concepts in the Bay deci-

sion-making process; third, to provide ready access to information, such as the status of ecosystem indicators and the potential for changes in one component of the ecosystem to affect other components.

1.2.1 Inform the public of this Strategy and its objectives, and the recommendations for reaching the ultimate goal: to restore a more balanced ecosystem in Chesapeake Bay.

ACTION ITEM: BY DECEMBER 1992, PUBLISH A BRIEF, ILLUSTRATED SYNOPSIS OF THIS STRATEGY AS A PUBLIC INFORMATION AID.

1.2.2. A poster illustrating ecosystem community relationships should be published and made available to managers.
The poster should be both accurate and attractive, therefore it will require peer review and professional graphics design. The poster should be distributed to Bay managers and staff along with a lecture and discussion, and made available to educational institutions and the public. A software version of the poster, keyed to a) ecosystem indicators and their status, and b) descriptive information, should be considered as a longer term objective.

ACTION ITEM: BY MAY 1994, DESIGN AND PUBLISH A POSTER THAT SHOWS THE MAJOR COMPONENTS OF THE CHESAPEAKE ECOSYSTEM AND HOW THEY ARE INTERCONNECTED BASED UPON A GENERALLY ACCEPTED CONCEPTUAL MODEL.

2. Ecosystem simulation and analysis

2.1. Pursue a long-term program to develop simulation models of the Chesapeake ecosystem to link resource management, habitat restoration and pollution reduction and prevention.
The many interactions between species, habitats, human uses, and management cannot be understood or quantified without models that incorporate the many processes that link these ecosystem components. It is especially important for many of the ecologically valuable species that their interactions with managed species (as prey, predators, competitors, or habitat formers) be quantified. Plans for management of harvested species and habitats require a common, ecologically sound basis to ensure that they work together, rather than in parallel and possibly in opposition. For example, a coastal fisheries model that considers multiple species has been shown to contradict the conclusions of a single-species model, to the potential detriment of the fishery and to populations of several other species (Murawski 1991).

2.1.1. The early phases of ecosystem simulation should include a variety of approaches to the problems of modeling such a complex system.
Bottom-up and top-down modeling concepts (see the section VISION—TOWARD A BALANCED ECOSYSTEM), network analysis (Baird and Ulanowicz 1989), spatial analysis (Costanza *et al.* 1990), bioenergetics models, individual-based models, and statistical extrapolations from long term databases (e.g., Vaas and Jordan 1991) all have validity as ecosystem simulation tools, relating to environmental properties and subject to trend analyses. All are presently being applied in some manner to address questions about the Chesapeake ecosystem or its components. Another way to characterize an ecosystem is by using functional groups. A promising way to characterize functional groups and to quantify their role in ecosystems is through analysis of food web patterns and dynamic properties. By integrating dynamic properties such as growth, mortality, production and recruitment, and combining this data with bioenergetics research, models could lead to an understanding of cause and effect relationships. At this early stage of numerical modeling of complex ecosystems, a multi-faceted approach is prudent because it ensures that the many-dimensional system will be viewed from many directions, and increases the probability that necessary questions will be asked.

2.1.2. Coordinate ecosystem modeling efforts to ensure convergence of the several modeling approaches being pursued. Facilitate collaboration between researchers, modelers, and statisticians. Coordination needs to be maintained both among investigators and among funding agencies.
The goal of obtaining consistent, valid answers to questions about the ultimate effects of management actions on the Chesapeake ecosystem must be kept in sight. Towards this end, a generic modeling framework, capable of accommodating different approaches to subsystems of the overall model, has been adopted by the participants in the present tributary (Patuxent and York Rivers) pilot projects. Coordination must be maintained through regular meetings and discussions among investigators and managers. In addition, models involving living resources will call on the expertise of both the Living Resources and Modeling Subcommittees to reach their full potential. Coordination and cooperation between these two groups are essential.

2.2. Convene a series of scientific workshops to build consensus on conceptual and technical issues involved in ecosystem simulation. At least one intensive workshop should be held each year.
The first of these workshops (Chesapeake Bay Ecosystem Processes Workshop) was held in March 1992. The next one is scheduled for July, 1993.

3. Habitat Restoration and Maintenance

3.1. Develop a comprehensive and integrated habitat restoration strategy for Chesapeake Bay.
Habitat restoration and maintenance need to be addressed through a comprehensive, integrated management plan.

Some major habitat considerations (SAV restoration, wetlands protection, barriers to fish migration, dissolved oxygen and SAV habitat requirements) have been addressed by plans or syntheses of habitat requirements (CEC 1988a,b,c; 1989; 1990; Jordan *et al.* 1992; Batiuk *et al.* 1992). Structural habitat needs have been identified and described for selected Bay species (Funderburk *et al.* 1991). All of these efforts, applied as intended, will benefit ecologically valuable species.

Additional habitat restoration and protection efforts are being undertaken, or have been proposed (e.g., use of waste materials to rebuild reef and shallow water habitats). Other important habitat needs, although they may be addressed by various state and Federal programs, have not come under the guidance of Bay-wide plans; for example, the need to conserve and restore critical shoreline habitats (wooded shores for raptors and wildlife, sandy beaches for diamondback terrapin nesting, intertidal foraging areas for seabirds and wading birds, etc.). An integrated habitat management plan would help greatly to set priorities, avoid conflicts and dilution of effort, and build the programmatic structure necessary to implement a fully coordinated habitat restoration and management program for the Bay. The plan should consider all aspects of habitat management, regardless of where current responsibilities may lie.

3.2. Compile habitat requirements for selected ecologically valuable species and species assemblages.
A supplement to *Habitat Requirements for Chesapeake Bay Living Resources* (Funderburk *et al.* 1991) should be developed, with emphasis on non-economic living resources. For example, chapters on phytoplankton, zooplankton, forage fish, and benthic assemblages would help to assemble information necessary to meet some of the recommendations of this strategy (e.g., ecosystem indicators, planning for habitat management). Such a document also would identify research needs and be an important educational tool.

4. Ecosystem indicators
Biological indicators of ecosystem integrity will be needed to measure progress towards the goals of the 1987 Chesapeake Bay Agreement. The geographical, temporal, and biological complexity of the Bay will require a system of indicators, rather than any single indicator. The necessary data are theoretically available from the Bay's comprehensive living resources monitoring program (CEC 1988b), however, additional work will be needed to implement such a system.

4.1. Develop and implement a consistent system of indicators of ecosystem integrity for Chesapeake Bay.
This recommendation should be met through a consensus process, overseen by the Chesapeake Bay Living Resources Subcommittee, within a year after adoption of the Strategy. The development of a consistent system will rely on a full understanding of the strengths and weaknesses of each biological indicator.

Candidate habitat indicator statistics are found in Table 2 and the section DESCRIPTION AND STATUS OF ECOSYSTEM INDICATORS. Recommendations for application and further development of the indicators that appear most promising, based upon use and interpretation of existing monitoring data, are currently being generated by several groups connected with the Chesapeake Bay Program. Habitat indicator statistics should be reported routinely (e.g., *State of the Bay Report*), both Bay-wide and for individual Bay segments. The list in Table 2 is intended to be neither inclusive nor exclusive; it specifies indicators known to the work group that are immediately available or in advanced stages of development.

4.2. Establish target levels for ecosystem indicators on a tributary-specific basis. These target levels will be used to set goals for nutrient and pollutant control strategies.

4.3. Develop, evaluate, and apply additional multi-species statistics as indicators of status and trends in the structure and function of the Chesapeake ecosystem.
It is important to avoid isolated interpretation of single-species statistics in an ecosystem context. Single-species statistics (e.g., Maryland and Virginia striped bass juvenile indices; Maryland oyster spat index; Bay-wide waterfowl and raptor counts) are useful for their intended purposes in managing the species. However, they sometimes are interpreted as indicators of system health, for which purpose they generally are not robust, as discussed above in the Status of Ecosystem Indicators section. Because of the complexity of the estuarine system and the diversity of species in the Chesapeake Bay, a functional group approach for each major salinity region is essential.

4.4. Continue to use SAV acreage as a key ecosystem indicator statistic.
The only multi-species indicator currently in general use for Chesapeake Bay is SAV acreage, which is monitored and reported on an annual basis.

ACTION ITEM: BY JUNE 1994, PUBLISH A HANDBOOK OF ACCEPTED ECOSYSTEM INDICATORS FOR CHESAPEAKE BAY, INCLUDING INFORMATION ON MEASUREMENT AND INTERPRETATION. A COMPREHENSIVE MATRIX DETAILING THE STRENGTHS AND WEAKNESSES OF EACH ECOSYTEM INDICATOR, AND A KEY OF USEFUL INTERPRETATIONS OF SINGLE-SPECIES STATISTICS WILL BE INCLUDED.

5. Monitoring

The Chesapeake Bay Living Resources Monitoring Plan (CEC 1988b) adopted an ecosystem perspective in developing recommendations for Bay-wide biological monitoring. Success in meeting the objectives of this strategy will depend heavily upon the continued availability of the comprehensive data generated by the monitoring programs.

5.1. Establish a stable, long-term funding mechanism for key living resources monitoring programs.

Such core elements of the program as SAV and zooplankton monitoring have faced annual struggles to obtain the funding necessary to continue them. This situation has arisen because the potential of the existing data has not been fully realized, and because consistent time series of 5-10 years are necessary in a system as large and complex as Chesapeake Bay in order to establish baselines against which to measure system health and progress towards restoration. In setting funding priorities, it should be understood that the value of monitoring programs of this type generally increases steadily with the length of the time series.

6. Data management and analysis

Several of the recommendations above will depend heavily on data management and analysis for their implementation. Development and application of biological indicators and ecosystem simulation models will require comprehensive, well-managed, and accessible data. Monitoring programs cannot serve their functions without sufficient attention to data management and analysis.

6.1. Publish a directory and user's manual for the Chesapeake Bay living resources database.

The Chesapeake Bay Program has put a great deal of effort into the acquisition of data sets on many living resources, quality assurance of those sets and their incorporation into a database. This database is generally accessible to knowledgeable users, but is not well known to many who could make good use of it. The directory should be designed and distributed so as to facilitate its use by researchers. It should specify procedures for downloading and communicating data to various kinds of storage media and computer systems.

6.2. Develop data sets from the living resources database to match specific questions and intended outputs (e.g., ecosytem indicators).

Well-focused, management-oriented questions can guide the structures of data sets. For example, management needs recently have stimulated development of specific data sets for synthesis of SAV and dissolved oxygen habitat requirements. Once a consensus system of biological indicators is established (Recommendation 4.1), the living resources database can be structured for efficient calculation of indicator statistics and comparisons with other (e.g., water quality) data.

6.3. Ensure support and direction for data analysis.

In general, monitoring programs and research grants and contracts provide support for data collection and analysis for specific purposes. Seldom is there sufficient time or funding available to apply the data to its full potential, especially for some of the purposes important to this strategy. One of the reasons monitoring programs often fail to fulfill their promise is because analysis is a "spare time" effort. The generation of important information can be overlooked or delayed.

Recently, the Chesapeake Bay Monitoring and Living Resources Subcommittees have jointly proposed analytical work on statistical power and trends for Bay-wide biological monitoring data. This effort should be supported.

7. Research

Research has a role in any strategy related to the recovery of a biological community. This is particularly true for ecologically valuable species. Research and monitoring complement and supplement each other, especially for those species which are not covered by fisheries management plans. Research should increase our knowledge of habitat requirements, life histories, and interrelationships among species, communities, and functional groups.

The experts who contributed to this strategy included recommendations for further work in monitoring, research, modeling, habitat and management, as well as some general recommendations for changes in our approach to studying the Chesapeake Bay ecosystem (see Appendix B). Using this list as the starting point, the Bay Program should be able to define new research needs and prioritize them.

7.1. Provide expanded opportunities for research into the life histories, ecological associations, functional roles, and habitat requirements of ecologically valuable species.

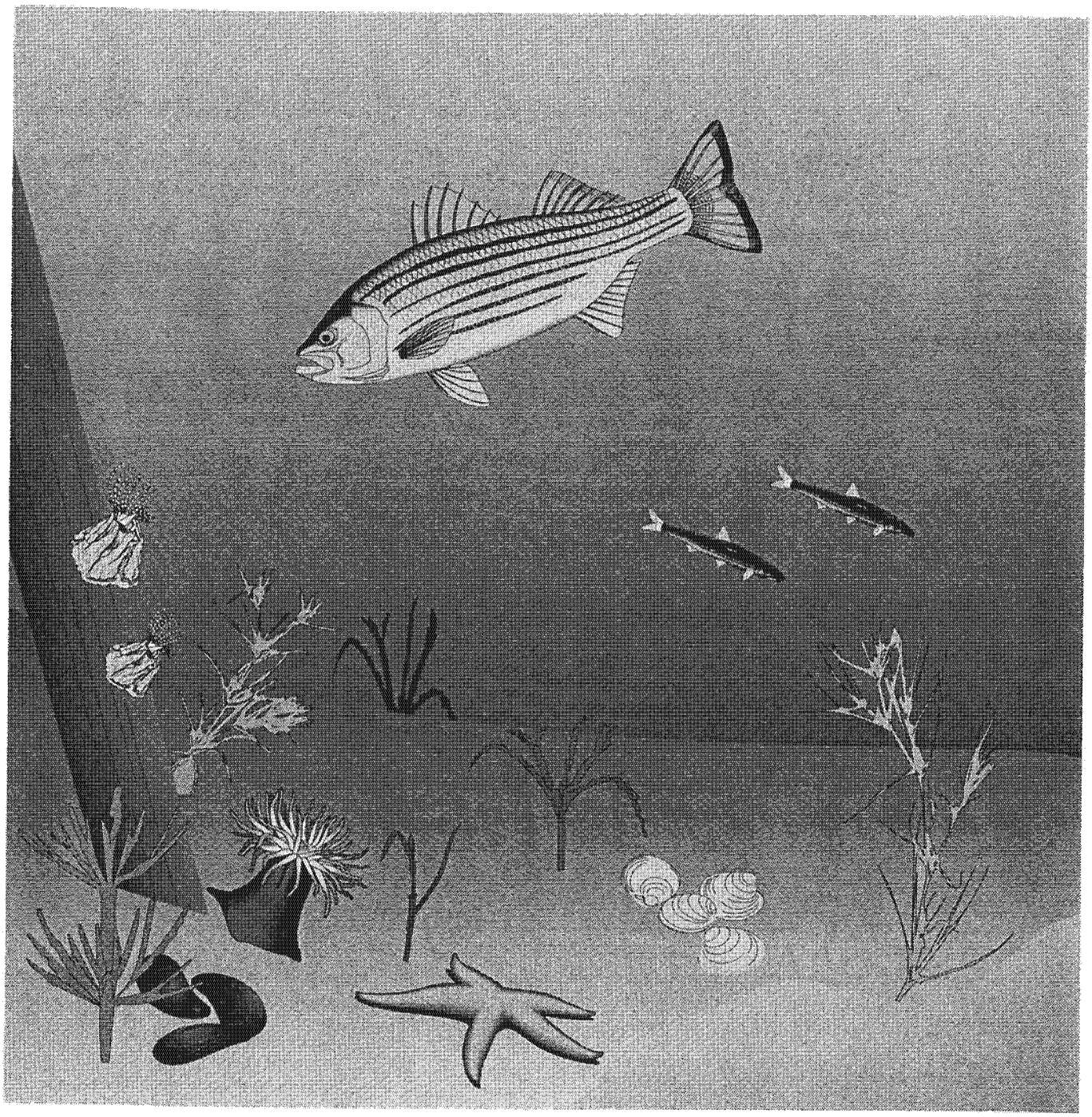
Solid research programs for planktonic and benthic biota have been maintained in Chesapeake Bay (partially benefited by the Bay-wide monitoring program). But it is notoriously difficult for scientists to gain support for basic biological and ecological research on many other non-economic species. Funding agencies and managers of research programs should encourage research into functions and interrelationships of species and species groups which have received inadequate attention. This research will help to support model development and further understanding of the Bay's complex web of life.

7.2. Develop a list of priority research topics oriented towards ecologically valuable species and communities.

Research managers often look for authoritative guidance in developing and tuning their programs. Sometimes too much emphasis is put on economically valuable species in both

generic and special purpose research programs. The recommended consensus list will help to remedy this situation.

The Chesapeake Bay Program Scientific and Technical Advisory Committee should oversee this project.



EVS IMPLEMENTATION MATRIX

ACTION ITEM	TIME FRAME	RESPONSIBILITY
1. General recommendations		
1.1. Develop the mechanism to make this Strategy a framework for coordination of the various fisheries management plans, waterfowl management plans, habitat restoration plans, and other Chesapeake Bay Program plans, promoting cross-program integration throughout the Chesapeake Bay Program.	to be determined	Ecologically Valuable Species Workgroup (Jordan)
1.1.1. Pursuant to the schedule of fishery management plan re-evaluations, revise or amend selected fishery management plans to include all available information on the effects of fisheries on the ecosystem.	refer to FMP schedule	Ecologically Valuable Species Workgroup (Jordan) / Fisheries Management Workgroup (Jensen)
1.1.2. Incorporate living resources habitat goals into tributary-specific nutrient reduction strategies.	August 1993	Living Resources Nutrient Reevaluation Task Force
1.2. Provide educational and informational aids to support and reinforce the ecosystem-based approach, as well as recognition and understanding of the importance of ecologically valuable species.		
1.2.1. Publish a brief, illustrated synopsis of this Strategy as a public information aid.	December 1992	Ecologically Valuable Species Workgroup (Cresswell)
1.2.2. Design and publish a poster that shows the major components of the Chesapeake ecosystem and how they are interconnected based upon a generally accepted conceptual model.	May 1994	Ecologically Valuable Species Workgroup and NOAA (Gillelan)
2. Ecosystem simulation and analysis		
2.1. Pursue a long-term program to develop simulation models of the Chesapeake ecosystem to link resource management, habitat restoration and pollution reduction and prevention.		
2.1.1. The early phases of ecosystem simulation should include a variety of approaches to the problems of modeling such a complex system.	on-going	Ad Hoc Ecosystem Modeling Panel (Batiuk / Jordan / Linker)
2.1.2. Coordinate ecosystem modeling efforts to ensure convergence of the several modeling approaches being pursued.	on-going	Ad Hoc Ecosystem Modeling Panel (Batiuk / Jordan / Linker)
2.2. Convene a series of scientific workshops to build consensus on conceptual and technical issues involved in ecosystem simulation. At least one intensive workshop should be held each year.	on-going	Scientific and Technical Advisory Committee

3. Habitat Restoration and Maintenance		
3.1. Develop a comprehensive and integrated habitat restoration strategy for the Chesapeake Bay.	December 1993	Habitat Objectives/Restoration Workgroup (Funderburk)
3.2. Compile habitat requirements for selected ecologically valuable species and species assemblages.	to be determined	Ecologically Valuable Species Workgroup (Jordan)
4. Ecosystem indicators		
4.1. Develop and implement a consistent system of indicators of ecosystem integrity for Chesapeake Bay.		
4.1.1. Publish a handbook of accepted ecosystem indicators for Chesapeake Bay, including information on measurement and interpretation.	June 1994	Ecologically Valuable Species Workgroup (Jordan)/Monitoring Workgroup of the Living Resources Subcommittee (Buchanan)
4.2. Establish target levels for ecosystem indicators on a tributary-specific basis.	to be determined	Ecologically Valuable Species Workgroup (Jordan)/Monitoring Workgroup of the Living Resources Subcommittee (Buchanan)
4.3. Develop, evaluate, and apply additional multi-species statistics as indicators of status and trends in the structure and function of the Chesapeake ecosystem.	to be determined	Ecologically Valuable Species Workgroup (Jordan)/ Monitoring Workgroup of the Living Resources Subcommittee (Buchanan)
4.4. Continue to use SAV acreage as a key ecosystem indicator statistic.	on-going	SAV Workgroup (Pendleton)/ Living Resources Monitoring Workgroup (Buchanan)
5. Monitoring		
5.1. Establish a stable, long-term funding mechanism for key living resources monitoring programs.	on-going; year to year	Living Resources Subcommittee
6. Data management and analysis		
6.1. Publish a directory and user's manual for the Chesapeake Bay living resources database.	to be determined	Data Acquisition Workgroup
6.2. Develop data sets from the living resources database to match specific questions and intended outputs (e.g., ecosystem indicators).	on-going	Living Resources Monitoring Workgroup (Buchanan)
6.3. Ensure support and direction for data analysis.	on-going	Data Analysis Workgroup (Magnien)
7. Research		
7.1. Provide expanded opportunities for research into the life histories, ecological associations, functional roles, and habitat requirements of ecologically valuable species.	on-going	Scientific and Technical Advisory Committee
7.2. Develop a list of priority research topics oriented towards ecologically valuable species and communities.	October 1993	Scientific and Technical Advisory Committee (Watkins)

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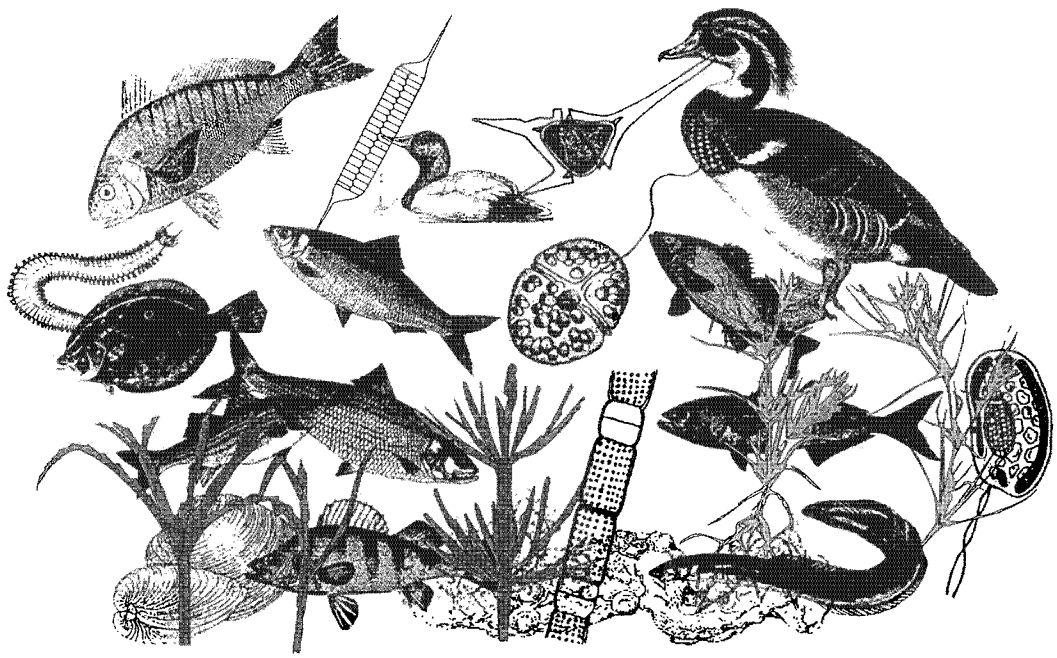
APPENDIX A

Ecologically valuable species and species groups of the Chesapeake Bay. Bacteria groups were identified by J. Tuttle, Chesapeake Biological Laboratory. Phytoplankton and zooplankton species were selected after careful discussions with scientists familiar with the Chesapeake Bay planktonic communities. The benthic infauna listed are representative assemblages of each salinity zone. The benthic epifaunal species are those representative of the mesohaline Chesapeake Bay. Fish species were chosen based on a minimum CPUE (catch per unit effort) of 0.1 in Maryland seine and bottom trawl samples (Carmichael *et al.* 1992) or from consultation with biologists for those species not represented in seine and trawl samples (notably reef fishes). Waterfowl species listed here were chosen for their degree of dependence on the living resources of the Chesapeake Bay. Vegetation species, both submerged and emergent, are separated into representative assemblages for each salinity zone. The groups of species listed here are meant to be representative rather than inclusive. In all groups, most of the species are indicative of a well-balanced system. All others, where high abundances may indicate problems, are marked with a superscript: 1 = pollution tolerant, 2 = indicative of eutrophication, 3 = exotics, i.e. non-native species.



Bacteria
heterotrophic aerobes[1,2]
sulfate reducers[1,2]

Phytoplankton
TIDAL FRESHWATER
Anacystis spp. (cyanobacteria)[2]
Aphanizomenon flos-aquae (cyanobacteria)[2]
Asterionella formosa (diatom)
Chroococcus limneticus (cyanobacteria)
Cyclotella meneghiniana (diatom)
Cyclotella striata (diatom)
Melosira distans (diatom)
Melosira granulata (diatom)
Merismopedia tenuissima (cyanobacteria)
Microcystis aeruginosa (cyanobacteria)[2]
Scenedesmus spp. (chlorophyte)
Skeletonema potamos (diatom)
OLIGOHALINE
Cerataulina pelagica (diatom)
Ceratium spp. (dinoflagellate)
Cryptomonas spp. (cryptomonad)
Cyclotella striata (diatom)
Gymnodinium spp. (dinoflagellate)[2]
Gyrodinium uncatenum (dinoflagellate)[2]
Melosira distans (diatom)
Melosira granulata (diatom)
Microcystis aeruginosa (cyanobacteria)[2]
Skeletonema potamos (diatom)
MESOHALINE
Asterionella glacialis (diatom)
Cerataulina pelagica (diatom)
Ceratium spp. (dinoflagellate)
Cryptomonas spp. (cryptomonad)
Cyclotella caspia (diatom)
Gymnodinium spp. (dinoflagellate)[2]
Gyrodinium uncatenum (dinoflagellate)[2]
Heterocapsa triquetra (dinoflagellate)
Katodinium rotundatum (dinoflagellate)
Leptocylindrus minimus (diatom)
Prorocentrum minimum (dinoflagellate)
Rhizosolenia fragilissima (diatom)
Skeletonema costatum (diatom)
POLYHALINE
Asterionella glacialis (diatom)
Cerataulina pelagica (diatom)
Ceratium lineatum (dinoflagellate)
Chaetoceros spp. (diatom)
Gymnodinium spp. (dinoflagellate)[2]
Gyrodinium uncatenum (dinoflagellate)[2]
Leptocylindrus minimus (diatom)
Leptocylindrus danicus (diatom)
Prorocentrum micans (dinoflagellate)
Rhizosolenia alata (diatom)
Rhizosolenia stolterfothii (diatom)
Skeletonema costatum (diatom)
Thalassionema nitzschioides (diatom)

Zooplankton
Euplotidae (protozoans)[2]
Tintinnidium (protozoans)
Synchaeta sp. (rotifers)
Brachionus sp. (rotifers)[2]
Bosmina longirostris (cladoceran)[2]
Leptodora kindtii (cladoceran)
Acartia tonsa (copepod)
Eurytemora affinis (copepod)
Chrysaora quinquecirrha (sea nettle)
Mnemiopsis leidyi (sea walnut)
Nemopsis bachei (hydroid)
larval fish
polychaete larvae
barnacle larvae

Benthic Infauna
TIDAL FRESHWATER
Ilyodrilus spp. (oligochaete)
Limnodrilus spp. (oligochaete)
Naididae (oligochaetes)
Corbicula fluminea (bivalve)[3]
Musculium spp. (bivalve)
Polypedilum spp. (insect)
Chironimidae larvae (insect)[1]
Chaoboridae larvae (insect)
OLIGOHALINE
Rangia cuneata (bivalve)[3]
Marenzellaria viridis (polychaete)
Cyathura polita (isopod)
Gammarus daiberi (amphipod)
Carinoma spp. (nemertean worm)
Gemma spp. (bivalve)
Tagelus spp. (bivalve)
Eteone spp. (polychaete)
Tubificoides spp. (polychaete)[1]
Asabellides spp. (polychaete)
Mysidopsis spp. (crustacean)
MESOHALINE
Macoma mitchelli (bivalve)
Macoma balthica (bivalve)[1]
Mya arenaria (bivalve)
Mulinia lateralis (bivalve)
Parvilucina spp.(bivalve)
Leptocheirus plumulosus (amphipod)
Leucon americanus (cumacean)
Monoculodes spp. (crustacean)
Glycinde spp. (polychaete)
Nereis succinea (polychaete)
Strebliospio benedicti (polychaete)
Heteromastus filiformis (polychaete)
Micrura spp. (nemertean worm)
POLYHALINE
Ascyhis elongata (polychaete)
Clymenella torquata (polychaete)
Macroclymene zonalis (polychaete)
Chaetopterus variopedatus (polychaete)
Diopatra cuprea (polychaete)
Glycera americana (polychaete)
Loimia medusa (polychaete)
Leitoscoloplos spp. (polychaete)
Notomastus spp. (polychaete)
Mediomastus ambiseta (polychaete)
Spiochaetopterus spp. (polychaete)
Paraprionospio pinnata (polychaete)
Pseudeurythoe paucibranchiata (polychaete)
Spiophanes bombyx (polychaete)
Nephtys picta (polychaete)
Upogebia affinis (decapod)
Mercenaria mercenaria (bivalve)
Ensis directus (bivalve)
Gemma gemma (bivalve)
Cerianthus americanus (anemone)
Tellina agilis (bivalve)

Benthic Epifauna
barnacles
sponges
Crassostrea virginica (oyster)
Brachidontes recurvus (bent mussel)
Electra crustulenta (bryozoan)
Membranipora tenuis (bryozoan)
Molgula manhattensis (tunicate)
Polydora ligni (mud worm)
Polydora websteri (oyster worm)
Corophium lacustre (amphipod)
Callinectes sapidus (blue crab)
Eurypanopeus depressus (mud crab)
Panopeus herbsti (mud crab)
Stylochus ellipticus (flatworm)

Fish
MARINE SPAWNERS
Anguilla rostrata (American eel)
Bairdiella chrysaura (silver perch)
Brevoortia tyrannus (Atlantic menhaden)[1,2]
Cynoscion nebulosus (spotted seatrout)
Cynoscion regalis (weakfish)
Leiostomus xanthurus (spot)[2]
Micropogonias undulatus (Atlantic croaker)
Paralichthys dentatus (summer flounder)
Peprilus alepidotus (harvestfish)
Pogonias cromis (black drum)
Pomatomus saltatrix (bluefish)
Sciaenops ocellatus (red drum)
Stronglyura marina (Atlantic needlefish)
ESTUARINE RESIDENT
Anchoa mitchilli (bay anchovy)
Cynoscion nebulosus (spotted seatrout)
Cynoscion regalis (weakfish)
Cyprinodon variegatus (killifish)
Fundulus diaphanus (banded killifish)
Fundulus heteroclitus (mummichog)[1]
Fundulus majalis (striped killifish)
Hypognathus regius (silvery minnow)[1]
Lepomis gibbosus (pumpkinseed)
Membras marinica (rough silversides)
Menidia beryllina (tidewater silversides)
Menidia menidia (Atlantic silversides)
Notropis hudsonius (spottail shiner)
Paralichthys dentatus (summer flounder)
Pseudopleuronectes americanas (winter flounder)
Rhinoptera bonasus (cownose ray)
Syngnathus fuscus (northern pipefish)
Trinectes maculatus (hogchoker)
ANADROMOUS
Alosa aestivalis (blueback herring)
Alosa mediocris (hickory shad)
Alosa pseudoharengus (alewife)
Alosa sapidissima (American shad)
Morone americana (white perch)
Morone saxatilis (striped bass)
Perca flavescens (yellow perch)
TIDAL FRESHWATER

Cyprinus carpio (carp)
Dorosoma cepedianum (gizzard shad)[1,2,3]
Etheostoma olmstedi (tesselated darter)
Fundulus diaphanus (banded killifish)
Hypognathus regius (silvery minnow)[1]
Ictalurus catus (white catfish)
Ictalurus nebulosus (brown bullhead)
Ictalurus punctatus (channel catfish)
Lepomis gibbosus (pumpkinseed)
Lepomis macrochirus (bluegill)
Menidia beryllina (tidewater silversides)
Micropterus salmoides (largemouth bass)
Notropis hudsonius (spottail shiner)
REEF FISH
Centropristis striata (black sea bass)
Chasmodes bosquianus (striped blenny)
Gobiesox strumosus (skilletfish)
Gobiosoma bosci (naked goby)
Opsanus tau (oyster toadfish)

Waterfowl
Aix sponsa (wood duck)
Anas rubripes (black duck)
Anas americana (American widgeon)
Aythya affinis (lesser scaup)
Aythya americana (redhead duck)
Aythya marila (greater scaup)
Aythya valisneria (canvasback)

Submersed Aquatic Vegetation
POLYHALINE
Zostera marina (eelgrass)
Ruppia maritima (widgeongrass)
Zannichellia palustris (horned pondweed)[1,2]
MESOHALINE
Zostera marina (eelgrass)
Ruppia maritima (widgeongrass)
Zannichellia palustris (horned pondweed)[1,2]
Potamogeton pectinatus (sago pondweed)
Potamogeton perfoliatus (redhead grass)
Myriophyllum spicatum (water milfoil)[2]
Vallisneria americana (wild celery)
OLIGOHALINE/FRESHWATER
Ruppia maritima (widgeongrass)
Potamogeton pectinatus (sago pondweed)
Potamogeton perfoliatus (redhead grass)
Myriophyllum spicatum (water milfoil)[2]
Vallisneria americana (wild celery)
Heteranthera dubia (water stargrass)
Hydrilla verticillata (hydrilla)[2,3]
Elodea canadensis (common elodea)
Ceratophyllum demersum (coontail)
Najas guadalupensis (southern naiad)
Zannichellia palustris (horned pondweed)[1,2]

Emergent Vegetation
TIDAL FLATS
Ulva lactuca (sea lettuce)
COASTAL MARSHES
High salinity
Spartina alterniflora (saltmarsh cordgrass)
Spartina patens (saltmeadow hay)
Low Salinity
Scirpus olneyi (olney threesquare)
Spartina cynosuroides (big cordgrass)
Tidal Fresh
Pontederia cordata (pickerelweed)
Zizania aquatica (wild rice)
FRESHWATER EMERGENT WETLANDS
Scirpus validus (softstemmed bulrush)
Bidens cernua (nodding bur marigold)
Chelone glabra (turtlehead)
Cicuta maculata (water hemlock)
Hypericum vergicum (St. Johnswort)
Justicia americana (water willow)
Lycopus virginicus (water horehound)
Mimulus ringens (square-stemmed monkeyflower)
Phragmites australis (reed grass)[1,3?]
Typha latifolia (common cattail)[1,2]
SHRUB WETLANDS
Alnus serrulata (common alder)
Asimina triloba (paw paw)
Cephalanthus occidentalis (buttonbush)
Rhododendron viscosum (azalea)
Myrica cerifera (southern wax myrtle)
FORESTED WETLANDS
Acer rubrum (red maple)
Chamaecyparis thyoides (Atlantic white cedar)
Betula nigra (river birch)
Fraxinus pensylvanica (red ash)
Nyssa sylvatica (black gum)
Taxodium distichum (bald cypress)
FRESHWATER PONDS
Nuphar luteum (yellow pond lily)
Myriophyllum spicatum (eurasian watermilfoil)[2]
Lemna minor (lesser duckweed)[2]

APPENDIX B

The following technical documents give the perspectives of research scientists on the Chesapeake Bay ecosystem. The Strategy for the Restoration and Protection of Ecologically Valuable Species emphasizes cooperation between managers, researchers and modelers. In this Appendix, each scientist gives his or her viewpoint on the particular component of the ecosystem which he or she studies. Many of their principal points have been included in the Strategy at the appropriate places, but here they are speaking in their own words.

A brief summary of their main recommendations:

MODELING: Each community needs to be included in water quality models. They should also be included in models which track energy or carbon transfers.

HABITAT RESTORATION: Vascular plants, whether submerged (SAV) or emergent (wetlands), are important to the habitats of all communities. Preservation of existing acreage should be given high priority.

MONITORING: Maintaining existing monitoring programs and the inclusion of ecologically valuable species previously excluded should have a high priority. Analyses should be carried out which will bring out community features having to do with function, such as the proportion of predators, proportion of large and small individuals, or respiration.

RESEARCH: Studies need to clarify linkages between water quality and biological communities, and between the plants, herbivores and predators of each community.

The most important message that these scientists wanted to give is to look at the Chesapeake Bay ecosystem as a large and complex community, where each species is linked to others and to the habitat.

THE MICROBIAL LOOP

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ABSTRACT

The microbial loop is composed of a large group of microscopic organisms ranging from bacteria to tiny animals (bactivors) which feed upon them. The loop functions in Chesapeake Bay as a major catalyst of nutrient and carbon cycling and may also form the base of a food web analogous to the more usual phytoplankton-zooplankton system. Two metabolic groups within the loop, aerobic heterotrophic bacteria which inhabit the Bay's water column and anaerobic sulfate-reducing bacteria residing chiefly in Bay sediments, are responsible for anoxic and hypoxic conditions in Bay deep waters. An unusually large amount of carbon and energy in the Bay now seems to be dissipated by the microbial loop rather than transferred up the food web. The magnitude of carbon flow and oxygen-consumption processes attributable to the microbial loop may be decreased by nutrient reduction (supply side) or species replenishment (demand side) strategies. Augmentation of filter-feeding communities (e.g., oysters) and submerged aquatic vegetation may be particularly important to the latter strategy. Monitoring efforts need to include assessment of microbial loop biomass and metabolism. Further research is necessary to explore ways to decrease the influence of the microbial loop in the Bay's ecosystem.

INTRODUCTION

To many people, mention of the terms "microbial loop" or "bacteria in the Bay" generates the vision of the Chesapeake as a large reservoir of disease-causing microorganisms. In reality, however, most aquatic microorganisms do not cause disease, but rather are important components of aquatic ecosystems within which they function to recycle organic materials and may, as well, form the base of a microbial food web analogous to the more classic phytoplankton-zooplankton-higher animal scheme. A key feature of this microbial food web is that it is composed of a greater number of energy transfers than the phytoplankton-zooplankton scheme. Thus, its efficiency is necessarily lower and a smaller fraction of production ultimately reaches higher, economically important trophic levels (e.g., fish, crustaceans, oysters).

The "microbial loop" is comprised of two major groups of microscopic organisms, bacteria (prokaryotes) and tiny animals (eukaryotes) which feed upon the bacteria. These animals, termed bactivors, comprise part of the microzooplankton. Ciliates, in particular, are known bactivors, but the importance and magnitude of energy transfer from bacteria to microzooplankton and from microzooplankton to mesozooplankton is poorly understood for natural aquatic environments (Brownlee and Jacobs 1987). Currently available data for the Bay suggest that the bacteria are a carbon sink (Ducklow *et al.* 1986, Malone and Ducklow 1990), but the potential in the Bay for substantial energy transfer from bacteria to higher organisms deserves further attention (see RECOMMENDATIONS).

REPRESENTATIVE SPECIES

Given the paucity of information on bactivory in aquatic environments in general and in the Chesapeake Bay in particular, much of the remainder of this discussion focuses on bacteria. The concept of bacterial indicator species has proved highly successful over a long period of time for assessing pollution (e.g., coliform counts as indicators of fecal contamination). With regard to ecosystems, however, the concept of indicator species has much less value for bacteria. It appears to be more useful in terms of describing the state of the ecosystem to divide the bacteria into metabolic groups which delineate the roles they play in geochemical cycling and carbon flow (Table 1). Of particular importance to the Bay ecosystem are those metabolic groups which play quantitatively significant roles in oxygen consumption, namely the aerobic heterotrophic group and the sulfate-reducing microbial community.

IMPORTANCE

Two key bacterially catalyzed processes drive oxygen depletion in the mesohaline region of the Bay (Tuttle *et al.* 1987a). Oxygen consumption may be linked directly to the oxidation of organic carbon (CH_2O) by aerobic heterotrophic bacteria (Table 1) residing in the water column (termed pelagic bacteria or bacterioplankton) and in oxygen-containing surficial sediments. This process (equation 1) is necessarily restricted to the aerated portion of the water column during anoxic events.

$$(CH_2O) + O_2 \longrightarrow CO_2 + H_2O \quad \text{(Eq. 1)}$$

Table 1. Simplified listing of some major bacterially catalyzed processes which occur in the Chesapeake Bay.

Process	Energy Source	Carbon Utilized	Electron Acceptor	Primary Bacterial Metabolic Group
Aerobic Decomposition	Organic C	Organic	Oxygen	Aerobic Heterotrophs
Sulfate Reduction	Organic C	Organic	Sulfate	Anaerobic Heterotrophs (Sulfate Reducers)
Sulfate Oxidation (Sulfide Oxidizers)	Sulfide	Inorganic	Oxygen	Aerobic Autotrophs
Nitrification	Ammonia Nitrite	Inorganic	Oxygen	Aerobic Autotrophs (Nitrifiers)
Denitrification	Organic C	Organic	Nitrate, Nitrite	Anaerobic Heterotrophs (Denitrifiers)
Methanogenesis	Hydrogen, Simple Organic C	Inorganic	Carbon Dioxide	Anaerobic Autotrophs (Methanogens)

The second process which contributes to oxygen consumption involves the cycling of sulfur. The key chemical reactions are depicted by equations 2 and 3.

$$2(CH_2O) + SO_4^{2-} \rightarrow H_2S + 2HCO_3^- \text{(Eq.2)}$$

$$H_2S + 2O_2 \rightarrow SO_4^{2-} + 2H^+ \text{ (Eq. 3)}$$

Equation 2 represents the oxidation of organic carbon by sulfate-reducing bacteria, anaerobic microorganisms which use sulfate rather than oxygen as a terminal electron acceptor (Table 1). Sulfide (H_2S), the product of sulfate reduction, reacts with oxygen directly (equation 3) or indirectly via reactions involving iron or other metals. Sulfide oxidation reactions occur abiologically as well as by the metabolism of sulfide-oxidizing bacteria (Table 1). Sulfide is produced mainly in the sediments, even when Bay bottom waters are anoxic (Tuttle *et al.* 1987a, 1987b). Oxygen consumption by sulfide oxidation (equation 3) occurs in surficial sediments or at the sediment-water interface when bottom waters contain dissolved oxygen and within the water column in the region of the pycnocline when bottom waters are anoxic.

Detailed description of processes affecting the establishment and maintenance of hypoxic and anoxic conditions can be found elsewhere (Tuttle *et al.* 1987a, 1987b), but it is important to consider here the magnitude and timing of the bacterially catalyzed processes depicted in equations 1 and 2. Sustained bacterioplankton abundances in the mid-Bay during the warmer months of the year are very high, averaging about 10^{10} cells per liter (Malone *et al.* 1986; Tuttle *et al.* 1987a; Jonas and Tuttle 1990). These large standing crops of bacteria consume oxygen at a rate of 1-1.5 mg O_2 per liter per day (Tuttle *et al.* 1987a). Sediment sulfate reduction (sulfide production) rates in the mid and lower Bay are among the highest found in marine environments (Tuttle *et al.* 1987a; Roden and Tuttle, in revision) and rates in the upper Bay are substantial, even at conditions of limiting sulfate concentrations (Roden and Tuttle, in review). Recent modeling exercises indicate that bacterioplankton oxygen consumption is most important in the spring, whereas sediment sulfide production and subsequent sulfide oxidation becomes dominant during the summer (Roden and Tuttle, in press; Kemp *et al.*, in prep.). These findings contradict earlier studies which attributed oxygen consuming processes chiefly to the water column (Taft *et al.* 1980) or sediments only (Officer *et al.* 1984).

Although a variety of other microbial groups are undoubtedly also important with regard to geochemical processes occurring in the Bay (Table 1), the sheer magnitude of organic carbon flow needed to support the metabolism of aerobic heterotrophic bacteria and sulfate-reducers as well as their demonstrated role as key players in oxygen consuming processes indicate that these groups should be targeted. The carbon flow question in particular has critical implications for the Bay ecosystem, even if nutrient reduction strategies to limit phytoplankton prove sufficient to eventually decrease the extent and duration of anoxia. In the mid-Bay, for example, pelagic bacteria alone can account for a very large portion of primary net production (Table 2). Addition to this of the roughly equal amount of carbon required to support sediment microbial processes, sulfate reduction in

Table 2. Percentage of phytoplankton net production metabolized by pelagic bacteria in the mesohaline Chesapeake Bay. Estimates taken from Baird and Ulanowicz (1989).

	Season			
	Spring	Summer	Fall	Winter
% of Phytoplankton Production	25	50	30	28

particular (Roden 1990), gives rise to an ecosystem unduly dominated by carbon and energy flow through the microbial loop.

STATUS/FUNCTION/COMMUNITY STRUCTURE INDICATORS

Status

Abundance is a good indicator of the status of pelagic bacteria, particularly if their biomass (which can be calculated from abundance estimates) is compared to that of phytoplankton (Jonas and Tuttle 1990; Gilmour *et al.*, in press). A decreasing ratio of bacterioplankton biomass to phytoplankton biomass would signal ecosystem improvement in that it implies decreased carbon flow from primary production through the microbial loop.

The status of the sediment community of sulfate-reducing bacteria is more difficult to assess because both culturing and direct count enumeration methods for them are inadequate and genetic probe methods (e.g., Devereux *et al.* 1989) for reliably estimating their biomass in natural environments have not yet been developed. Because their function (i.e., sulfide production) is of greatest interest, measurements of their metabolism by ^{35}S procedures (e.g., Jorgensen 1978; Roden and Tuttle, in press) is also an appropriate estimate of their status. These methods are, however, labor intensive, relatively expensive, and require substantial technical expertise. A more reasonable approach would be to monitor water column sulfide concentrations during anoxic events. Roden and Tuttle (in press) have demonrated that sulfide flux from mid-Bay sediments approximates ^{35}S-estimated sulfate reduction rates when the sediments are overlain by anoxic bottom water. Therefore, decreases in sulfide concentrations in anoxic waters should be indicative of decreased sediment sulfate reduction rates.

Function

The function of microbial communities is typically assessed by measuring some feature of their metabolism or their productivity. Production by aerobic heterotrophic bacterioplankton is commonly estimated from ^{3}H-methyl thymidine incorporation measurements (e.g., Malone *et al.* 1986; Ducklow *et al.* 1986; Tuttle *et al.* 1987a; Jonas *et al.* 1988; Jonas and Tuttle 1990; Gilmour *et al.*, in press).

Community function can be characterized in more detail by using radiotracer methods to assess the metabolism of specific carbon sources such as amino acids, carbohydrates, fatty acids, etc. (Jonas *et al.* 1988; Bell 1990; Gilmour *et al.*, in press). The function of sulfate-reducing microbial communities is assessed by measuring the reduction of ^{35}S-sulfate (see above).

Community Structure

The structure of natural microbial communities has been determined by culturing samples in a variety of specific media (e.g., plate counts, most probable number techniques). These methods are very tedious and often lead to underestimation of the microorganisms present. It has become more popular to infer community structure from metabolism measurements (see Function), but in this case, we gain information only about metabolic groups within the community. Species and genera cannot be identified. Genetic probe methods with which we could test for codes of specific processes, genera, or species hold the promise of permitting us to rapidly and accurately assess microbial community structure. However, it is likely to be several years before these methods are at the stage of development where they can be reliably used with environmental samples.

QUALITATIVE AND QUANTITATIVE TARGETS

In order to set targets for the microbial loop component of the Bay's ecosystem, we must first address the question of whether the situation now existing in the Bay represents a "healthy" or "unhealthy" ecosystem. For reasons discussed above (see IMPORTANCE), it is clear that a large portion of primary production in the mid-Bay is currently dissipated by microbial processes which are directly responsible for oxygen consumption and thereby for the establishment and maintenance of hypoxia and anoxia. From a pragmatic point of view, one can argue that if this represents a "healthy" situation, management efforts to improve water quality and production of harvestable living resources will prove difficult at best.

Two questions regarding ecosystem structure seem germane to the Bay ecosystem health problem. These are:

1. Is the current Bay ecosystem fundamentally different from that which occurred in the past, i.e., was the microbial loop as important a player in the past as it is now?

2. Is the current Bay ecosystem fundamentally different from that of other marine or estuarine environments less impacted by anthropogenic inputs?

Both these questions are difficult to answer directly because experimental methods to adequately assess microbial biomass, production, and metabolism on a large system

scale have existed for only two decades or less. However, recent evidence from examination of mid-Bay sediments (Cooper and Brush 1991) indicates increased sulfur cycling since colonial times. Analysis of historical (mid-1930s to mid-1980s) mid-Bay deep water dissolved oxygen levels in the vicinity of Cove Point shows statistically significant decreased dissolved oxygen concentrations over successive time spans of about a decade (Cargo *et al.* 1986). Both these lines of evidence are consistent with increased microbial metabolism.

The second question is equally difficult to answer because complete ecosystem evaluation data for marine and estuarine systems are relatively rare. Nevertheless, network analysis of carbon flow through several marine ecosystems indicates that the Chesapeake is a stressed environment, characterized by an ecosystem having shorter cycles and more rapid carbon turnover than less impacted environments (Baird *et al.* 1991). These features are consistent with ecosystems in which the microbial loop plays a disproportionately large role. Thus, such data as are now available all point to microbial loop communities in the Bay which process a disproportionately large quantity of available organic carbon and which have a detrimental effect on water quality.

In terms of establishing qualitative or quantitative targets for reducing the impact of microbial communities, one must ask: *is it in fact possible to manage microbial communities on the scale of the Chesapeake Bay ecosystem?* Given the likely condition that the magnitude of microbial biomass, production, and metabolism in the Bay is ultimately related to the amount of internal organic carbon production (autochthonous phytoplankton primary production) and external inputs (allochthonous carbon from terrestrial sources), it is theoretically feasible to control microbial communities by:

1. Decreasing autochthonous production through nutrient reduction strategies and allochthonous carbon inputs by effective waste treatment and land management practices (bottom-up or supply side control), and by

2. Redirecting a portion of autochthonous production and allochthonous carbon through compartments of the ecosystem other than the microbial loop (top-down or demand side control).

The first of these strategies, already in practice and aimed primarily at decreasing phytoplankton production, would be expected to decrease microbial loop community production with a concurrent decrease in oxygen consumption and improved water quality. However, there is no reason to expect that the *proportion* of carbon processed by microbial communities would be altered (i.e., even less production would be available for transfer to higher trophic levels).

The second strategy, relying on higher trophic level consumers (e.g., oysters) whose community could be directly managed, would permit a greater proportion of production to be "captured" by species more desirable than microorganisms. Modeling studies comparing filtering rates of historic and current oyster abundances (Newell 1988; Newell *et al.* 1989), model scenarios depicting increased oyster densities in rafted aquaculture or on oyster bars (Gerritsen *et al.* 1989), and field measurements assessing the current Bay trophic state (Tuttle *et al.* 1987a) suggest that increasing oyster densities should positively impact Bay water quality and revitalize the nearly extinct Chesapeake Bay shellfish industry. Indeed, field studies on pelagic microbial processes and organic carbon at an oyster aquaculture facility demonstrate significant removal of phytoplankton, microbially labile particulate organic carbon, and pelagic bacteria within the oyster raft area compared to waters outside the raft area (Jonas and Tuttle, in press). The field results have been supported qualitatively by a quasi-equilibrium, mass action model of the exchanges transpiring in the mid-Bay (Ulanowicz and Tuttle, in press). The predictions of this model, the findings of the aquaculture field study, and the hypothesis that submerged aquatic vegetation (SAV) baffling effects could enhance settling of suspended material and phytoplankton to the benthos (R. Newell and W. Dennison, personal communication), give rise to the following simplified ecosystem result of increasing SAV and oyster densities:

> SAV & OYSTERS = < PHYTOPLANKTON = < PELAGIC BACTERIA = < O_2 DEMAND = > O_2 CONCENTRATIONS = > FISH

Potential problems arising from this "bioremediation" scheme are that increasing oyster densities could stimulate phytoplankton production via remineralization of nutrients from oyster biodeposits (e.g., Jordan 1987) and the biodeposits themselves could increase sediment oxygen demand (Gerritsen *et al.* 1989). However, increased cell-specific phytoplankton production has not been observed in oyster aquaculture field studies (Jonas and Tuttle, in press; Ulanowicz and Tuttle, in press) and preliminary results of a current study of microbial processes (including sulfate reduction) and oxygen demand in sediments beneath oyster aquaculture rafts suggest that increases in oxygen demand and microbial metabolism are relatively small and of short duration (Tuttle and Jonas, unpublished). It is thus reasonable to propose that increasing oyster densities (and perhaps SAV as well) represents a potentially useful method to augment the strategy of mitigating eutrophication in the Bay through reduction of nutrient inputs (Ulanowicz and Tuttle, in press).

Unfortunately, our knowledge of the microbial loop as it now functions in the Bay environment is insufficient to set

quantitative targets for reducing its influence. It is possible to predict with some certainty, however, that management strategies which decrease phytoplankton production or partially interrupt carbon flow directly from phytoplankton to bacteria will likely result in decreased microbial abundances and activities, particularly of pelagic microbial communities.

RECOMMENDATIONS

Monitoring

1. Include enumerations of bacterioplankton in the Chesapeake Bay Monitoring Program.

Bacterioplankton abundance is directly proportional to water column oxygen consumption rate (Tuttle *et al.* 1987a; 1987b). Therefore, it is possible to assess both the state of lower trophic levels (by comparison with phytoplankton biomass estimated from chlorophyll) and follow oxygen consumption with one, relatively simple measurement. Direct epifluorescent counting of microorganisms is less labor-intensive than making measurements of oxygen consumption and, after the initial purchase of appropriate microscopic equipment, is cheaper. Decreased bacterioplankton abundance will signal improving ecosystem health in the Bay, particularly if the ratio of bacterial biomass: phytoplankton biomass also decreases.

2. Monitor H_2S in the Bay and tributaries during anoxic events.

Although sulfide is being measured in the monitoring program, detailed (e.g., 1-2 m intervals) profiles are not made to my knowledge. As discussed above, sulfide loading (integrated sulfide concentrations) to the water column is an approximate indicator of sediment sulfate reduction rates. Decreased sulfide loading (as well as areal extent and duration of anoxia) to the water column, particularly from year to year, will be indicative of improving sediment conditions and because sulfide is toxic to animal and plant life, an indicator of improving habitat.

Research

1. Accelerate and expand studies aimed at quantifying how increased oyster stocks and SAV can improve water quality and increase the health of the ecosystem.

Bioremediation strategies based on increased oyster densities have been evaluated so far only in open creek systems where mass balances cannot be obtained. Laboratory or mesocosm studies are needed to quantify how the ecosystem components change under controlled conditions. Field studies should include combined water column and sediment assessments at aquaculture facilities and at oyster bars.

2. Continue research on oyster diseases and the development of disease resistant oysters.

Bioremediation procedures will be relatively ineffective if substantial portions of the augmented communities become infected with MSX or Dermo.

3. Estimate the contribution of microbial loop production to higher organisms.

This is a key gap in our knowledge of how the Bay ecosystem operates. If there are important Bay species which depend upon this path of carbon flow, desirable components of the ecosystem could be decreased by clean up strategies which decrease bacterial biomass and production.

4. Determine what factor(s), if any, control microbial loop biomass and production.

Conventional wisdom suggests that organic carbon is probably limiting the heterotrophic bacterial community, but neither this, nutrients (N and P), or predation have been investigated as possible limiting factors. Results from this research could permit us to select appropriate methods and set attainable targets for those methods aimed at controlling biomass and production of the microbial loop.

5. Assess the importance of the microbial loop in the Upper and Lower Bay and in the tributaries.

Most of the information on the role of the microbial loop in the Chesapeake has been gained from studies on the mesohaline mainstem. We know little about the situation existing in the Lower, more saline mainstem or the less saline Upper Bay. Likewise, apart from the Patuxent, we know virtually nothing about the tributaries. The role of allochthonous carbon in fueling bacterioplankton production and microbial sediment processes needs to be determined. A recent study has found that, at times, bacterioplankton production in the upper reaches of the Patuxent exceeds primary production, presumably due to allochthonous carbon input (Gilmour *et al.*, in press). If this is characteristic of the upper reaches of other tributaries and the Bay itself, the elevated importance of the microbial loop could have a profound influence on the status and function of the ecosystem existing there.

6. Estimate the response of the microbial loop to dinoflagellate blooms.

Sellner (e.g., Sellner and Olson 1985, Sellner and Brownlee 1990) has aptly pointed out that dinoflagellate blooms, although relatively short in duration, could provide substan-

tial organic carbon to the Bay and its tributaries. Preliminary evidence (Tuttle, unpublished) indicates major increases in bacterioplankton biomass, production, oxygen consumption, and nutrient concentration associated with these blooms. The influence of these large but transient carbon inputs on the Bay's ecosystem is largely unknown.

Modeling

1. Include bacterioplankton in water quality models.

2. Expand models by including major sediment bacterial processes (e.g., sulfur cycling, methanogenesis, iron reduction, nitrogen cycling).

Management

1. Improved efforts to control exploitation and replenish predator stocks should be encouraged.

As discussed above, there are reasons to believe the top-down control could influence the microbial loop so as to produce a "healthier" ecosystem.

Habitat

Decreases in biomass of and carbon flow through microbial loop communities are most likely to improve habitats by decreasing organic carbon loss, oxygen consumption, and the extent and duration of anoxia.

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PHYTOPLANKTON

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INTRODUCTION

Phytoplankton are microscopic plants found throughout aquatic systems and form the base of the food web in most of these systems. Their production, accumulation and subsequent decomposition govern higher trophic level productivities as well as nutrient and dissolved oxygen (DO) concentrations in the Chesapeake Bay and its tributaries. The on-going Chesapeake Bay Water Quality Monitoring Program for Maryland and Virginia, funded through the respective states and the U.S. EPA, is largely committed to establishing potential linkages between these primary producers and nutrient loads and concentrations in the systems. The basic premise is that the reduction of nutrient loads to the system will reduce phytoplankton production which, in turn, will lead to lower biological oxygen demand (BOD) in the system and higher DO concentrations in bottom waters of stratified Chesapeake Bay.

On another level, phytoplankton are also strongly linked to production of higher trophic levels in the system, including commercially valuable fish and shellfish stocks. The transfer of energy from these planktonic autotrophs governs production in the highest trophic levels through a complex food web from phytoplankton to suspension feeding herbivores to small and larger carnivores. These linkages are dependent on size and "taste" of the phytoplankton as well as system characteristics that provide either favorable or restricted habitats for potential grazers and predators in the system. The efficiency of this linkage may then control production of our living resources in our system.

The smallest phytoplankton are the picophytoplankton, hereafter referred to as picoplankton, averaging 1-2 μm and ranging from 0.2-2 μm. Nanophytoplankton, or nanoplankton, range from 2-20 μm, while larger cells are included in the microplankton (20-200 μm) and mesoplankton (>200 μm). Previous estimates of the relative contributions of these size classes of phytoplankton to the total community indicate major contributions in the nanophytoplankton, primarily as centric diatoms and microflagellates. As shown in most recent studies, picoplankton generally contribute on the order of 10-20% of total pigment and biomass production but have contributed up to 50% (Lacouture *et al.* 1991, Malone *et al.* 1991, Sellner *et al.*, in prep., a). Larger cells in the microplankton may dominate the phytoplankton community early in the spring bloom (e.g., *Cerataulina pelagica*, *Rhizosolenia* spp.) and in some summer dinoflagellate blooms (e.g., *Gymnodinium*, *Ceratium*). Nanoplankton and smaller macroplankton are preferred food items for the largest planktonic herbivores, which in turn are the primary prey for larval and some forage fish in the system.

Dissolved oxygen concentrations in mesohaline and polyhaline bottom waters of Chesapeake Bay are a function of stratification intensity derived through spring runoff, nutrient loads to the head of the Bay early in the spring, and the magnitude of the spring phytoplankton bloom. The magnitude of the spring bloom is dependent on nutrient levels entering from the Susquehanna River early in the year (see Malone *et al.* 1988) with the size of the bloom tightly coupled to the delivery of nitrogen, phosphorus and silicon from January-March. If runoff is reduced during this period or is delayed until after this period (as in 1989), the spring bloom will be smaller with lower total phytoplankton accumulation in the system (Sellner *et al.*, in prep., b). Most of this spring diatom production settles directly to the bottom of the Bay forming a large reservoir of labile organic matter that fuels high oxygen demand, largely bacterial, in late May-early June causing a precipitous decline in DO and hypoxic to anoxic conditions in bottom waters of the deep trough of Chesapeake Bay from June-September. The gradient in salinity across the pycnocline, a function of freshwater runoff, determines the ease to which bottom waters are re-aerated during the continuously low DO summer period in the Bay as well as the ease with which regenerated nutrients from decomposing spring bloom production mixes into surface waters fueling summer phytoplankton productivity (Malone 1992, Malone *et al.* 1986, 1988).

Quantifying the importance of phytoplankton to production of the higher trophic levels has been more difficult to assess in Chesapeake Bay. In general, zooplankton are not thought to be limited by a scarcity of phytoplankton food

in Chesapeake Bay, with a few exceptions (e.g., *Eurytemora affinis* in the Patuxent River; Heinle and Flemer 1975). Our estimates suggest that zooplankton remove on the order of 20-30% of annual mesohaline phytoplankton production (K. Sellner and F. Jacobs, unpubl. data) with the highest demand in February-March when phytoplankton standing crops and production in surface waters are low and August-September when the copepod *Acartia tonsa* dominates the zooplankton. This seasonal heterogeneity in zooplankton herbivory and reworking of phytoplankton is also supported in carbon and pigment deposition rates for mesohaline Chesapeake Bay (Boynton *et al.* 1991).

The absence of food limitation for the zooplankton suggests that zooplankton densities might be controlled through top-down rather than bottom-up mechanisms. Therefore, much of the Bay's phytoplankton production probably cycles through pico-microheterotrophs of the "microbial loop." This processing mechanism, i.e., degradation in the microbial loop, is a less efficient pathway for the transfer of energy from the phytoplankton to higher trophic levels resulting in lower production in our commercially valuable resource stocks than would be expected from the classic phytoplankton-copepod-fish food web.

REPRESENTATIVE GROUPS IN THE PHYTOPLANKTON

There are certainly specific groups of phytoplankton in Chesapeake Bay and its tributaries that could be categorized as indicators of "healthy" or "unhealthy" conditions in the system; there are even some species that could be considered representative of "good" or "bad" conditions. However, use of *one* species as an index of the system's balance without considering accompanying changes in water quality and the plankton is to be avoided. A responding system includes the interactions of many species as well as species-water quality interactions; therefore, many species and the surrounding particulate and dissolved pools must be examined before the "health" of the system can be ascertained.

Phytoplankton groups or characteristics that might be employed with other system parameters to indicate "health" include:

1) Abundance of "nuisance" species such as bloom-forming colonial cyanobacteria (e.g., *Microcystis aeruginosa*, *Agmenellum* or *Aphanizomenon*) or dinoflagellates (e.g., *Gymnodinium*, *Gyrodinium*, *Ceratium*);

2) Relative contributions of net phytoplankton (>10 μm), picoplankton (<3 μm) or eucaryotes to the total phytoplankton community; and

3) Relative contributions of specific phyla in a system, as diatoms/cyanobacteria or diatoms/total phytoplankton.

However, these indices must be compared to other characteristics of the system collected over long time periods that include vertical stratification, short- and long-term meteorology (e.g., wind- or storm induced mixing), zooplankton stocks present (e.g., micro- vs. mesozooplankton dominance) as well as stocks of benthic (oysters) or nektonic (menhaden) herbivores in a region. These factors all influence phytoplankton composition on short time scales that if not examined over a long period could lead to erroneous conclusions about phytoplankton responses to a managed Chesapeake Bay.

The importance of these factors in defining system "health" can be seen with the following examples. In the Potomac River, nutrient loads have been declining over the last decade. Accompanying this decline has been the virtual disappearance of bloom-forming cyanobacteria in tidal-fresh portions of the upper river (Fig. 1). This decline in cyanobacteria with a corresponding increase in the ratio of eucaryote biomass/total phytoplankton biomass has also been paralleled by a decline in the biomass of microzooplanktonic herbivores in the system suggestive of a reduced importance of the microbial loop in the river.

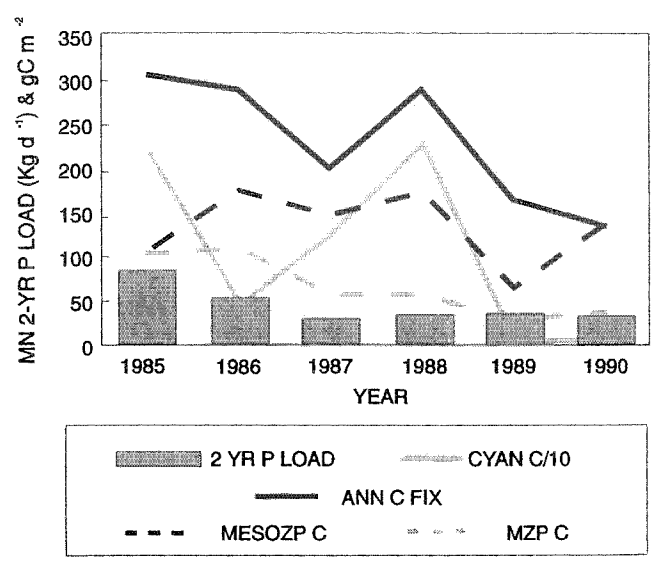

Figure 1. Plankton responses to declining phosphorus loads in the surface mixed layer of the tidal-fresh Potomac River, 1985-1990. Loads represent average 2 year loads for 1984-1985, 1985-1986, 1986-1987, 1987-1988, 1988-1989 and 1989-1990. The vertical axis represents phosphorus loads (kg per day) and carbon responses (g per square meter), respectively. CYAN C/10 is the carbon produced by bloom-forming cyanophytes divided by 10, ANN C FIX is the annual productivity, MZP C and MESOZP C represent biomass of the microzooplankton and mesozooplankton, respectively.

Thus, for the Potomac, reduced nutrient inputs appear to reduce the importance of non-nutritious cyanobacteria which in turn reduces the contribution of the smallest herbivores, the microzooplankton, and potentially the microbial loop. This reduction in the high oxygen-demanding microbial loop, in turn, might be accompanied by an increase in larger phytoplankton, larger zooplanktonic herbivores and more efficient transfer of phytoplankton production to commercially-valuable fish stocks through the classic food web.

Top-down control of phytoplankton has also been suggested as a factor to be considered in Bay management strategies. The elimination of most of the oyster stocks in the Bay has been suggested as a prime reason for the emergence of picoplankton as a dominant member of the phytoplankton community (Newell *et al.* 1988) with a concomitant increase in the importance of the "microbial loop" in the system. This loop, in turn, supports low bottom DO concentrations over most of the Bay's deep trough. One would expect the picoplankton/total phytoplankton ratio to increase as the oyster stock declined. One proposed means to (1) reduce phytoplankton stocks decomposing in bottom sediments leading to low DO and poor habitat and (2) remove of a large portion of the energy entering the microbial loop as picoplankton production would be to suspend bivalves over large portions of the surface (mixed layer) of the Bay and its tributaries. These suspension feeders could incorporate excessively high phytoplankton production into harvestable tissue, effectively reducing bottom water BOD as well as water column oxygen demand characteristic of the active microbial loop of the watershed.

The reduction in nutrient loads, particularly silicon, in delayed spring runoff or in drought can be accompanied by unusually low diatom biomass in the spring in Chesapeake Bay (Wagoner *et al.* 1990; Conley and Malone 1992; Sellner *et al.* in prep., b). In 1989, peak runoff was delayed in the spring until May. This delay resulted in much lower diatom accumulations in the spring and reduced diatom loading to the bottom. As a result, DO decline in bottom waters of the deep trough was also delayed. Relative to normal runoff years, the duration of low bottom water DO was reduced (R. Magnien, unpublished data). Part of the explanation for reduced diatom production was attributable to unusually low silicon concentrations in mesohaline Chesapeake Bay during the optimum temperature period for diatom growth. This control of diatom accumulation in the region through silicon limitation implies some potential for control of phytoplankton production through manipulation of nutrient loads in point- and, to a lesser degree, non-point source contributions. As Officer and Ryther (1980) have suggested, silicon additions to sewage treatment effluents might effectively select for more nutritious diatoms possibly leading to more effective energy transfer to the top predatory fish as well as formerly dominant oyster populations.

Changing water quality (high nutrients or elevated metal levels) can also cause a shift in size of the dominant phytoplankton resulting in elevated production of the smallest phytoplankton (see Sanders *et al.* 1981) and their planktonic herbivores (e.g., heterotrophic flagellates), reduced production in the larger copepods and top predators, the fish and a selection for ctenophores and medusae in some systems (Greve and Parsons 1977, Landry 1977, Parsons 1979). Shifts in community structure such as these are easily followed in controlled mesocosms but definitive examples in complex natural systems are less obvious. However, shifts in size distributions of the phytoplankton, as in biomass of the <10 μm fraction to the total community biomass, could provide an indication of potential problems for the Bay if examined over a sufficiently long time period.

Linkages between phytoplankton and top predators are even more difficult to establish. In a recent review of three separate ichthyoplankton data bases for the Bay and two of its tributaries, Sellner and Brownlee (unpubl. data) noted strong correlations between striped bass and white perch larvae densities and zooplankton biomass when copepods exceeded 50 per liter or, alternatively, when >44 μm non-tintinnid microzooplankton, exceeded 940 per liter. In addition, coincident high fish larvae densities and zooplankton biomass were also accompanied by correspondingly high juvenile indices for these periods for the respective fish species (Buchanan 1992). High zooplankton densities in the spring in these systems are coincident with abundant net phytoplankton biomass and the absence of "nuisance" species. The larger and apparently more palatable and oxidizable phytoplankton community supports successful zooplankton production and hence fish larvae development in these systems.

SUMMARY

Phytoplankton in Chesapeake Bay are the primary integrators of ambient water quality and as such, provide ideal "indicators" of system health. The abundance of small picoplankton in the Bay and the overwhelming importance of bacterial oxygen demand during the decomposition of settling phytoplankton implies that the microbial loop is the primary shunt for phytoplankton production in the system. This cycling of energy and nutrients in the smallest autotrophs and heterotrophs results in lower energy transfer to the highest trophic levels and might partially explain (at some minor fraction of fishing pressure) some of the lower fish and shellfish stocks in the region. In addition, nuisance algae, such as cyanobacteria blooms in the Potomac River

in the last several decades and red or mahogany tides resulting from dinoflagellate blooms, favor microbial processes rather than the classic phytoplankton-copepod-fish food webs, further reducing the transfer of primary productivity of the phytoplankton to our commercially valuable fish and shellfish stocks.

Monitoring distributions of these algae as well as total contributions of larger net phytoplankton will provide information on the size spectra of the primary producers present and therefore the dominant patterns of energy and nutrient cycling in the system: large contributions from the smallest algae relative to larger eucaryotes implies limited production in higher trophic levels relative to production when large phytoplankton predominate.

Future management strategies should include large components for assessing phytoplankton size distributions simultaneously with water quality, vertical stratification and distributions of potential herbivores in the system. We can effectively assess the "health" of Chesapeake Bay and its tributaries only by assessing all of these parameters simultaneously; no one character will provide distinct and definitive indication of Bay recovery.

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PHYTOPLANKTON

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INTRODUCTION

The phytoplankton community in the lower Chesapeake Bay is a composite of neritic species entering at the mouth of the Bay, freshwater populations transported from the various river systems, and resident estuarine species within the Bay. They include at least nine taxonomic categories that are seasonally dominated by diatoms, cryptomonads, dino-flagellates and cyanobacteria (Marshall 1980, 1991; Marshall and Alden 1990a). In addition, autotrophic picoplankters and a variety of microflagellates are also found within these waters (Affronti 1990; Affronti and Marshall 1990). These picoplankters and the larger phytoplankton communities are the producers for microbial and metazoan populations. Due to this relationship, and subsequent zooplankton linkages to higher trophic levels, the Chesapeake Bay is a plankton driven system.

REPRESENTATIVE SPECIES

Early studies of phytoplankton composition in Chesapeake Bay include Wolfe *et al.* (1926) and Patten *et al.* (1964), with the importance of nanoplankton in these waters first emphasized by McCarthy *et al.* (1974) and Van Valkenburg and Flemer (1974). More recently, Marshall (1991) and Marshall and Alden (1990a) discussed results from an extensive five year data base that included the composition, spatial and temporal patterns of phytoplankton in the lower Chesapeake Bay, and their relationships to water quality variables. This lower Bay population included over 480 phytoplankton species. Annually they went through six to eight successional stages, where specific floral assemblages had seasonal maxima, during spring, summer and fall. The total phytoplankton can also be divided into broader "cold" and "warm" water floral groups, that occur during winter-spring and summer-fall months. These various maxima and their assemblages are influenced by changes in salinity, temperature, nutrients and turbidity levels, and vary annually in their onset, magnitude and duration. Phytoplankton in the local tributaries also have spatial and temporal patterns of development, with a transition of species assemblages occurring downstream, as tidal fresh water algae are replaced by estuarine flora (Marshall and Alden 1990b).

The characteristic species associated with the different saline concentrations in the lower Bay and its tributaries are given in Table 1. These phytoplankters, and a variety of other background species, will vary in their abundances throughout the year.

INDICATOR SPECIES

The phytoplankton of the lower Chesapeake Bay is characterized by a seasonally dynamic and diverse group of species. Their growth is not excessive, and they are apparently not over-grazed, with the Bay plume distinct in its composition and concentrations of cells in comparison to neritic waters (Marshall 1982, 1991). Due to their brief life span, phytoplankton cells will respond within hours to environmental changes and new species assemblages can develop within days in response to changing water quality conditions. These changes often favor the growth of certain phytoplankton species, and may even promote the development of blooms resulting in more stress to the local biota. At present, blooms in the lower Bay are not extensive, frequent, or long lasting (Marshall 1989). They are associated with dinoflagellate growth, and mostly confined to the local river systems, where they are more common. Blooms that occur in the lower Bay system are monitored by our laboratory to follow their occurrence and associated environmental conditions.

In contrast to bloom formation, more lasting assemblages are correlated to the succession of species which takes place during eutrophication stages. Population shifts in the major floral categories indicate stress associated with eutrophic changes. Examples would include a change from a system dominated by diatoms to one dominated by cyanobacteria, or the change from nano- and micro-phytoplankton components to a picoplankton-dominated habitat.

LONG TERM TRENDS

Applying a series of statistical steps to a five year data set, Marshall and Alden (1991) evaluated long term trends of

Table 1. Dominant phytoplankters associated with various salinity regions in the lower Chesapeake Bay and its tributaries.

TIDAL FRESHWATER	OLIGOHALINE	MESOHALINE	POLYHALINE
Asterionella formosa	*Cryptomonas* spp.	*Asterionella glacialis*	*Asterionella glacialis*
Chroococcus limneticus	*Cyclotella striata*	*Cerataulina pelagica*	*Ceratium lineatum*
Cyclotella meneghiniana	*Melosira distans*	*Cryptomonas* spp.	*Cerataulina pelagica*
Cyclotella striata	*Melosira granulata*	*Cyclotella caspia*	*Chaetoceros* spp.
Melosira distans	*Microcystis aeruginosa*	*Heterocapsa triquetra*	*Leptocylindrus minimus*
Melosira granulata	*Skeletonema potamos*	*Katodinium rotundatum*	*Leptocylindrus danicus*
Merismopedia tenuissima		*Leptocylindrus minimus*	*Prorocentrum micans*
Microcystis aeruginosa		*Prorocentrum minimum*	*Rhizosolenia alata*
Scenedesmus spp.		*Rhizosolenia fragilissima*	*Rhizosolenia stolterfothii*
Skeletonema potamos		*Skeletonema costatum*	*Skeletonema costatum*
			Thalassionema nitzschioides

phytoplankton abundance and biomass composition within the lower Chesapeake Bay and several tributaries in relation to water quality and other variables. This analysis indicated a slight, but significant trend of increased abundance and biomass for phytoplankton in Bay waters above the pycnocline, which was most pronounced in summer. This increase was associated with higher concentrations of dinoflagellates, small centric diatoms and several other phytoflagellates. In contrast, a modest, but significant decline occurred below the pycnocline for both abundance and biomass. This pattern was most distinct during winter. These patterns were associated with a significant seasonal trend of increased species diversity above and below the water column. These results support conclusions made by Marshall and Lacouture (1986) that changes have been taking place in the composition of Bay phytoplankton. When examined over short time intervals, these changes can be expected to be subtle, but it is evident from our studies that this community is sensitive and responsive to the gradual water quality changes occurring in the Bay. These annual statistical analyses of phytoplankton and water quality data will be continued, to provide specific information relevant to evaluating the health status of the lower Chesapeake Bay.

RECOMMENDATIONS

Monitoring

1. Continue monitoring phytoplankton populations in the lower Chesapeake Bay. Phytoplankton populations represent the major food producer and oxygen source within the Chesapeake Bay. Knowledge of the composition and concentrations of the phytoplankton community will provide direct information regarding local stress and the regional health status of the Bay. Changes in phytoplankton composition will act as one of the first indicators of stress in the ecosystem. A long term monitoring program is necessary to obtain adequate data to distinguish true trends from population changes that may be attributed to normal and/or annual ranges of development.

2. Greater emphasis should be placed on reporting the incidence and location of blooms by toxin and non-toxin producing species. More information on the increasing concentrations of phytoplankton now occurring will be needed for future management decisions. The Old Dominion University Phytoplankton Laboratory will continue to be the depository for information on bloom events in the lower Chesapeake Bay.

3. Phytoplankton monitoring should continue to include the autotrophic picoplankton community. The balance, or changes that occur between these populations will aid in evaluating the health status of the lower Bay, or in specific areas of the system.

Research Activities

1. Greater understanding is needed on trophic relationships between the flora and fauna within the microbial loop. Although picoplankton are recognized as major producers within the Bay system, little is known about the fate of these cells and their linkages to metazoan populations. Such relationships would become more significant if a shift to a more picoplankton dominated system develops.

2. The Elizabeth River is a unique habitat under stress. More data is needed to understand local associations of picoplankton, phytoplankton, and zooplankton and the impact the degraded water quality has on these couplings.

SUMMARY

The lower Chesapeake Bay contains a diverse assemblage of phytoplankters and a representative autotrophic picoplankton population. Specific phytoplankton assemblages are found in the eastern, western and north central sections of the lower Bay, and these assemblages pass through a series of six to eight successional stages a year. These temporal changes are associated with major periods of growth and a transition in species composition.

These studies also indicate that the phytoplankton contains a variety of potentially harmful species that may produce extensive blooms and degrade water quality. For instance, Marshall and Soucek (1993) reported that five different dinoflagellates produced extensive blooms in the lower Bay from July through September 1992. The largest bloom was produced by *Cochlodinium heterolobatum* and persisted for four weeks over an area of 215 km^2 in the Bay. In addition, the first Chesapeake Bay record of the toxin-producing dinoflagellate *Pfiesteria piscimorte* has been reported by Alan Lewitus of the University of Maryland (Greer 1993) from Jenkins Creek off the Choptank River. These events indicate that the Bay and its fisheries are vulnerable to harmful phytoplankton species.

In conclusion, Marshall and Alden (1993) updated their previous phytoplankton trend studies in the lower Bay using a six-year database (1985-1991). They found significant seasonal trends of reduced cell concentrations across all their stations. These trends mainly developed during spring and were associated with reduced diatom abundance and lowered phosphorus levels. Future monitoring of the Bay phytoplankton populations will provide information on: 1) whether these trends will prevail, or are short-lived, 2) the response of present phytoplankton assemblages to changes in existing water quality conditions, 3) what are the linkages to environmental factors and biota that influence the growth of the various phytoplankton categories, and 4) how these findings will be useful to management in reducing the occurrence and impact of bloom events.

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ZOOPLANKTON

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INTRODUCTION

The zooplankton community sampled by the Chesapeake Bay Program is a principal component of the estuarine ecosystem. Zooplankton form an essential link in the food web and provide the bulk of the forage prey for most larval and juvenile fishes as well as many other estuarine organisms. Although we have a conceptual framework for the Chesapeake Bay ecosystem, details of the linkages, fluxes, sinks and shunts involving major functional groups such as zooplankton are for the most part poorly understood. It is apparent, despite this rudimentary understanding, that a disproportionately large amount of algal carbon and energy in the bay presently seems to enter the microbial loop (see "The Microbial Loop" chapter). Primary consumers in the zooplankton as well as the benthos and other groups are not passing large enough quantities of algal primary production up the food web, and excessive amounts of algal materials are being shunted to the microbial loop. Possible reasons why critical trophic linkages are decoupling are poorly understood but may include 1) an increase in the smaller zooplankton (microzooplankton) favored by eutrophy and less preferred as food for larval fish, 2) excessive cropping of larger zooplankton (mesozooplankton) by zooplankton predators, and 3) inhibited growth and reproduction caused by toxics, hypoxia or poor water quality. Models, long-term data sets, and ecosystem indicators can be powerful tools in furthering our understanding of the complex Chesapeake Bay ecosystem and in eventually managing man's impacts on the bay. These three kinds of tools require individual blends of monitoring data and research results in order to generate information useful to management agencies. Construction of working models of the Chesapeake Bay ecosystem has received much attention. The early models are heuristically valuable but much remains to be done. Zooplankton variables, for example, are not "turned on" in the current Chesapeake Bay 3D Water Quality Model, and functions describing zooplankton need to be refined. Long-term data sets are known to provide robust baselines from which to measure system health and progress towards restoration. The value of these types of data generally increases with time. Presently, we have 6 and 8 year zooplankton data sets which are just beginning to show significant trends that track changes in water quality. Biological indicators, or bioindicators, of ecosystem "health" are now widely recognized as useful tools with which to evaluate an ecosystem's ability to function and support diverse communities. Efforts are just now underway to develop and implement zooplankton indicators of ecosystem integrity for Chesapeake Bay.

REPRESENTATIVE GROUPS AND THEIR IMPORTANCE IN THE ECOSYSTEM

The zooplankton are often divided into three size categories which somewhat reflect their roles in ecosystems. Microzooplankton (<.202 mm, includes rotifers, ciliate and tintinnid protozoans and copepod nauplii) are closely linked to the microbial loop as consumers and are usually not a predominant prey of the larger plankton and nekton (free-swimming individuals such as fish). Mesozooplankton (>.202 mm, includes copepods, cladocerans, ostracods, barnacle larvae) are typically effective grazers/predators and are frequently the predominant prey of larval fish and many nekton. Macrozooplankton (includes the jellyfish group, amphipods, mysid shrimp, and insect and polychaete larvae) are generally omnivores or predators, and are caught by a .500 mm mesh.

As a means of assessing the health of the bay the zooplankton community has much to recommend it. The community is temporally and spatially ubiquitous and may be sampled at any time and any place. The community is not subject to direct human exploitation and therefore interpretation is not complicated by factors such as fishing mortality. The zooplankton community is biologically diverse with some 400 taxa commonly appearing in Chesapeake Bay and therefore its constituent species display varying sensitivities to a wide variety of environmental factors and these sensitivities often differ from those of other monitored communities. The zooplankton community has high trophic connectivity within the bay ecosystem and contains many primary and secondary consumers. The high level of linkage provided by the community between the primary producers and the upper trophic levels renders it useful as an integrator of the state of the system.

INDICATORS OF ZOOPLANKTON STATUS, FUNCTION AND COMMUNITY STRUCTURE

The Chesapeake Bay has been, and continues to be, the setting for several zooplankton research efforts. A recent tendency of the numerous universities, institutions, and state and federal agency laboratories in the bay area to coordinate research efforts and focus on ecosystem modelling has encouraged research into zooplankton functions in the bay ecosystem. Although life histories of many dominant species are fairly well documented, knowledge about habitat requirements and interrelationships among species, communities and functional groups is still fragmented.

Zooplankton monitoring by management agencies has been a part of the comprehensive monitoring efforts in the Chesapeake Bay since 1984 (Maryland, District of Columbia) and 1986 (Virginia). The purpose of these programs is to characterize the Bay communities, to establish a long-term baseline for trend analyses and to identify zooplankton associations with water quality and living resources. The programs have focused in early years on characterizing the spatial and seasonal values and patterns of the zooplankton community. It is the variations from normal patterns or reference sites that provide information through which the integrity of the Bay's existing zooplankton communities may be evaluated.

At present, the Chesapeake Bay zooplankton monitoring programs are using the following indicators of the health of the zooplankton community. The interpretation of these statistics must be done against the backdrop of a long-term baseline that documents the annual cycle of abundance and takes into account the effects of salinity on abundance, biomass and diversity.

Biomass

When corrected for salinity effects, low average biomass of the mesozooplankton is correlated with poor water quality. Comparisons of mesozooplankton biomass have been made for Virginia sites, excluding bloom event (>100 mg per cubic meter) to avoid the distortion provided by a few very large values. Plots of average values against salinity provided an easy way to identify outlier sites. In Figure 1 the outliers SBE2, SBE5 and RET4.3 all experience frequent to chronically poor water quality.

Microzooplankton biomass is relatively high in freshwater reaches with high nutrient loads and decreases when nutrient loads are reduced. A recent reduction in annual phosphorous loads in the Potomac river appears to have produced a drop in cyanobacteria biomass which has been parallelled by a decline in microzooplankton biomass, suggesting that these small consumers are responding to lower food levels (Figure 2).

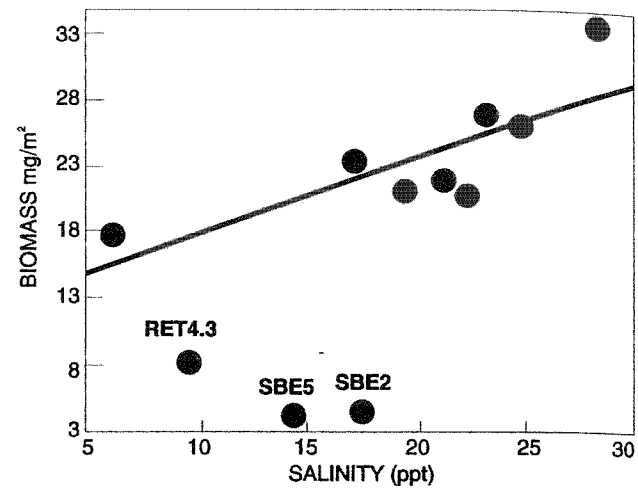

Figure 1. Average zooplankton biomass excluding blooms (>100 mg/m³) v. salinity in Virginia meso- and polyhaline water of the Chesapeake Bay. Trend line excludes identified outlier sites.

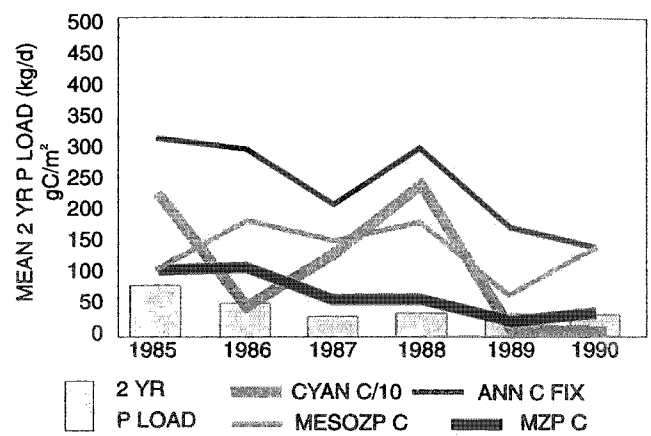

Figure 2. Plankton responses to declining phosphorus loads in the surface mixed layer of the upper Potomac estuary, 1985-1990. Loads represent average 2 year loads for 1984-1985, 1985-1986, 1986-1987, 1987-1988, 1988-1989 and 1989-1990. The vertical axis represents phosphorus loads (kg per day) and carbon responses (g per square meter), respectively. CYAN C/10 is the carbon produced by bloom-forming cyanophytes divided by 10, ANN C FIX is the annual productivity, MZP C represents biomass of the microzooplankton and mesozooplankton, respectively.

Abundance

As with biomass, zooplankton average abundance correlates with water quality when corrected for salinity and bloom events (Figure 3). The advantage of abundance data over biomass data is that the determination is not prevented by heavy detrital contamination that frequently occurs at oligohaline sites. The disadvantage is that high abundances of small species can distort the relative importance of those species in the community.

Diversity
Between-site comparisons in Virginia have not revealed noticeable decreases in absolute zooplankton diversity, even at heavily impacted sites such as those in the Elizabeth River. However, there are shifts in species dominance as rarer species become more common with the reduction of the normally dominant forms. Long-term trends in diversity at some sites have been noted and may be an effect of changing water quality.

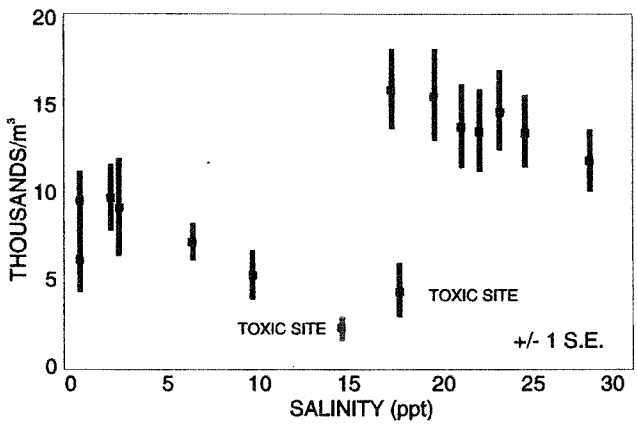

Figure 3. Average summer zooplankton biomass at mainstem station in the Virginia Chesapeake Bay.

Unnatural variability in abundance and biomass
High frequency of extreme abundance or biomass values is indicative of community instability and is associated with poor water quality. Virginia sites that experience chronically poor water quality display different abundance and/or biomass patterns than those with episodically poor water quality. Extreme values in mesohaline and polyhaline waters are presently defined for mesozooplankton abundance as >100,000 per cubic meter and <1,000 per cubic meter, and for mesozooplankton biomass as >100 mg per cubic meter and <2 mg per cubic meter. These definitions were selected through comparison with values from other East Coast estuaries and by comparing Bay sites that were apparently impacted with those that were not based on water quality characteristics. These definitions are subject to refinement and interpretation is subjective.

Ratios of specific taxonomic groups
A high ratio of microzooplankton biomass to total zooplankton biomass is frequently associated with poor water quality in the bay. This supports the hypothesis that as eutrophication occurs there is a shift to smaller, microzooplankton species in the planktonic community. In the Maryland mainstem, the upper Bay has the highest concentrations of nitrogen and phosphorus and the highest ratio of microzooplankton to total zooplankton. Lower ratios and lower nutrient concentrations are found in the mid-Bay and lower tributaries.

Other possible indicators of health of the Chesapeake Bay zooplankton community were recently identified at a regional workshop (Buchanan 1992) and are presently being developed. They include:

Ratios of various mesozooplankton taxa
A high ratio of calanoid copepods to cyclopoid copepods and cladocerans seems to be associated with good water quality in freshwater reaches of some tributaries.

Microzooplankton biomass in the deep trough
Microzooplankton biomass decreases in the deep trough of the mainstem after prolonged hypoxia-anoxia. It may be possible to use microzooplankton biomass as an indicator of some critical change that occurs as water quality deteriorates during summer hypoxia-anoxia.

Relative abundance of pollution tolerant and sensitive species
Specific species can be used as indicators of pollution events or water quality. Differences in physiology and ecology as well as differences in physical location in the habitat cause taxonomic groups to respond in diverse ways to a water quality condition. It has been shown that some species in the zooplankton community show a sensitivity to certain pollutants not seen in other monitored elements of the biota, for example, dissolved zinc, copper and free cupric ions are particularly toxic to one of the Bay's dominant copepods, *Acartia tonsa* (Sunda *et al.* 1990).

Presence of hypotrichs
One group of sediment dwelling microzooplankters, the hypotrich ciliates, are proving to be excellent indicators of low DO conditions in the system ($p<.02$). Anoxia or the accumulation of hydrogen sulfide in surficial sediments appears to cause the migration of these ciliates into overlying waters containing at least some oxygen. Future research might determine the "memory" of these events, and the ciliates could be used as indicators of recent DO events.

Size structure
Compression of the size frequency distribution of the mesozooplankton towards small sizes is a known indicator of over-exploitation by forage fish.

Food limitation of larval fish

An intensive analysis of three fish larvae databases obtained from J. Uphoff (MD DNR), E. Houde and E. Rutherford (University of Maryland) and R. C. Jones and D. Kelso (George Mason University) and the Maryland zooplankton monitoring data showed that on those occasions when high densities of striped bass or white perch larvae were encountered, mesozooplankton numbers exceeded 50-100 per liter or excessively high microzooplankton densities were observed. The zooplankton monitoring data indicates that mesozooplankton numbers in the bay and tributaries are frequently below the experimentally-determined minimum prey densities for normal larval growth (Figure 4).

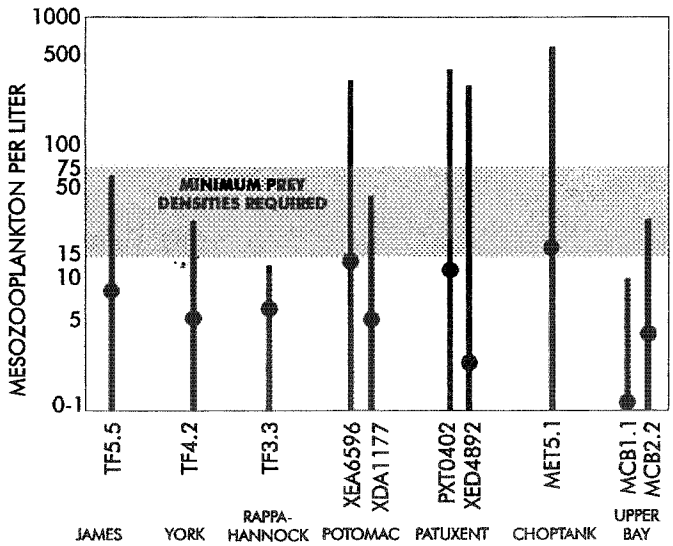

Figure 4. Spring abundance of mesozooplankton in spawning and larval nursery areas of anadromous finfish in Chesapeake Bay (number per liter). Minimum prey densities required for normal larval growth of striped bass are approximately 15-75 mesozooplankton per liter, depending upon species composition. The larvae typically feed first on microzooplankton and then switch to mesozooplankton as they grow. Median microzooplankton values (MD tributaries) usually exceed the required minimum prey densities for first-feeding larvae; this figure indicates median mesozooplankton frequently do not exceed minimum prey densities for later stage larvae.

● **Median April-May-June densities**

| **Range of maximum and minimum during sampling period (1985-1991 Maryland, 1985-1989 Virginia)**

Possible association of mesozooplankton index in spring and juvenile finfish index in summer

Further examination of the zooplankton monitoring data suggests the coincidence of high spring mesozooplankton abundances and high larval fish abundances can sometimes be associated with high juvenile indices later in the summer.

TRENDS

A major focus of the Chesapeake Bay Program zooplankton monitoring has been the detection of long-term environmental changes, both natural and man induced (Birdsong and Alden 1991). A scarcity of historical information on Chesapeake Bay zooplankton populations prevents direct comparisons of existing conditions with those that prevailed as recently as the 50's and 60's. Zooplankton monitoring is only now of a duration that exploration of the data in search of trends in bioindicators of health is proving fruitful. Some of the biomass, abundance and diversity data have been analyzed with a series of nonparametric trend tests that included a seasonal interblock test based on the Kendall Tau statistic (Hirsch *et al.* 1982), the aligned rank test described by Sen (1968), the Van Belle and Hughes chi-square test (Van Belle and Hughes 1984) and the seasonal Kendall slope estimator (Gilbert 1987). These tests have been shown to be generally both powerful and robust when tested on representative data sets from the Chesapeake Bay monitoring program (Alden *et al.* 1990).

A synopsis of the trends is given below. Continued monitoring and trend analyses is likely to strengthen some of these apparent trends and invalidate others. The correlation of these apparent zooplankton shifts and water quality trends should be viewed with circumspection.

In the polyhaline, Virginia mainstem, an increase in the spring abundance (February, March, April) and in the March and April diversity has been noted. These increases were accompanied by tendencies towards declines of silicates, nitrates, orthophosphates, total phosphorus and total nitrogen and increases in secchi depth and ammonia. Also, summer diversity (July, August) showed an overall decline that was accompanied by an overall increasing trend in phytoplankton above the pycnocline and a tendency towards decreasing nitrates. Winter values displayed an overall decline in abundance (November and December) and biomass (November) that was accompanied by a tendency toward declining nitrates.

In the lower salinity mainstem, no discernable changes in the zooplankton community over time have been found for the Maryland monitoring program's 8 year time span. Mesozooplankton in the mesohaline portion continue to be stressed by hypoxia and anoxia in the summer and those in the upper, freshwater Bay are severely depressed by turbidity, nutrient enrichment and other factors. Peaks in the annual patterns of mesozooplankton and microzooplankton abundance show considerable variability in timing and intensity from year to year, although the dominant copepods *Eurytemora* and *Acartia* show strong, regular seasonal signals.

Zooplankton seasonal signals in the tributaries are often shifted in time or rendered indistinct due to the considerable inter-annual and inter-tributary variation in river flow. Despite the variability, tributary trends are evident. For example, zooplankton populations in the Potomac and Patuxent are improving as nutrient loads decrease (see above). Conversely, mesozooplankton populations in the James River are deteriorating as nutrients increase. Mesozooplankton diversity and biomass have decreased as secchi depth decreased and surface total phosphorus, surface and bottom total nitrogen, bottom ammonia and bottom nitrate increased at up-river stations. These trends were accompanied by an overall increasing trend in phytoplankton biovolume (Marshall and Alden 1991) and, at one station (RET 5.2), an increasing trend in benthic biomass (Dauer 1991).

QUALITATIVE GOALS

It is only possible at this time to state qualitative goals for the zooplankton community. Too little is still known about zooplankton habitat requirements and the interrelationships among species, communities and functional groups.

One obvious goal is a shift in zooplankton community structure such that dominance of the mesozooplankton over the microzooplankton is strengthened, and algal carbon and energy is more likely to be passed up the food web rather than to the microbial loop. This may occur as nutrient loads - and eutrophication - are reduced, however fishing pressure may also play a role in accomplishing this goal. Specifically, overfishing of gamefish (usually the top predators) can allow excessive populations of forage fish to become established. These in turn exert severe predation pressure on the mesozooplankton and reduce their ability to regulate phytoplankton populations. Research into the direct and indirect effects of the absence of ecologically important fishery species on lower trophic levels should be encouraged in ecologically-based management plans for these fisheries.

RECOMMENDATIONS

1. The zooplankton monitoring program should continue in some form similar to and compatible with that presently being conducted.

2. The zooplankton monitoring data base remains largely unexplored for water quality sensitive taxa and other subtle indices reflecting water quality. The diverse nature of the zooplankton community present the strong likelihood that sensitive bioindicators may be discovered. The necessary data for this exploration are available and costs would not be great. This effort should be a primary research focus.

3. Directed studies that link biological shifts with water quality in a causal relationship should be conducted for all monitored components of the zooplankton.

4. Communication between managers and researchers should be enhanced. In the past managers have often been unfamiliar with the array and the interpretation of the biological data available to them. Conversely, researchers need to improve the form and presentation of data such that it is accessible and useful to environmental managers.

5. Enhance use of zooplankton data in water quality and ecosystem models.

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FORAGE FISHES

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INTRODUCTION

Forage fishes are small fishes that mature at a young age and are abundant enough to be highly visible components of the system. Their trophic status is variable. They may be zooplanktivores, phytoplanktivores, detritivores or omnivores. Reproductive modes are also variable, but all (except killifishes) have pelagic larvae stages and, though few data exist, recruitment levels probably fluctuate significantly from year to year.

Forage fishes are included in a functional group of intermediate consumers that potentially affect Chesapeake Bay water quality through "top-down" trophic impacts. There is no doubt that these small fishes are important foods of top-level piscivores in the Bay and fishery management ultimately must consider how this forage base sustains stocks of striped bass, weakfish, bluefish and summer flounder. The so-called forage fishes are a diverse assemblage taxonomically and they occupy a variety of habitats. They also share the intermediate consumer categorization in food webs with invertebrates such as gelatinous zooplankton, which may compete with the forage fishes for limited food resources and channel consumed energy into trophic pathways that do not lead toward harvestable fish resources.

Although the role of forage fishes in food chains that fuel the production of piscivores is intuitively clear, their importance seldom has been quantified. Baird and Ulanowicz (1989) undertook a network analysis of the Chesapeake Bay ecosystem. In that analysis only bay anchovy, and to a lesser extent menhaden, stand out among fish species as obviously important in an energetics sense - in terms of probable consumption, storage and potential to fuel production of larger fish. Results of the network analysis may be correct but it is possible that the better-studied fish species have received disproportionate weight in the analysis and their presumed importance has been overstated. The level of consumption and production of "forage fishes" such as gobies, silversides, juvenile river herrings, killifishes, etc. all may be significant, especially within the specific habitats where they live. In a recent analysis of Atlantic coastal and estuarine fish production, Peters and Schaaf (1991) noted two major information gaps: 1) poor understanding of the role of detritus in food chains and 2) a lack of data on the cost of forage fish production.

KEY SPECIES

There are key forage fishes that deserve special attention. Bay anchovy and menhaden fall into this category. Roles of other species are less clear but naked goby (*Gobiosoma bosci*) and silversides (*Menidia* spp.) are important consumers and producers, as are killifishes (*Fundulus* spp., *Cyprinodon variegatus*) in their respective habitats. During the juvenile stage, several key Chesapeake Bay fishes may serve as important forage species. For example, young-of-the-year spot are abundant and productive, and are important forage for piscivores in the Bay during this transition stage of their life history.

There are key invertebrate species that have at least "overlapping functional roles" with forage fishes in the Bay ecosystem. The gelatinous medusae and ctenophores are plankton consumers serving that role. They not only potentially compete with the fishes but may, together with the fishes, cause a degree of top-down control over plankton productivity and even water quality itself. Recent studies suggest that consumption by the medusae and ctenophores generally does not control copepod production in the Bay mainstem (J. Purcell, pers. comm.), except under local and temporally-restricted conditions (Purcell and Nemazie, in press). Ingestion estimates for bay anchovy, although rather preliminary, indicate that immediately after the peak recruitment period (September-October) in Chesapeake Bay a significant fraction of the standing stock and daily production of copepods could be consumed (Vazquez 1989, Klebasko 1991).

IMPORTANCE TO THE ECOSYSTEM

A promising way to characterize functional groups and to quantify their role in ecosystems is through analysis of food web patterns. Food webs are complex. In aquatic ecosystems, they may be especially complex because of shifts in trophic status of individuals as they grow from larval to adult stages. However, recent progress in theory and analysis indicates that webs are "orderly and intelligible" and can be a useful

tool to understand community dynamics (Pimm *et al.* 1991). Properties of webs, the lengths of food chains, and the roles of component species can define important ecosystem properties such as dominance and connectedness. The networking analysis of Baird and Ulanowicz (1989) was an important initial step in determining functional groups in the Chesapeake Bay. This approach and others that serve to define trophic webs and properties, combined with bioenergetics research, can lead to a proper evaluation of how well the Bay is functioning. A workshop report on Bay Research Needs (Houde 1987) essentially reached this conclusion five years ago.

Two general kinds of approaches are needed to quantify and measure the properties of "functional groups." These could be termed *status indicators* and *dynamic properties.* Together they may define the "wellbeing" of forage fish or, more generally, functional groups in the Chesapeake Bay. *Status* measures include abundance, biomass, diversity, and distribution patterns. These measures can be converted into *indices*, related to environmental properties and subjected to trend analyses. They are the heart of a monitoring program. *Dynamic* measures are more difficult to obtain but they define the *properties* of individual species and of functional groups. Dynamic properties include measures of growth, mortality, production, and recruitment, and also of the variability in these properties. These functional properties, when combined with food web analysis and bioenergetics research/modeling, can lead towards an understanding of cause and effect relationships.

Several dynamic properties of species and groups can be used as status indicators if they are estimated repeatedly, and can be analyzed to determine temporal and spatial variability. Some of these indicators will be non-dimensional properties that serve well in comparative analyses. Examples are assimilation and growth efficiencies, or production to biomass ratios (P/B) - opportunist species exhibit high P/B, while equilibrium species display low P/B ratios. Trends in these properties or distributional patterns for individual species or functional groups can help to define the "health" of the Bay and its subsystems.

MODELING STRATEGIES

While key species can be singled out for research, their interactions with other species are complex and their effects on ecosystems difficult to evaluate. Models that elucidate the functional role of intermediate consumers are needed to learn how they structure communities, promote stability or facilitate desirable production properties in the Bay. Food web analysis and bioenergetics modeling can be effective in this regard. Network analysis (Baird and Ulanowicz 1989) has provided a good start to define the linkages and connectedness of key species and their relationship to component subsystems. Pimm *et al.* (1991) offer encouragement in the use of food web theory to define "health" in systems and changes in status over time.

Bioenergetics modeling can be particularly effective in clarifying how food availability and temperature link forage species to predators in a functional way (Hewett 1989, Hewett and Johnson 1989). In a simulation mode, bioenergetics models can be used to predict how changes in habitat that affect organism distribution (e.g., dissolved oxygen or temperature), combined with estimates of organism abundances, will affect productivity of key species. In more complex multispecies bioenergetics models, predator and prey dynamics and productivity can be modeled, an effective way to learn how piscivore production depends upon that of forage fishes. A bioenergetics and food web approach to modeling in the Chesapeake Bay will add an important "top-down" perspective to the "bottom-up", nutrient-driven modeling that now predominates.

Some key species, because of their dominant status in ecosystems or their economic value, require both intensive monitoring and application of modeling approaches to understand their dynamics in Chesapeake Bay. Individual-based models (IBM), in contrast to models that depend upon estimated population parameters, follow the fates of individual organisms through their life. These models are becoming increasingly popular among fish ecologists (Huston *et al.* 1988) and are being developed for some species that are important in Chesapeake Bay, e.g., bay anchovy (Cowan *et al.*, in prep.) and striped bass (Cowan and Rose 1991, Rose and Cowan, submitted). In IBM models, the dynamics of large populations are simulated by applying expected rates or probabilities to individuals throughout their lives. Population-level consequences are sensitive to changes in habitat quality, food availability, and predator-prey relationships as they affect growth and survival of individuals at each life stage. The IBM approach is attractive because it allows relatively fast exploration via simulation of the consequences of changes in biotic or abiotic variables on target species dynamics. If an IBM is to be applied effectively, a considerable base of biological knowledge, not only species-specific information but also life-stage specific material, is required.

RECOMMENDATIONS

The realities of budgets and affordability constrain all ecosystem research. In the case of ecologically valuable fishes, status indicators that incorporate fish community surveys and habitat evaluation into various indices, includ-

ing the Index of Biotic Integrity (Jordan *et al.* 1991), potentially can show temporal and spatial trends (Vaas and Jordan 1991). Survey collections from which such indices can be developed are carried out routinely in Bay tributaries and can be applied effectively for tributary habitats. Equivalent surveys in the Bay proper that might index forage fish abundance would require greater and more costly efforts.

Affordable research and modeling that focus on the functional aspects of forage fish biology can provide the knowledge required to determine what, if any, additional monitoring efforts are needed. Some modeling approaches, for example, bioenergetics modeling, are developed well enough for fishes so that modest research efforts on Bay species may be rewarding. For some presumed key species, such as bay anchovy and menhaden, there already may be enough data on fish abundance, prey abundance and consumption rates, as well as temperature data, to develop bioenergetics models and apply them to Chesapeake Bay. The same may be said for individual-based modeling on bay anchovy and menhaden.

The coastwide fish production analysis by Peters and Schaaf (1991), which concluded that the dearth of understanding of forage fish production was a major gap in knowledge, holds true for Chesapeake Bay. A research effort to determine the nature and cost of forage fish production is appropriate. Modeling efforts (food webs, bioenergetics, IBM, ecosystem) are perhaps the only way to define and quantify the probable importance of forage fishes in the Bay ecosystem. Some routine, and probably not very costly, additional monitoring of forage fishes may be desirable but adoption of new programs seems unwarranted until research and modeling results convince us of the need.

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BENTHOS

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INTRODUCTION

The benthos consists of organisms that dwell on the bottom of marine, estuarine and freshwater ecosystems. This synopsis is restricted to the macrobenthic infauna of sedimentary habitats because this group of the benthos is emphasized by the Chesapeake Bay biological monitoring programs in both Virginia and Maryland. These are animal species retained on a 0.5 mm screen when processing sediment samples. Estimates of the macrobenthic infaunal community are used to indicate environmental health because benthic animals (1) are relatively sedentary (cannot avoid water quality problems), (2) have relatively long life spans (indicate and integrate water quality problems over time), and (3) consist of species that exhibit different tolerances to stress (benthos can be classified into functional groups based on tolerances to water quality stresses). Species of benthos that are commercially important and are generally epifaunal (dwell at or on the sediment-water interface) are not covered in this synopsis.

BENTHIC SPECIES ASSEMBLAGES

The macrobenthic infauna of the Chesapeake Bay consists of more than 300 species belonging to many invertebrate groups. Representative species are best characterized by the biomass dominants of the major salinity regions of the Chesapeake Bay, as presented in Table 1. The distribution and abundance of benthic species is controlled by several environmental factors, with salinity the primary determinant. Sediment type and dissolved oxygen concentration are important secondary factors influencing benthic community composition in Chesapeake Bay (Holland *et al.* 1988, 1989; Dauer *et al.* 1989; Shaughnessy *et al.* 1990; Scott *et al.* 1991).

In the polyhaline lower Bay, the dominant functional group consists of subsurface deposit feeders, and suspension feeders are of secondary importance (Holland *et al.* 1988, 1989; Dauer *et al.* 1989). In other areas benthic biomass is dominated by obligate and facultative suspension feeders.

BENTHOS IN THE BAY ECOSYSTEM

The benthos have important ecological roles in (1) controlling water quality by removing phytoplankton (Table 2) and other suspended particles; (2) nutrient recycling through feeding, ventilation and sediment alteration activities; (3) trophic dynamics and energetics as important food sources for higher trophic levels including fish and blue crabs; and (4) affecting the flux of sediment contaminants through bioturbation and transfer of contaminants to higher trophic levels through uptake (Berner 1976; Aller 1978, 1982; Virnstein 1979; Holland *et al.* 1980; Swartz and Lee 1980; Boesch and Rosenberg 1981; Cloern 1982; Dauer *et al.* 1982a, b; Hartley 1982; Hargrave and Theil 1983; Officer *et al.* 1982; Phillips and Segar 1986; Bilyard 1987; Gerritsen 1988; Gray *et al.* 1988; Warwick *et al.* 1990; Weston 1990).

Macrobenthic production in Chesapeake Bay is moderate to high, but varies markedly among regions and habitats. Tidal fresh and transitional habitats are the most productive, where annual production of the suspension feeding bivalves *Rangia* and *Corbicula* can reach several hundred g m^{-2} y^{-1} (Holland *et al.* 1989). The deep, high mesohaline portions of the mainstem and Potomac River are the least productive habitats, because they are subject to annual hypoxia in the summer months. Total annual production in these habitats is less than 1 g m^{-2} y^{-1}. Hypoxic conditions also occur in the deeper portions of the mouths of several tributaries along the central mainstem (e.g. Patuxent and Patapsco rivers; occasionally Choptank, Chester, and Rappahannock rivers), and as a result macrobenthic productivity in these habitats is also relatively low (Holland *et al.* 1989; Shaughnessy *et al.* 1990).

BENTHIC INDICATORS OF STRESS

Currently there is no consensus on the best benthic indicators of stress; however, unstressed benthic communities can be characterized by (1) high biomass, (2) high species diversity and (3) community composition dominated in biomass by long-lived, often deep-dwelling equilibrium species. Figure 1 represents an analysis of environmental stress using graphical models of expected community parameters based upon macrobenthic infaunal data from the Virginia benthic biological monitoring program (see Dauer *et al.* 1989 for further details of the sampling program). This is one approach to quantifying expected benthic community parameters.

Table 1. Representative benthic taxa for the major salinity regions of the Chesapeake Bay.

Tidal Fresh	midge larvae	Chironimids, Chaoborids
	oligochaetes	*Limnodrilus*
	clam	*Corbicula*
Transitional	polychaete	*Marenzelleria*
	clam	*Rangia*
	crustacean	*Leptocheirus, Cyathura, Gammarus*
Mesohaline	polychaetes	*Marenzelleria, Heteromastus, Nereis, Streblospio, Eteone, Paraprionospio, Glycinde*
	clams	*Macoma, Rangia, Mya, Mulinia, Gemma*
	crustaceans	*Leptocheirus, Cyathura, Monoculodes*
	nemertean worm	*Carinoma*
Polyhaline	polychaetes	*Asychis, Chaetopterus, Clymenella, Diopatra, Loimia, Macroclymene, Nephtys, Notomastus, Pseudeurythoe, Spiochaetopterus*
	clams	*Ensis, Mercenaria, Tellina*
	mud shrimp	*Upogebia*
	anemone	*Cerianthus*

Table 2. Removal of phytoplankton by suspension feeders was estimated from benthic and plankton production estimates, and from a model of suspension feeding (Gerritsen 1988, Holland *et al.* 1989). These findings suggest that macrobenthos are at least equivalent to zooplankton in overall importance as consumers of phytoplankton, and that benthos are the most important consumers in shallow reaches. Uneaten phytoplankton cells are available to bacteria and planktonic protozoa, and can contribute to the development of hypoxic conditions in the central mainstem of the Bay. Malone *et al.* (1986) estimated that approximately 60% of primary production was consumed by bacteria in the central mainstem.

Habitat Type	Primary Production Consumed
Tidal Fresh, shallow	50-80%
Low Mesohaline	30-50% (zooplankton crop same amount)
High Mesohaline, deep	10-15% (zooplankton crop 20-30%)

Models of expected values of macrobenthic community structure are presented for six measurable attributes. Foremost among these is species richness, or the number of species encountered, since within a habitat, stable, relatively unstressed habitats tend to support more species. Two other attributes commonly used to characterize macrobenthic community structure are community biomass and numbers of individuals. Three parameters less often used, but promising for the future are: the presence and contribution of deep-dwelling species, equilibrium species, and opportunistic species. Models present mean values for each parameter from 1985 through 1989 with 95% confidence intervals plotted against salinity. In the absence of reliable historical data from pristine habitats, stations considered minimally impaired were chosen to calculate expected values. Values for two stations (SBE2 and SBE5) from highly contaminated sediments of the Southern Branch of the Elizabeth River consistently deviated from expectation (also shown in Figure 1). Evaluation of restoration efforts could use such models with the expected values serving as restoration "goals".

Based on the indicator of benthic species richness, we can identify two problem areas and a suspected third in the upper Chesapeake Bay (Scott *et al.* 1991). First is the central mainstem, which is depauperate and stressed from annual summer hypoxia and anoxia. Second, portions of Baltimore harbor are depauperate, most likely due to toxic substances in the sediment. The third habitat of concern is tidal fresh regions, where some areas had depauperate benthos, but

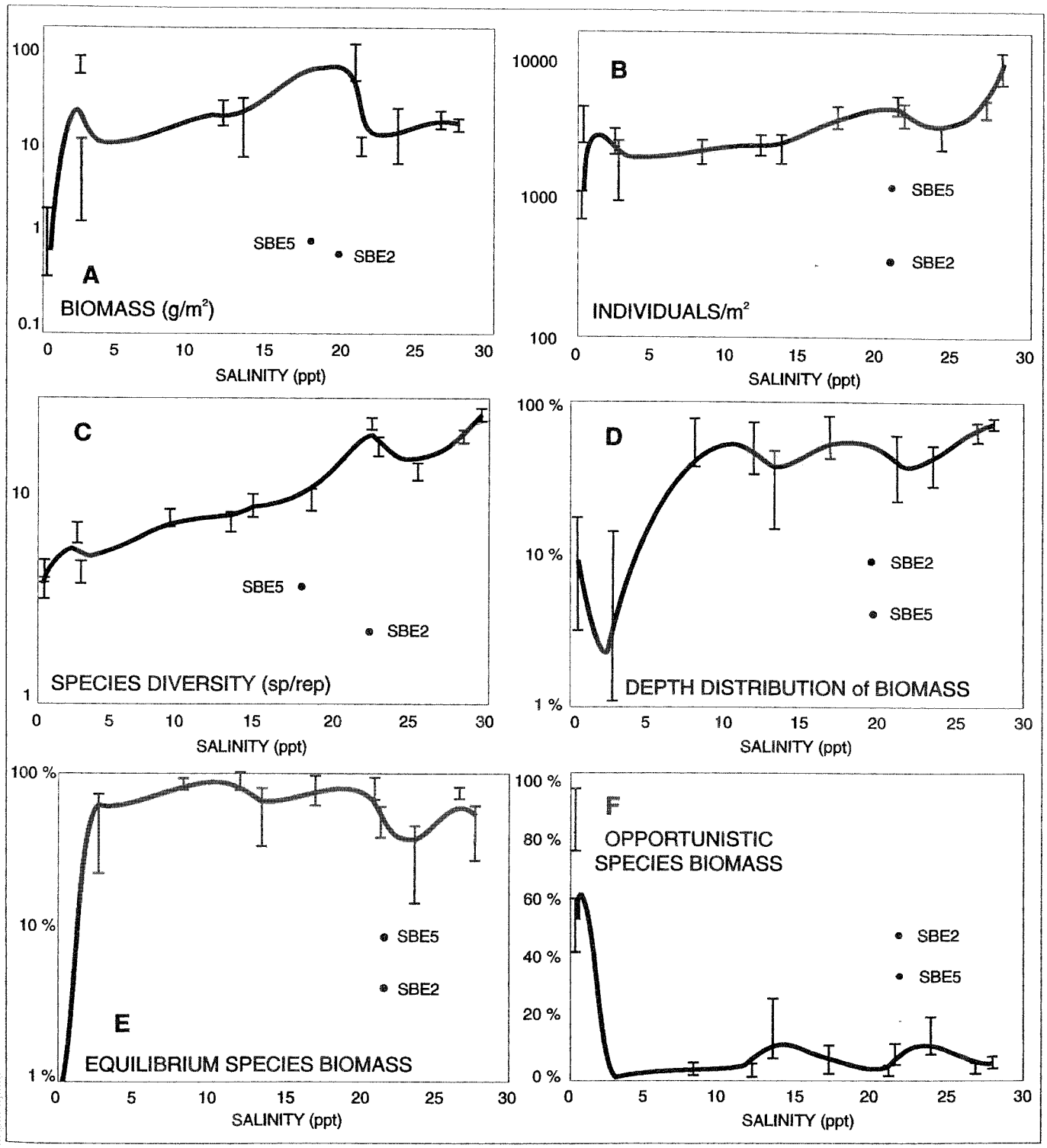

Figure 1. Relationships between community parameters as a function of salinity. Salinity values are five year means (1985-1989) and 95% confidence intervals (n=60). Line shown is a splined curve to aid visual interpretation. Comparison of expected community parameters with stations exposed to contaminated sediments of the Southern Branch of the Elizabeth River (SBE2 and SBE5). Values for SBE2 and SBE5 are mean values for data from 1989 (n=12). A. Community biomass in g/m², B. Number of individuals per m², C. Species diversity in species/replicate. D. Deep-dwelling biomass as percentage of community biomass below 5 cm. E. Percentage of community biomass composed of equilibrium species, F. Percentage of community biomass composed of opportunistic species.

with no known instances of hypoxia or sediment toxicity. Tidal fresh habitats are the first to receive stormwater runoff and the pollutants associated with runoff, and some species may be sensitive to ephemeral runoff phenomena (Hall 1987), reducing species richness of tidal freshwater habitats.

BENTHIC RESTORATION

The first step for restoring benthic community integrity throughout the Bay will be to reduce the frequency and severity of hypoxia so that benthic diversity is restored in many of the areas now periodically impacted by low dissolved oxygen. It must be noted that the deepest portions may have experienced periodic hypoxia even before European settlement because of the reduced circulation during summer stratification, and that no restoration may occur in those areas. The second step for benthic restoration will be to reduce the sediment toxicity of industrialized embayments, such as Baltimore harbor and the Elizabeth River.

Currently, in the Maryland mainstem Bay, up to 60% of the total primary production is not consumed by benthos or macrozooplankton, and is available to, and apparently consumed by, microzooplankton and bacteria (Malone *et al.* 1986; Holland *et al.* 1989). Respiration of microzooplankton and bacteria below the summer pycnocline is implicated in the development of summer hypoxia in Chesapeake Bay. The severity of the summer hypoxic events could be lessened by a reduction of mid-Bay primary production brought about by a decrease in the stocks of limiting nutrients, or by increased cropping of the phytoplankton production.

A suspension feeding model has been used to examine the feasibility of using suspension feeding bivalves to crop and remove excess primary production from Chesapeake Bay as a means of improving water quality and reducing summer oxygen deficits (Gerritsen *et al.* 1989). The analysis considered three methods of biological water quality control: (1) bivalve (oyster) culture, (2) riparian buffers along streams in the Bay watershed, and (3) use of SAV to control nutrients. Raft mariculture of oysters may be a viable means for enhancing water quality and reducing the frequency and severity of hypoxic events in the mainstem Bay and Potomac. It would require the development of an extensive oyster mariculture and support industry. While there are a host of technical problems that remain to be solved to make oyster mariculture feasible, it could have major economic benefits for the Bay region in addition to contributing to improved water quality.

These pollution control strategies are subject to limiting returns on investment as the reduction goal is approached. The high oyster production required to remove substantial phytoplankton production may exceed demand for the product, requiring subsidies to continue the program. Similarly, forest or wetland buffers on streambanks may require as much as 5% of agricultural and residential land area for substantial nutrient reduction, increasing resistance to such a program and possibly driving land prices higher as the goal is approached. We therefore recommend an integrated approach: tertiary and advanced treatment to reduce point source loadings; economically sustainable raft mariculture of oysters to improve Bay water quality; and forest and wetland buffers along selected streams to reduce non-point source nitrogen loadings. The preliminary conclusions presented here need to be refined, and if they appear to be valid, a research plan for testing them should be developed.

RECOMMENDATIONS

Monitoring

Benthic monitoring programs emphasizing macrobenthic infauna are essential components of any estuarine monitoring program and should be recognized as having three primary objectives:

(1) to characterize the health of the Chesapeake Bay as indicated by the structure of the benthic communities,

(2) to perform trend analyses on long-term data to relate spatial and temporal trends of the benthic communities to changes in water quality within the Chesapeake Bay,

(3) to warn of environmental degradation by producing an historical data base that will allow updated annual evaluations of biotic impacts due to changes in water and/or sediment quality.

(4) Validation of benthic indicators.

Research

The following four areas represent research needs relative to the benthos:

(1) Understanding the functional relationship between nutrient reduction strategies, benthic nutrient flux dynamics and the composition of benthic communities.

(2) Understanding the functional relationship between sediment contaminant levels, sediment contaminant flux and bioturbation activities of the benthos.

(3) Understanding the functional relationship of benthic secondary production and dynamics of higher trophic levels.

(4) Development of biological criteria for benthos to serve as restoration goals for management.

Because of the complexity of the estuarine system and the diversity of benthic species in the Chesapeake Bay, a functional group approach for each major salinity region is essential. Functional groups can be defined based on (1) feeding characteristics (e.g. suspension feeding, surface deposit feeding, subsurface deposit feeding), (2) sediment alteration characteristics (e.g. sediment stabilizers, sediment destablizers; see Woodin 1983), (3) life history characteristics (e.g. equilibrium species, opportunistic species, stress tolerant species) or (4) combinations of the above groups.

Modeling

Future water quality modeling efforts should include the benthos and emphasize functional groups based upon results from research recommended above. Relationships between benthos and higher trophic levels (including many species of economic and commercial importance) within years are well known; however, predictable relationships between years are much less certain (Arntz 1980; Woodin 1983).

Habitat

Various attempts to define critical life stages and critical habitats are well intended efforts to direct limited resources. However, the implication that there are less critical or even non-essential habitats is contrary to the primary goal of restoring a balanced ecosystem. Relative to the benthos, the primary habitat recommendation would be the promotion of vegetation in (1) shallow subtidal habitats (SAV), (2) intertidal habitats (salt marsh grasses and (3) bordering terrestrial habitats (buffer strips). These plant communities act as filters (removing nutrients and sediments), nurseries and ecological refuges.

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OYSTER REEFS

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INTRODUCTION AND REPRESENTATIVE SPECIES PRESENT IN CHESAPEAKE BAY

The economic significance of the eastern oyster harvest in Chesapeake Bay has long been recognized (Kennedy and Breisch 1981) and the continuing decline in harvests is adversely affecting the economy of many fishing communities. What is only now becoming widely appreciated is the importance of the oyster in the natural functioning of the complex ecosystem that is Chesapeake Bay. Historically, oysters may have been important in maintaining water quality by removing algae and silt from suspension. Furthermore, the hard bottom substrate formed by natural oyster reefs (=bars =rocks) is essential to the existence of many other benthic organisms, and beneficial to many species of demersal and pelagic finfish.

Although soft mud bottom benthic communities are currently predominant within the Bay (Holland *et al.* 1989), only 100 years ago, prior to the major oyster harvests of the latter part of the 19th Century, oyster reef communities were extensive (Newell 1989). In an effort to obtain some of the benefits historically provided by oyster reefs the Chesapeake Bay program is currently implementing an "artificial aquatic reef" habitat plan that is directed to increase the amount of hard bottom substrate available in Chesapeake Bay (Myatt and Myatt 1990).

The sessile invertebrate assemblage that grows on and among oysters forms a temporally and spatially complex community that includes many species. Among the most abundant sessile and sedentary invertebrates are barnacles (*Balanus improvisus*), bent mussels (*Brachidontes recurvum*), bryozoans (*Electra crustulenta* and *Membranipora tenuis*), tunicates (*Mogula manhattensis*), and mud worms (*Polydora ligni*) (Dame 1976, 1979).

Oyster reefs also provide habitat and food resources for a number of mobile species that are ecologically important to the Chesapeake Bay ecosystem. Both the density and diversity of some taxa of mobile fauna are considerably higher within oyster reefs than over adjacent soft bottom habitat. Common mobile invertebrates include amphipods (especially *Corophium lacustre*), which are important prey of fishes (Hildebrand and Schroeder 1927), xanthid mud crabs, and the blue crab (*Callinectes sapidus*). In addition, over a dozen species of benthic and demersal fishes utilize mesohaline oyster reefs during summer in Chesapeake Bay. The abundance of these benthic fish in oyster reefs without heavy sediment load can be extremely high; densities of naked goby (*Gobiosoma bosc*) in excess of 30 individuals/m^2 have been reported for both Maryland and Virginia oyster reefs (Nero 1976; Breitburg 1992). Besides reef-dependent fish, many other benthic and demersal fishes including spot (*Leiostomus xanthurus*), striped bass (*Morone saxatilis*) and black drum (*Pogonia cromis*) regularly forage on oyster reefs and remain in close proximity to reefs for extended periods of time.

Interactions among species are important factors that lead to the actual community composition on oyster reefs even though some of these interactions may limit the abundance of oysters. For example, there are complex competitive interactions among various sessile invertebrates (barnacles, tunicates, bryozoans, etc.) and oysters for space (Osman *et al.* 1989). Such competition may influence the success of oyster recruitment onto the limited hard substrate in Chesapeake Bay. In addition, several mobile invertebrates commonly found in oyster reefs are important predators of oyster spat. Among these are the blue crab (*Callinectes sapidus*), xanthid crabs (including *Eurypanopeus depressus* and *Panopeus herbstii*), and the flatworm *Stylochus ellipticus* (McDermott 1960; Krantz and Chamberlin 1978; Bisker and Castagna 1987; Newell *et al.* 1990; Abbe and Breitburg 1992). Small spat are most susceptible to these predators, and predation is likely to be an important factor influencing the recruitment of spat to existing reefs.

IMPORTANCE OF THESE SPECIES

It is self-evident that the oyster is the most important organism within the oyster reef community. This is due to the importance of oyster shell in providing a settlement substrate for sessile invertebrates and shelter for mobile species. Oysters, and other suspension feeding organisms that form part of the reef community (e.g. mussels, tunicates, barnacles, etc.), can improve water quality because their feeding activity significantly reduces suspended particle

concentrations in estuarine waters (Newell 1988). The resulting biodeposits can form an important food source for other oyster reef residents, thus increasing species diversity and biomass. This enhanced biodeposition by oysters serves to sequester nutrients into sediments, reducing their availability in the water column.

The sessile species that constitute the reef community are an important component of the food web in Chesapeake Bay, providing a source of food for many ecologically and commercial important predators, such as the blue crab. Mobile members of the reef community, such as the naked goby, are also important prey items for a number of larger finfish species (Markle and Grant 1970, Nero 1976). The naked goby utilizes oyster reefs for both shelter and reproduction. Its larvae are major consumers of zooplankton and thus constitute a mechanism whereby carbon is transported from the plankton to the benthos. Naked goby larvae are also an important food source for other species as they are generally the first or second most abundant species in icthyoplankton samples collected during summer in the Chesapeake Bay and its tributaries (Massman *et al.* 1963, Shenker *et al.* 1983).

The oyster toadfish, which is the largest of the resident oyster reef fish, is unique among Chesapeake Bay fish in that larval and early juvenile development occur within a guarded nest (Gudger 1910). In all likelihood, oyster toadfish remain on a single oyster reef, or at least within a very confined geographic area, from the adhesive benthic egg stage at least until temperatures begin to drop substantially in autumn. The oyster toadfish is an important predator of mobile oyster-reef fauna. This, coupled with its sedentary nature, may make it a useful vertebrate indicator of local toxics concentrations due to bioaccumulation of toxics in the food chain.

INDICATORS OF OYSTER REEF STATUS

Traditional means of assessing oyster populations have focused on parameters important to the fishery, especially annual recruitment and landings. A review of current oyster monitoring programs and suggestions for improvements has recently been performed by a workgroup (Newell and Barber 1990).

As outlined above, the species assemblage that comprises the oyster reef community is highly diverse, ranging from sessile invertebrates to mobile vertebrates. Such diversity makes it difficult to devise a single monitoring technique that can be used to quantitatively sample all components of the animal community, especially the mobile species, at a large number of locations. Even quantifying sessile species is difficult because their patchy distribution necessitates that large numbers of samples must be taken. The identification and enumeration of all species within such samples is very time consuming. Also, each species in the reef community requires different combinations of salinity and temperature to flourish. Therefore, there is not just one oyster reef community present in Chesapeake Bay but a temporally and spatially complex mosaic of species. Thus, it is difficult to define what is the normal or typical species composition of the oyster reef community at any one location or sampling date.

There is little information available on how to assess the suitability and quantity of oysters reefs as hard bottom habitat for reef dwelling species. We suggest that what is important is a combination of abundance of the living oyster and cultch material and the 3-dimensional aspect of the reef (=height of the material above the bottom). Certainly, prior to the overexploitation of the oyster stocks in the 1880's, oyster bars were large structures that extended high into the water column. Such a structure, still extant in intertidal oyster populations south of the Carolinas, provides many crevices and surfaces for other animals to utilize, much in the same way that coral reefs or wrecks provide refuges for fish.

Another problem associated with the reduction in height of the oysters reefs is the increased susceptibility of the cultch to siltation. Oyster larvae require a clean, silt-free oyster shell on which to attach when they metamorphose from free-swimming larvae into juvenile oysters. Excessive removal of oysters from oysters reefs meant that the structure became eroded and vulnerable to siltation associated with excessive sediment runoff into the bay. Similarly, for many other invertebrates the value of the oyster shell is diminished when it becomes buried by an overburden of silt.

QUANTITATIVE TARGETS FOR OYSTER REEF ABUNDANCE

An obvious target for the abundance of oyster reefs would be to reestablish the populations that existed in the surveys by Yates at the turn of last century. Realistically, such a scenario would be difficult to achieve due to the lack of cultch material to reestablish oyster bars. Also, the continuing epizootics of MSX and Dermo are likely to prevent the reestablishment of large oyster populations in the higher salinity regions of Chesapeake Bay. Instead, with suitable management of the bottom cultch, many of the lower salinity and relatively disease free regions of the bay may once again support a flourishing oyster population.

The ongoing discussions concerning introduction of the Pacific oyster, *Crassostrea gigas*, as an aquaculture species to Chesapeake Bay may have important implications for the abundance of oyster reefs. It is possible that if the

introduced oyster becomes established as a naturally reproducing species, then an increased abundance of reef habitat will naturally develop. At this time, however, the potential positive and negative ecological effects of introducing of *C. gigas* have not been fully evaluated.

In the absence of disease tolerant or resistant oysters to propagate and establish new oyster reefs, the amount of hard reef material can not be increased by any management activity other than physically putting that material on the bottom. Much remains to be learned concerning how such material should be placed in relation to prevailing water currents in order to reduce siltation. Ultimately, however, the amount of material that can be deployed is limited by the money available. Also, cultch material is becoming a scarce resource, with adverse environmental effects associated with dredging it from the bottom. One possibility for improving the existing bottom material is some type of active cultivation to remove sediment. Work by DNR involving bagless dredging has met with only limited success. More vigorous mechanical agitation with scrapeboards has been successful in Canada (C. MacKenzie, NMFS-Sandy Hook, pers. comm.). Such activities should be tested in Chesapeake Bay.

RECOMMENDATIONS FOR RESEARCH

Because of the variability in abundance and habitat requirements of species associated with oyster reefs, the primary focus of a realistic monitoring program should be on the quantity, depth distribution, structure, and degree of siltation of living oysters and shell which are the key elements needed to form an oyster reef community. It is impractical to monitor these characteristics of oyster reefs by SCUBA due to logistical considerations. However, it may be practical to use underwater video cameras mounted on Remote Operated Vehicles (ROV) to rapidly survey many oyster bars and provide a permanent record. Such a survey could be performed in the fall when water clarity is maximal. By using these techniques on natural and artificial oyster reefs it will be possible to follow the development of the hard bottom invertebrate communities and assess qualitative differences between the two types of substrates. Such methods should also be used to evaluate innovative methods for removing the overburden of silt from cultch on moribund oyster bars.

On a subset of reefs, a more thorough sampling program, using SCUBA divers, ROV, and remote sampling, should be conducted during summer when visibility is poor but many important biological and physical events take place. On these reefs, associated fauna and macroalgae should be sampled, identified and enumerated, and summer sediment accumulation should be monitored. It will also be important to monitor dissolved oxygen since episodes of severe hypoxia that have little effect on oysters can cause heavy mortality of associated fauna (Breitburg 1990, 1992). In addition, juvenile oysters and settlement substrates could be deployed at this subset of reefs to provide direct measures of variation in growth, survival and recruitment of sensitive life stages of oysters and other sessile invertebrates. The proposed monitoring of this subset of reefs should help clarify the relationship between the physical structure of oyster reefs and the development of a typical oyster reef community. This should provide information needed to set goals for reef restoration and preservation. Based on current knowledge, it can be assumed that high species richness and high abundances of species in all trophic levels should be characteristic of natural oyster reef communities. However, no specific data are currently available to permit the characterization of oyster reefs as healthy or degraded based on associated fauna.

Many aspects of oyster reef communities are still poorly understood. Fundamentally we need to know if an artificial reef composed of fossil oyster shell, or some substitute material such as cement, consolidated fly ash, old tires, etc., is capable of sustaining as productive an associated community as a natural oyster reef, in which the hard substrate is primarily provided by living oysters. The primary difference is that living oysters provide a large amount of organic material from their biodeposits as a source of food to associated organisms. In hard-bottom reefs without oysters this supplemental food source is absent. Thus, we might expect that meiofauna and detrivores, such as worms and crabs, to be less abundant in the artificial reefs. In addition, some artificial reef structures may leach toxic compounds that can be taken up by organisms in the fouling community. We suggest that comparative studies of natural oyster reefs and artificial reefs be conducted to elucidate differences in invertebrate community composition.

An associated problem is the lack of information on the importance of oyster reefs to fish populations in the Bay. Except for species that require hard substrate for egg deposition, we do not have the basic information required to assess how changes in the areal extent or biological characteristics of oyster reefs affect population dynamics or growth rates of fish species that also utilize other habitats. Such information is needed for the establishment of goals and methods for oyster reef restoration, and for the assessment of the success of such programs.

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CRUSTACEANS

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INTRODUCTION

Crustaceans are a diverse group of animals that often occupy key ecological positions in the benthos, plankton and microbial communities. Copepods are the dominant planktonic herbivores in the Chesapeake Bay. Harpacticoid copepods are similar to planktonic forms, but are usually associated with benthic communities. Brachyurans, true crabs, are also important predators in benthic habitats such as oyster reefs and clam beds. These decapods are also important prey items for higher trophic levels within the bay (striped bass, American eels, bluefish, etc.) (Manooch 1973; Wenner and Musick 1975; Wilson *et al.* 1987; 1990a;b).

NON-DECAPOD CRUSTACEANS

Zooplankton grazing can be a key factor in utilization of primary production and passage up the food web to higher trophic levels. Species composition of spring phytoplankton blooms in stressed marine systems can be altered, often resulting in the dominance of smaller flagellated species instead of diatoms. The loss of the normal diatom species can directly effect feeding efficiencies, growth and survival of herbivorous copepod species. This often results in increased production of smaller zooplankton species which support ctenophores and medusae over fish production (Greve and Parsons 1977). Theories of topdown control in Chesapeake Bay suggest that jellyfish and ctenophores may have a significant effect on zooplankton populations, including copepods and planktonic larval stages of benthic crustaceans (Feigenbaum and Kelly 1984; Kramer 1979). The apparent lack of a spring bloom in the Elizabeth River (Alden *et al.* 1991) would suggest a major shift in usage of primary production away from zooplankton grazers and towards the microbial loop in the most industrialized sections of the bay. Because of the apparent transfer of large amounts of Chesapeake Bay primary productivity into the microbial loop further assessment of the fate of this carbon is required. Transfer of microbial biomass/carbon to higher trophic levels including planktonic crustaceans remains in debate. The general consensus is that crustacean macrozooplankton, while possessing the ability to ingest nanoplankton, do so at very low efficiencies (Ducklow *et al.* 1986; Turner *et al.* 1988). The most common hypothesis for transfer of microbial carbon is via intermediate trophic levels (Sherr *et al.* 1986; Stoecker and Cappuzo 1990; Verity 1991). A more direct link between benthic bacterial production and higher trophic levels via harpacticoid copepods has been suggested. Harpacticoid copepods have been shown to consume significant levels of bacterial production. Harpacticoid copepod production can subsequently be passed up the food web via benthic invertebrates and demersal fish. Alternatively, there is evidence from oligotrophic fresh water systems that smaller holoplanktonic cladocerans can, under the appropriate conditions, clear significant levels of nanoplankton biomass from the water column (Wyle and Currie 1991). The role of small crustaceans both in the water column and in the benthos should not be immediately dismissed.

DECAPOD CRUSTACEANS

Given their dominant position in the benthic ecology of the Chesapeake Bay, large scale changes in decapod crustacean population size may have long-term implications for the Bay's ecology. While it is not the only ecologically important brachyuran in Chesapeake Bay, the blue crab has received extensive study.

Best known for its economic importance, the blue crab *(Callinectes sapidus)* is also ecologically important to the Bay. The blue crab at varying stages in its life history occupies several different trophic levels: herbivore, detritivore, and carnivore. Prey preference varies with crab size, habitat, and seasonal availability of prey (Tagatz 1968; Alexander 1986; Laughlin 1982; Van Heukelem 1991). Smaller blue crabs (<60 mm) consume greater quantities of detritus and plant materials than larger crabs. There is an increased reliance on predation with increasing size. Adults are a dominant epibenthic carnivore and scavenger in Chesapeake Bay and are important in the predatory control of coastal communities of the western Atlantic and Gulf of Mexico (Hines *et al.*, 1990). Blue crab predation on benthic communities can be significant with bivalves composing 34 to 42% of the diet. On soft bottoms, they consume the ecologically and economically important soft-shelled clam, *Mya arenaria* and the Baltic clam, *Macoma balthica*, which are dominant infaunal components (Hines and Comtois, 1985). Several studies have suggested that the blue crab may control the

size of bivalve and associated fauna populations (Virnstein 1977, 1979, Van Heukelem 1991). The decline in bivalve populations in the Bay could result in major shifts in foraging behavior in the blue crab population.

A major concern of fisheries management is the potential for population over-fishing, especially in the face of declining catches of other commercially important species in the bay.

The chief measure of population abundance for the blue crab is the commercial landings reported by Maryland and Virginia. While there are problems with catch statistics for this species they offer a long-term data record that can be used for comparative purposes. Based on catch data, the annual population level of blue crabs in the bay fluctuates around a mean level. These annual fluctuations can be wide but the current data suggests that the blue crab is maintaining its population levels despite increasing fishing effort.

A major contributor to annual fluctuations is post-larval recruitment from the continental shelf. This recruitment appears to be dominated by meteorological and physical processes (McConaugha 1988; Epifanio *et al.* 1989). Post-settlement mortality also may be a major contributor to inter-annual differences in population densities. Early juvenile stages (<25 mm) of the blue crab appear to prefer grass-bed habitats to either marsh or sandy bottom habitats (Orth and van Montfrons 1987, 1990). The recovery of submerged aquatic vegetation (SAV) in the lower Bay has increased the availability of this refuge habitat. Larger juveniles (>25 mm) appear to move out of the grass beds and to prefer sandy bottom areas. For larger crabs, because of their ability to burrow rapidly into the substrate, sandy bottom habitats provide a better refuge (Wilson *et al.* 1990a). Brachyuran crabs like the blue crab are most vulnerable prior to, during, and just after ecdysis of the old cuticle (molting). Males of the species appear to utilize shallow water tidal creeks as a refuge against predation during the molt (Hines *et al.* 1987). This suggests that availability and quality of shallow tidal creek habitats may have a significant impact on population dynamics of the blue crab. Blue crabs inhabit shallow estuarine areas and are exposed to run-off that carries herbicides, pesticides and other forms of pollution. Larval stages are the most susceptible to poor environmental quality. Habitat requirements and toxicity data for this species have recently been reviewed (Van Heukelem 1991) and will not be dealt with here.

RESEARCH NEEDS

The actual spawning stock size of the blue crab in the Chesapeake Bay appears to vary from year to year (Jones *et al.* 1990). Fecundity per female also varies within and between years (Prager *et al.* 1990). These reported inter-annual differences in reproductive stock size and fecundity within and between years need to be re-examined to determine their effect on population dynamics. Additional work is required to understand the recruitment dynamics of this species. For example, does post-larval recruitment or post-settlement mortality control year class strength?

Recent studies have suggested a stock-recruitment relationship for *C. sapidus* (Tang 1985; Lipcius and Van Engel 1990). Data on the variations in reproductive biology of this species is needed to fully understand the impact of this hypothesis on the long-term population levels of the blue crab. If there is a stock-recruitment relationship which is somehow coupled with the meteorologically dominated larval transport process, the potential for recruit over-fishing and a sudden collapse of the fishery is high. The ecological as well as the commercial importance of this species dictates the need for further studies of this species.

MONITORING ACTIVITY

A long term monitoring program is needed. Newly hatched crabs are the principal source of crabs hatched two years hence. There are few reliable measures of blue crab abundance at any life history stage. More information is needed about the life stages in order to understand natural variation in crab abundance. Are fluctuations in abundance of any life stage related to environmental variables?

Continued monitoring efforts for this species can be incorporated into the annual catch statistics and fishery independent surveys currently in place. Documentation of reproductive patterns and catch per unit effort data in fishery independent surveys would provide a more detailed understanding of changes in population dynamics. Catch per unit effort statistics have been proposed but implementation is critical. It would be helpful to obtain better and more consistent data on recreational catch.

It is important to monitor those areas of the Bay used for spawning and nursery areas. We must take greater steps to prevent deterioration of water quality. This may require stronger controls on industry, agriculture and the public to reduce nutrient loading and toxic discharges into the Bay and its tributaries. Associated research on other indicators of the "health of the Bay" in general, is vital.

MODELING

While numerous studies have documented the ecological importance of the brachyuran crabs including the blue crab, models addressing the ecological effects on the benthos following large scale changes in abundance of crabs (increase and decrease) are not available. Because they are omnivorous, detritivorous, cannibalistic and scavengers, it

is difficult to place them at one trophic level. Because changes in diet coincide with growth, models should treat the food web as dynamic and flexible in time and space (Laughlin 1982). Models that incorporate predation on bivalve populations, especially spat and juveniles, may provide insights on the potential for reestablishing the oyster and clam populations in Chesapeake Bay.

The presence of anoxic conditions in the Bay during the summer may also be responsible for crab mortality. Nutrient loading from agricultural run-off, sewage and industrial sources has caused an increase in oxygen depletion in the Bay and in its tributaries. Recently this has started earlier in the summer, affected larger volumes of water and been more severe (Cronin, 1987). More study is needed on causes and methods of decreasing anoxia.

MANAGEMENT

Submerged aquatic vegetation (SAV) beds are an important habitat for blue crabs, especially during molting. Restoration programs for SAV and remediation of factors involved in the decline should be continued. The condition of other habitats such as marshes and oyster beds (which often have greater densities of crabs than other bottom areas (Cronin, 1987)), and the availability of prey species (which may affect distribution and local abundance of crabs) must also be considered.

Overfishing of any life stage, molt stage or sex affects the future of the entire stock. Knowledge of the life cycle and associated movements is important in making informed management decisions. It is also necessary for effective coordination in management, legislation and enforcement between Maryland and Virginia. However, if goals and objectives could be agreed upon, the regulations would not have to be uniform.

GENERAL RESEARCH NEEDS

An area that requires further investigation not only in the crustaceans but for all benthic animals is the role of meroplanktonic larvae in water column - benthos ecology. There are several papers that suggest that meroplanktonic larvae of benthic invertebrates may remove considerable carbon from the water column during settlement and metamorphosis (Bhaud 1979; McConaugha 1992). Transfer of carbon from the benthos to the water column may also occur. Oysters may release up to 50% of their biomass as gametes (Newell, pers. comm.). Larvae of demersal fish may also have an important ecological impact on the flux of carbon between the water column and the benthos. Because larvae tend to feed on smaller particles they may have a seasonal effect on carbon flux in the Bay.

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WATERBIRDS

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ABSTRACT

The Chesapeake Bay region is an exceptional habitat for waterbirds. These waterbirds represent primary, secondary, tertiary, and quaternary consumers in the Bay ecosystem. The number and distribution of herbivorous waterfowl decreased at the same time SAV (submerged aquatic vegetation or seagrasses) declined; therefore they should respond to restoration of SAV in the Bay. Monitoring techniques such as aerial photographic censuses of these species in SAV areas could provide meaningful comparative data. Additional surveys of the open water areas of the Bay are necessary to assess the populations and their distribution.

INTRODUCTION

The Chesapeake Bay provides exceptional habitat for a broad variety of waterbirds. During pre-colonial times, waterbirds were attracted to the Bay's abundant plant and animal communities. Numbering many millions of birds and consuming hundreds of tons of aquatic foods, waterbirds were a significant component of energy transfer and nutrient cycling in the Bay. Although their populations have greatly declined, waterbirds continue to be an important component of the Bay's ecosystem.

REPRESENTATIVE SPECIES IN CHESAPEAKE BAY

Counting only those birds directly dependent on the waters, over 47 species of migratory waterbirds make the Chesapeake Bay their home (Table 1). Many other species of migratory birds are dependent on adjacent wetlands and shores.

The greatest number of waterfowl use the Bay during the fall and winter. Canada geese, canvasbacks, mallards, greater and lesser scaup, bufflehead, oldsquaw, surf scoters, goldeneye, and black ducks are the most abundant and important species during winter (December through March).

The Bay is known for its abundant winter waterfowl populations, but less well known for the many thousands of loons, grebes, herons, and gulls that also depend on its rich waters for their winter survival. Ring-billed gulls, herring gulls and red-throated loons are the most abundant. Other species of wintering nongame birds, such as bald eagles, are not as numerous, but the welfare of the several hundred birds which winter on the Bay may be critical to the Atlantic coastal population.

After the wintering populations migrate to northern breeding grounds there are still large populations of waterfowl, thousands of colonial waterbirds, bald eagles and osprey that depend on the rich fishery and secluded nest sites of the Bay region to raise their young.

ECOSYSTEM IMPORTANCE

Information about the structure and temporal dynamics of their food webs is critical for understanding waterbird population dynamics and how they contribute to energy flow in the ecosystem (see Schoenly and Cohen 1991 for review of food web concepts). Waterbirds are important in transfer links and turnover rates of energy and nutrients in the Bay during winter. Most fish and invertebrates inhabiting the bay are preyed on by some birds, but the role of birds in limiting populations, removing less fit individual fish, preying on competitors of commercial fishes, or competing with commercial fisheries is largely unknown.

Detailed studies of food habits have been conducted on only a few species and accurate population figures are difficult to obtain due to the migratory nature of the birds and their varied and widespread distributions. The functional roles of waterbirds are best defined for redheads and canvasbacks in the Bay (Howerter 1990, Rhodes 1989). These species will be used as examples of the interaction between habitat and species abundance. Redheads are dependent on aquatic plant communities that contain or are dominated by widgeon grass *(Ruppia maritima)*, wild celery *(Vallisneria americana)*, sago pondweed *(Potamogeton pectinatus)*, eelgrass

Table 1. Estimated populations of waterbirds in Chesapeake Bay.

Species	Population Estimate	Survey [1]	Season
Common Loon (*Gavia immer*)	4,000	a	winter
Red-throated Loon (*Gavia stellata*)	12,000	a	winter
Red-necked Grebe (*Podiceps grisegena*)	1,000	a	winter
Horned Grebe (*Podiceps auritus*)	2,000	a	winter
Northern Gannet (*Sula bassanus*)	5,000	a	winter
Double-crested Cormorant (*Phalacrocorax auritus*)	13,000	a	winter
Tundra Swan (*Cygnus columbianus*)	30,000	b	winter
Mute Swan (*Cygnus olor*)	2,000	b	winter
Brant (*Branta bernicla*)	5,000	b	winter
Snow Goose (*Chen caerulescens*)	5,000	b	winter
Canada Goose (*Branta canadensis*)	300,000	b	winter
Green-winged Teal (*Anas crecca*)	2,500	b	winter
American Black Duck (*Anas rubripes*)	27,000	b	winter
Mallard (*Anas platyrhynchos*)	60,000	b	winter
Northern Pintail (*Anas acuta*)	2,500	b	winter
Gadwall (*Anas stepera*)	2,000	b	winter
American Wigeon (*Anas americana*)	6,000	c	fall
Wood Duck (*Aix sponsa*)	100,000	c	summer
Canvasback (*Aythya valisineria*)	60,000	b	winter
Redhead (*Aythya americana*)	3,000	a+b	winter
Ring-necked Duck (*Aythya collaris*)	10,000	b	winter
Greater and Lesser Scaup (*Aythya marila & A. affinis*)	80,000	a+b	winter
Common Goldeneye (*Bucephala clangula*)	50,000	a+b	winter
Bufflehead (*Bucephala albeola*)	60,000	a+b	winter
Ruddy Duck (*Oxyura jamaicensis*)	42,000	a+b	winter
Oldsquaw (*Clangula hyemalis*)	100,000	a	winter
Black Scoter (*Melanitta nigra*)	26,000	a	winter
Surf Scoter (*Melanitta perspicillata*)	115,000	a	winter
White-winged Scoter (*Melanitta fusca*)	17,000	a	winter
Common Merganser (*Mergus merganser*)	6,000	a	winter
Red-Breasted Merganser (*Mergus serrator*)	40,000	a	spring
Great Blue Heron (*Ardea herodias*)	17,000	c	summer
Little Blue Heron (*Egretta caerulea*)	300	c	summer
Great Egret (*Casmerodius albus*)	4,000	c	summer
Snowy Egret (*Egretta thula*)	2,000	c	summer
Black-crowned Night Heron (*Nycticorax nycticorax*)	2,500	c	summer
Bald Eagle (*Haliaeetus leucocephalus*)	400	c	summer
Osprey (*Pandion haliaetus*)	4,000	c	summer
Great Black-backed Gull (*Larus marinus*)	6,000	a	winter
Herring Gull (*Larus argentatus*)	75,000	a	winter
Laughing Gull (*Larus atricilla*)	abundant	c	summer
Ring-billed Gull (*Larus delawarensis*)	125,000	a	winter
Bonaparte's Gull (*Larus philadelphia*)	5,000	a	winter
Black-legged Kittiwake (*Rissa tridactyla*)	1,000	a	winter
Common Tern (*Sterna hirundo*)	6,000	c	summer
Least Tern (*Sterna antillarum*)	1,700	c	summer
Royal Tern (*Sterna maxima*)	6,000	c	summer
Black Skimmer (*Rynchops niger*)	1,000	c	summer

1) Sources: a) population estimates from offshore winter surveys; b) midwinter waterfowl survey or fall surveys; c) estimates from state biologists

(Zostera marina) and other less dominant species (e.g. naiads) (Haramis 1991). Currently, canvasbacks are dependent on the Bay's widely distributed Baltic clam community with nutrient and energy flow from the plankton to Baltic clams to canvasbacks. However, Baird and Ulanowicz (1989) estimated that all waterfowl using the Bay consume about 1.5% of benthic prey production. With updated population estimates, we suspect waterfowl consume up to 3.0% of

benthic prey production. The traditional diet of canvasbacks was dominated by SAV (60%), therefore an improvement in the community structure of SAV is expected to produce a change in their diet favoring use of plant foods.

As herbivores, waterfowl such as redheads transfer energy and nutrients from SAV to the Bay water column via urinary and fecal outputs. These outputs become available to macro- and micro-invertebrates in the water column and to the benthos.

Because of their dependence on aquatic plants, redheads, wood ducks, and dabbling ducks can be classified as herbivores, whereas the canvasback, scaup, and other diving ducks can currently be classified as epibenthic predators of clams and other invertebrates (refer to Hall and Raffaelli 1991 for food web concepts). Bald eagles are considered quaternary consumers as they prey heavily on waterfowl during the winter. Most loons, grebes, herons, egrets, cormorants, gulls, terns, and osprey feed primarily on forage fishes ranging from sculpins to menhaden making them primary predators.

Submerged aquatic vegetation was the single most important food resource for dabbling and diving ducks (Anatinae and Athyini). Annual surveys of this resource have been conducted since the early 1970's (Orth and Moore 1988). Changes in SAV in specific areas of the Bay have been reported for more than 40 years (e.g. Bayley *et al.* 1978). Bay-wide monitoring of SAV provides digitized outlines of SAV beds that can be used as references to focus surveys for redhead, wigeon, and canvasback ducks. However, not all SAV beds will attract these species in fall or winter. For example, tubers and winter buds of aquatic plants such as wild celery and widgeon grass are preferred by redheads and canvasbacks, but horned pondweed *(Zannichellia palustris),* redhead grass *(Potamogeton perfoliatus),* and Eurasian watermilfoil are SAV species that are not preferred as food or are not available during winter (Bayley *et al.* 1978, Munro and Perry 1982). During autumn, wigeon often eat SAV less desirable to other ducks, dabbling for plant leaves floating near the water surface. However, because wigeon prefer the fleshy parts of aquatic plants, winter senescence of leaves and stems of some SAV species limits their use by wigeon.

INDICATORS OF THEIR STATUS

Most waterbirds of the Chesapeake Bay are migratory, thus their populations and survival are not solely influenced by the health of the Bay. The populations of waterbirds should be viewed as a suite of species because individual species may be limited by factors outside the Bay region. Only with a thorough knowledge of the birds' food habits, life history, and conditions they encounter in other areas can we understand what fluctuations in waterbird populations mean. Interpretations of population changes must be made at the species-specific level with full knowledge of foraging habits, interspecific competition, and tolerance of human activities.

Nevertheless, abundance and distribution patterns of waterbirds during winter can provide evidence of population status. Counts of birds, such as the Mid-winter Waterfowl Survey and nest counts of colonial waterbirds and raptors, do provide a consistent index. When viewed in relation to counts throughout the Atlantic Flyway we can make judgements as to how the status of the birds in the Bay relates to other areas.

Aerial surveys initiated in 1992 count waterbirds within strip transects while crossing the Bay from shore to shore. These surveys allow us to estimate populations in the offshore waters of the Bay. Populations for many nongame birds, seaducks, and some diving ducks presented in Table 1 were derived from this survey. This survey should be expanded to other seasons before accurate estimates of the ecological role of waterbirds in the Bay can be assessed.

Age and sex ratios of diving ducks at specific wintering areas are influenced by flock size, competition for food resources, weather conditions, and breeding success. For example, during mild winters, more females and young-of-the-year are expected to establish winter residency rather than continue migration to southern winter areas. Also, if food resources are abundant and competition among individuals is less, more females and young should be observed in winter flocks. Thus, monitoring age and sex ratios is an important component of the status of a species.

CHOICES OF INDICATOR SPECIES

Monitoring populations in the Chesapeake Bay should be based on the food web concept, whereby waterfowl should be selected as indicators of the foods they eat. Several aspects of the food web must be considered when selecting a species as an indicator of a focus resource such as SAV, mollusks, or other foods: (1) the number of trophic links between the indicator and the focus species, (2) the number of predators (both monitored and not monitored species) using the focus species, and (3) sensitivity of the indicator species to reflect changes in the focus food species. Monitoring criteria must be carefully selected to match the foraging ecology of each species (Hall and Raffaelli 1991); for example, redheads are herbivores, while canvasbacks and black ducks are omnivores. Submerged aquatic vegetation responds to improved water quality and redheads should respond to increased SAV; therefore, annual surveys of

redheads for distribution and population numbers, combined with the more intensive waterfowl surveys done at national wildlife refuges should provide good indicators of progress toward restoration of SAV.

Redheads are potentially the best waterfowl indicator species of SAV abundance and distribution in the Bay. We predict that redheads will return to the Bay in numbers proportional to restoration of submerged aquatic plant resources. Canvasbacks might be a good secondary or alternative indicator species because (1) they often use the same SAV habitats as redheads, (2) their diet should regain a dominance of plant foods throughout early and mid-winter as SAV recovers in the Bay, and (3) they can be censused at the same time of year as redheads by using aerial census (e.g. winter inventory) or photographic techniques (e.g. Ferguson *et al.* 1981, Haramis *et al.* 1985).

Although redheads and canvasbacks do not breed in the Chesapeake Bay region (Geis 1974), they are noted for their traditional use of SAV in the Bay during fall migration and winter (Stewart 1962). Populations of both species decreased at the same time that SAV declined throughout the Bay (Munro and Perry 1982). Canvasbacks have been able to shift their diet from SAV to Baltic clams (Stewart 1962, Perry and Uhler 1988). In contrast, redheads are one of the most vegetarian of waterfowl species using the Bay, and did not shift to alternative foods following the decline of SAV (Haramis 1991). Due to poor breeding conditions in the prairie regions, poaching, and their inflexible food preference, winter populations of redheads almost disappeared with the decrease of submerged aquatic vegetation. Where once the Bay population of redheads numbered in the tens of thousands, now fewer than several thousand are counted in annual winter surveys (Haramis 1991).

Black ducks use the Chesapeake Bay during all seasons of the year, and prefer shallow salt marshes and brackish water areas for foraging and nesting (Krementz 1991). Although this species is omnivorous, it readily forages in beds of SAV when available (Munro and Perry 1982). Several characteristics limit their value as an indicator species: (1) winter diets consist mostly of animal foods obtained from coastal wetlands, (2) they are difficult to census in marsh habitats, and (3) they are widely distributed in small groups or pairs. However, if an indicator species of breeding waterfowl is desired to monitor Bay restoration, then the black duck might be the best choice.

American wigeon and gadwall are important herbivores during fall migration. American wigeon were once noted for their use of SAV in the Bay during fall migration (Stewart 1962). Some of these birds remain in the Bay as winter residents (Bellrose 1980), however, use of the Bay by wigeon declined at the same time as SAV. Because wigeon are primarily herbivores, their numbers and distribution should change in response to restoration of SAV which grows during winter. Therefore, wigeon might be an excellent choice as an indicator species of SAV restoration during the fall migration, and possibly as a good alternative indicator species during winter.

The two species of birds with the largest relative increase in populations are the mute swan and the mallard. These species are more of a sign of degradation of the Bay rather than recovery because they readily adapt to man and highly altered environments and reduce diversity by displacing other species. Swans are an exotic species which are territorial and consume SAV, thus they compete with native birds. Mallards are abundant and breed in Bay habitats, but should not be used as an indicator species because (1) breeding mallards were likely developed from game farm stock; pure prairie mallards only winter in the Bay, (2) habitat use by mallards raised in captivity most likely is not representative of habitat use by wild birds, (3) captive-reared and wild mallards extensively use marinas and other highly altered habitats that would not be good habitat for other birds.

Surf scoters, bufflehead, common goldeneye, and scaup occur in scattered flocks throughout the Bay during winter. They are omnivorous, favoring animal foods. Because little information is available concerning their present-day foraging ecology, the value of these diving ducks as indicator species is questionable despite relatively large populations.

QUANTITATIVE AND QUALITATIVE GOALS

For most waterfowl, ideal population goals would be represented by the population indexes obtained in the 1950's. Unfortunately the populations of many waterbirds and some sea ducks are still unknown or poorly understood and often completely lacking from the 1950's indexes. In addition, population goals based on 1950's levels may be unrealistic for some species such as redheads. Currently, annual winter counts of redheads range from 600 to 3000 birds for the entire Chesapeake Bay (Haramis 1991) and the 1950's number would be 115,000 birds. The Chesapeake Bay Waterfowl Policy and Management Plan (CEC 1990) established a goal for the year 2000 of the mean 1973-78 level or 8,200 redheads.

Qualitative goals for SAV dependent waterbirds such as redheads and wigeon should be based on the geographic distribution of recovering SAV beds (Haramis 1991; map 38). Areas used by redheads throughout the Bay in past years might provide the best locations to initially focus SAV

restoration. Annual aerial and photographic censuses for redheads at these focal sites would provide the best opportunity to detect changes in SAV communities and redhead populations.

For canvasbacks, the 1950's goal would be 220,000 birds, but a more realistic interim goal should be 63,000 birds by the year 2000 (CEC 1990). Initially, restoration of SAV in the Bay might only redistribute the current Atlantic Flyway population. We expect canvasbacks to compete with redheads for SAV resources, therefore mixed flocks are likely to be observed during aerial and photographic censuses. The historic geographic distribution of canvasbacks is similar to redheads, and should coincide with focal points of SAV restoration based on traditional redhead distributions in the Bay. Wigeon are expected to compete for some of the same SAV resources used by redheads, canvasbacks, and other waterfowl, but their ability to eat plants less desirable to other waterfowl should reduce competition and also influence their distribution throughout the Bay.

RECOMMENDATIONS

Monitoring

Information gained from monitoring migratory waterbirds may provide ambiguous indications of Chesapeake Bay habitat quality. Population levels are determined in part by factors influencing recruitment and survival on breeding and migration areas beyond the Chesapeake Bay region (Haramis 1991). For example, in a particular year, populations of canvasbacks may be limited by drought or wetlands loss on prairie breeding grounds, while arctic breeding species such as oldsquaw may have good reproduction and large populations. Osprey abundance could be limited by lack of fish or heavy pesticide loads accumulated while on their wintering grounds in South America. Changes in bird populations usually lag behind changes in habitat quality. Waterbirds generally can adjust to changing habitat conditions, but they may remain in traditional areas following habitat degradation and decline of food resources. However, waterbirds are also highly mobile and able to quickly exploit new food resources in previously unused or newly created habitats. For example, when Eurasian watermilfoil *(Myriophyllum spicatum)* replaced native SAV species on the Susquehanna Flats during the early 1960's, waterfowl use declined until native species returned (Bayley *et al.* 1978).

The drastic decline in SAV food resources produced a decline in redheads after a relatively short lag-time, but the response time was much longer for canvasbacks, which changed their primary diets from SAV to animal foods. The time for redheads to positively respond to restoration of SAV in the Bay should be short, perhaps one to three years for each restored site, assuming that the response involves changes in distribution rather than recruitment of redheads into the population.

The Mid-winter Waterfowl Survey conducted each January along all shorelines of the Bay should be continued as it provides a consistent count of waterfowl species which inhabit nearshore areas of the Bay (see Stewart 1962 and Nichols 1991 for review). Although accuracy of this survey may suffer because of the responses of waterfowl to weather, disturbance, or other proximate factors, it has been conducted consistently in the watershed from 1957 and provides our only link for comparison to the past. This survey is also conducted throughout the nation providing a measure of the proportion of waterfowl that use the Bay in comparison to other major wintering habitats.

Aerial surveys initiated in 1992 which count waterbirds in offshore waters of the Bay within strip transects provide population estimates of waterbirds. These areas and many of the species have been uncensused in the past. This survey should be continued for a couple of years to determine variability of the densities, and some form of this survey should be conducted in other seasons.

We recommend a coordinated SAV/waterfowl monitoring program to monitor waterfowl population changes and use of SAV beds. This monitoring approach involves conducting additional waterfowl surveys in areas where SAV beds existed during the annual SAV survey. The SAV/waterfowl survey should be conducted at least twice annually: in late October to determine fall waterfowl use of SAV beds, and in mid-December to determine winter waterfowl use. Because waterfowl can deplete accessible resources in SAV beds during the earliest stages of winter, the second SAV bed/ waterfowl survey should not be conducted after January 15th.

Variability of waterfowl food resources are important monitoring data. Estimates of long-term food abundance, baselines, and estimates of short-term variations are important factors to understand waterfowl abundances. This information can be used as inputs for various ecosystem models of the Bay.

Another potentially important consideration is the effect of toxic substances. Contaminants accumulated in food resources might be harmful to ducks and make it hard to determine how they respond to SAV restoration. Environmental contaminants could bias interpretation of monitoring data.

Modeling

Ecosystem models should be developed and evaluated based on tests of hypotheses and predictions (Wetzel and

Hopkinson 1990). Generally, sufficient information to develop even simple food-web models related to waterbird use (foraging ecology and food bases) is available only for redheads, canvasbacks, and black ducks. Currently, conceptual models of the Bay ecosystem include waterfowl as components of SAV and benthos subsystem models (Wetzel and Hopkinson 1990). Perhaps a more direct and useful approach might be based on energetics or carbon transfer (Baird and Ulanowicz 1989).

Management

The focus of management goals and field monitoring efforts should be to provide the required food resources needed to maintain desired populations. The availability of food resources must be monitored annually and compared with desired food abundances. Habitat restoration and management efforts should continue until average long-term stability of food resources and waterfowl populations is reached and maintained.

Waterbird abundance can be related to current and potential Bay management strategies. One approach is to estimate what historical food resources and corresponding waterfowl populations were supported by the Chesapeake Bay (e.g. Bayley *et al.* 1978), then decide what waterfowl species and how many individuals of each species (population size) the Chesapeake Bay can consistently support for a given period of time.

Restoration of Bay water quality should restore preferred waterbird foods and increase use by wintering birds. The nutritional quality of foods is also an important factor, especially when present foods are neither the preferred nor the historical diet of many species. Management programs to restore specific species of SAV need to consider information about physiological and ecological requirements of birds (e.g. Korschgen and Green 1988, Kahl 1991).

Disturbance of both wintering and nesting birds is an important factor in their ecology. Disturbance of wintering birds can reduce their fitness by causing them to fly and expend energy needed for survival or migration. Disturbance of nesting birds may cause adults to abandon nests or young and eggs to fall from nests or be lost to predators.

Disturbance should be limited when possible. A few possibilities are: limiting access to islands during critical periods, establishing buffers around sensitive nesting areas, instituting open water sanctuary areas with restricted hunting, and limiting boating speeds for areas with exceptionally large concentrations of diving ducks.

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SUBMERSED AQUATIC VEGETATION

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INTRODUCTION

One of the major factors contributing to the high productivity of Chesapeake Bay has been the historical abundance of submersed aquatic vegetation (SAV). Submersed aquatic vegetation are rooted flowering plants that have colonized soft sediment habitats in coastal and estuarine areas throughout the world. In Chesapeake Bay, seagrasses in saline regions and freshwater angiosperms that have colonized lower salinity portions of the estuary constitute a diverse community (Stevenson and Confer 1978, Orth and Moore 1984).

A baywide decline of all SAV species in Chesapeake Bay began in the late 1960's and early 1970's (Orth and Moore 1983). This SAV decline was related to increasing amounts of nutrients and sediments in the Bay resulting from development of the Bay's shoreline and watershed (Kemp *et al.* 1983).

SPECIES

There are approximately 24 species of SAV reported in Chesapeake Bay with twelve commonly reported (Table 1) (Orth *et al.* 1989, 1991; Orth and Nowak 1990). The presence of a species in a particular salinity regime is dependent on its salinity tolerance (Table 1). *Zostera marina* is the only true seagrass, whereas two species in the tidal freshwater and oligohaline areas, *Hydrilla verticillata* and *Myriophyllum spicatum*, are exotics. *Hydrilla* has rapidly spread in the Potomac River since it was first reported in 1983, and is abundant principally in the tidal freshwater and oligohaline areas of this river. *Hydrilla* has also been found less abundantly on the Susquehanna Flats. *Ruppia maritima*, a species with the widest salinity range, has shown a significant resurgence in the mid-1980's in many sections of the middle bay, and in the Rappahannock River.

ECOSYSTEM IMPORTANCE

Submersed aquatic vegetation provide food for waterfowl and are critical habitat for shellfish and finfish. It supports some of the densest and most diverse benthic faunal communities in the bay. Submersed aquatic vegetation also affect nutrient cycling, sediment stability and water turbidity (Kemp *et al.* 1984, Thayer *et al.* 1984; also reviewed in McRoy and Helfferich 1977, Phillips and McRoy 1980, and Larkum *et al.* 1990).

Table 1. Species of SAV found in the different salinity regimes of the Chesapeake Bay and tributaries (from Orth et al. 1991). Species which are abundant in more than one salinity regime are listed appropriately.

Salinity Regime/Species	Common Name
Polyhaline	
Zostera marina	eelgrass
Ruppia maritima	widgeongrass
Zannichelia palustris	horned pondweed
Mesohaline	
Zostera marina	eelgrass
Ruppia maritima	widgeongrass
Zannichelia palustris	horned pondweed
Potamogeton pectinatus	sago pondweed
Potamogeton perfoliatus	redhead grass
Myriophyllum spicatum	water milfoil
Vallisneria americana	wild celery
Oligohaline/Freshwater	
Ruppia maritima	widgeongrass
Potamogeton pectinatus	sago pondweed
Potamogeton perfoliatus	redhead grass
Myriophyllum spicatum	water milfoil
Vallisneria americana	wild celery
Heteranthera dubia	water stargrass
Hydrilla verticillata	hydrilla
Elodea canadensis	common elodea
Ceratophyllum demersum	coontail
Najas guadilupensis	southern naiad
Zannichelia palustris	horned pondweed

INDICATORS OF STRESS

A conceptual model of the interactions and interdependence of the SAV habitat requirements (Fig. 1) illustrates the water quality parameters that influence SAV distribution and abundance. A wealth of scientific studies from around the

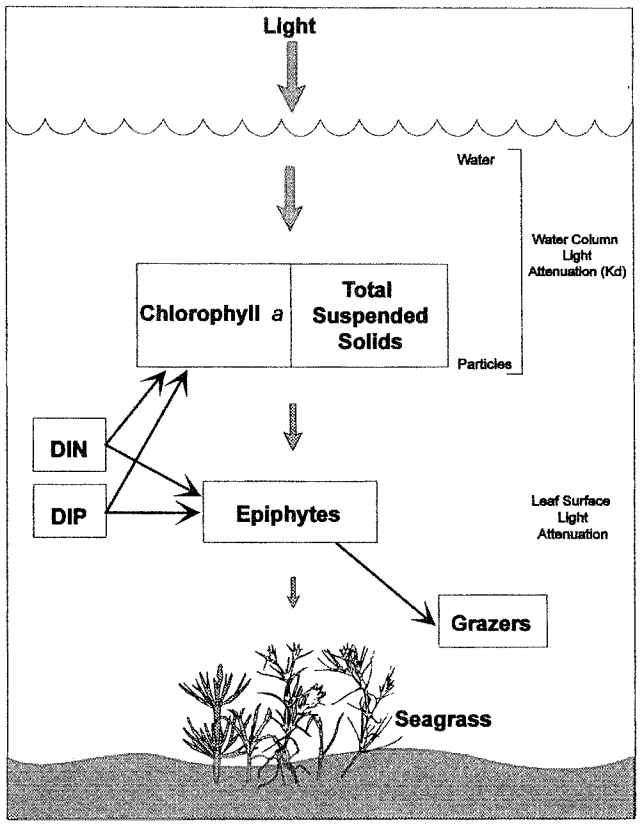

Figure 1. Availability of light for SAV is determined by light attenuation processes. Water column attenuation, measured as light attenuation coefficient (K_d), results from absorption and scatter of light by particles in the water (phytoplankton, measured as chlorophyll *a*; total organic and inorganic particles, measured as total suspended solids) and by absorption of light by water itself. Leaf surface attenuation, largely due to algal epiphytes growing on SAV leaf surfaces, also contributes to light attenuation. Dissolved inorganic nutrients (DIN = dissolved inorganic nitrogen, DIP = dissolved inorganic phosphorus) contribute to phytoplankton and epiphyte components of overall light attenuation, and epiphyte grazers control accumulation of epiphytes.

world have established the importance of light availability as the major environmental factor controlling SAV distribution, growth and survival (Dennison 1987, Kenworthy and Haunert 1991). The primary environmental factors contributing to light attenuation are used to formulate SAV habitat requirements: light attenuation coefficient (K_d), chlorophyll *a*, total suspended solids, dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP).

The minimum light requirement of a particular SAV species determines the maximum water depth for survival. This can be depicted graphically as the intersection of the light intensity vs. depth curve with the minimum light requirement value (Fig.2) Light is attenuated exponentially with water depth (Fig. 2 right side). The minimum light requirement of a particular SAV species, as a percent of

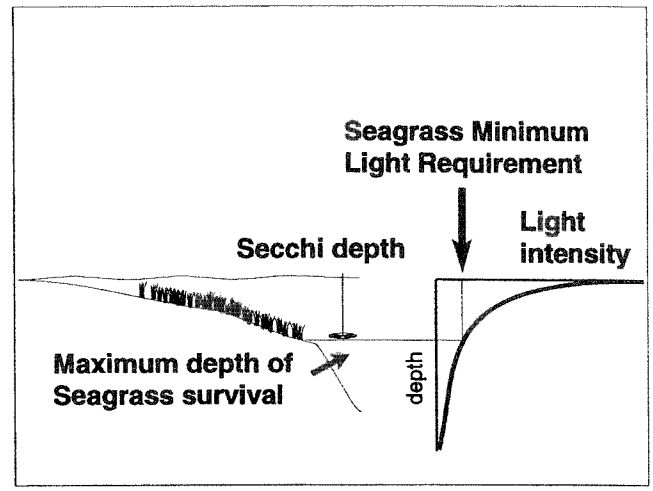

Figure 2. The interrelationships between light attenuation, SAV minimum light requirement, Secchi depth and the maximum depth of SAV survival depicted schematically. The intersection of the minimum light requirement and light attenuation curve determines the maximum depth of SAV survival.

incident light, intersects the light curve to give a predicted maximum depth of SAV survival for that species (Fig. 2, left side). Knowledge of any 2 of the 3 unknowns (average light attenuation coefficient (K_d), minimum light requirement, and maximum depth of seagrass survival) allows determination of the remaining unknown. In this manner, SAV depth penetration is used as an integrating "light meter" to assess light regimes on appropriate temporal and spatial scales without intensive sampling programs (Kautsky *et al.* 1986). Secchi depth, a long standing field measurement of light attenuation, can be used to determine the light attenuation coefficient (K_d) by a conversion factor established for Chesapeake Bay (Batiuk *et al.* 1992). Hence, Secchi depth measurements, along with SAV minimum light requirements, can be used to determine the maximum depth of SAV survival.

Empirical relationships between water quality characteristics and SAV distributions provided the means of defining requirements for seagrass survival. Submersed aquatic vegetation habitat requirements were formulated by a) determining SAV distributions by transplant survival and bay-wide distributional surveys, b) measuring water quality characteristics along large scale transects that spanned vegetated and non-vegetated regions, c) combining distributional data and water quality levels (as in Fig. 3) to establish minimum water quality that supports SAV survival. This type of analysis (referred to as correspondence analysis) was strengthened by factors common to each of the case studies. Field data was collected over several years (almost a

Table 2. Chesapeake Bay seagrass habitat requirements. For each parameter, the maximum growing season median value that correlated with seagrass survival is given for each salinity regime. Growing season defined as April--October, except for polyhaline (March--November). Salinity regimes are defined as tidal fresh = 0 - 0.5%, oligohaline = 0.5 - 5%, mesohaline = 5 - 18%, polyhaline = 18+%.

Salinity Regime	Light Attenuation Coefficient (Kd; m^{-1})	Total Suspended Solids (mg/l)	Chlorophyll a (µg/l)	Dissolved Inorganic Nitrogen (mg/l)	Dissolved Inorganic Phosphorus (mg/l)
Tidal Freshwater	2.0	15	15	-	<0.02
Oligohaline	2.0	15	15	-	<0.02
Mesohaline	1.5	15	15	<0.15	<0.01
Polyhaline	1.5	15	15	<0.15	<0.02

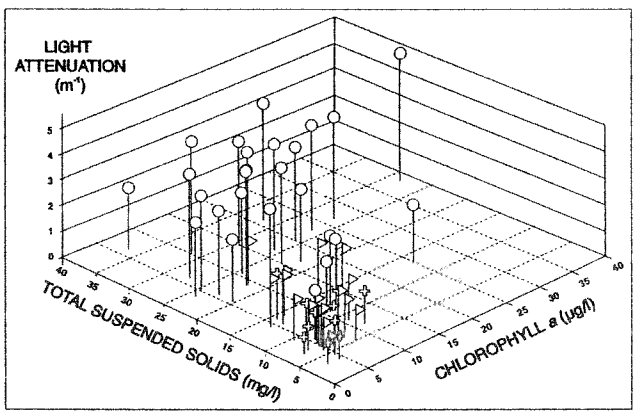

Figure 3. Three dimensional comparisons of May-October median light attenuation coefficient, total suspended solids and chlorophyll *a* concentrations at the Choptank River stations for 1986-1989. Plus = persistent SAV; flag = fluctuating SAV; circle = no SAV.

decade in the Potomac River) in varying meteorologic and hydrologic conditions by different investigators. Distributions of SAV in four case studies (Susquehanna Flats, upper Potomac River, Choptank River, and York River) across all salinity regimes were responsive to the five water quality parameters used to develop habitat requirements. In addition, inter-annual changes in water quality led to changes in seagrass distribution and abundance in each region that were consistent with habitat requirements.

The diversity of SAV communities throughout Chesapeake Bay, with its wide salinity range, has led to the establishment of separate habitat requirements, based on salinity regime. Water quality conditions sufficient to support survival, growth, and reproduction of SAV to water depths of one meter are used as SAV habitat requirements (Table 2). For SAV to survive to one meter, light attenuation coefficients <2 m^{-1} for tidal fresh and oligohaline regions and <1.5 m^{-1} for mesohaline and polyhaline regions were needed. Total suspended solids (< 15 mg/l) and chlorophyll *a* (< 15 µg/l) values were consistent for all regions.

However, habitat requirements for dissolved inorganic nitrogen (DIN) and phosphorus (DIP) varied substantially between salinity regimes. In tidal freshwater and oligohaline regions, SAV survive episodic and chronic high DIN, consequently habitat requirements for DIN were not determined for these regions. In contrast, maximum DIN concentrations of 0.15 mg/l were established for mesohaline and polyhaline regions.

The SAV habitat requirement for DIP was <0.02 mg/l for all regions except mesohaline regions (<0.01 mg/l). Differences in nutrient habitat requirements in different regions of Chesapeake Bay are consistent with observations from a variety of estuaries that shifts in the relative importance of phosphorus vs. nitrogen as limiting factors occur (Valiela 1984).

Habitat requirements for SAV represent the absolute minimum water quality characteristics necessary to sustain plants in shallow water. As such, exceeding any of the five water quality characteristics will seriously compromise the chances of SAV survival. Improvements in water clarity to achieve greater depth penetration of SAV would not only increase depth penetration, but also increase seagrass density and biomass. In addition, improvements of water quality beyond the habitat requirements could lead to the

maintenance or reestablishment of a diverse population of native SAV species. Habitat requirements for SAV provide a guideline for mitigation efforts involving transplants. If SAV habitat requirements are not present, reestablishment of SAV communities via transplant efforts would be futile.

The empirical approach used here allows for predictive capacity without detailed knowledge of the precise nature of SAV/water quality interactions. Since SAV are disappearing rapidly on a global scale, there is a need to provide guidelines on water quality before a more complete understanding of the complex ecological interactions is reached. The application of a habitat requirements approach to other ecosystems should be explored. Submersed aquatic vegetation beds are convenient "light meters," integrating water clarity of coastal waters over appropriate time scales. Other organisms also possess critical thresholds for a variety of environmental factors that can be used to establish habitat requirements. This approach has the important advantage of low technology, high information yield that can be employed in a variety of settings.

RECOMMENDATIONS

Monitoring

Monitoring of SAV distribution and abundance is critical in order to assess the success of nutrient reduction strategies currently in place, or proposed for implementation, in Chesapeake Bay. This monitoring program should consist of several elements:

1. An annual survey of SAV distribution and abundance using current aerial photographic techniques;

2. Groundtruth surveys of citizens and scientists conducted concurrently with the aerial survey to provide confirming documentation on the presence of SAV and species found;

3. Monitoring of water quality at selected stations in the shallows where SAV grows to complement the mid-channel monitoring stations; and,

4. Regular evaluation of the trends in SAV abundance and water quality and, in particular, assessment of current status in relation to restoration targets established in the SAV Technical Synthesis.

Research

The following areas should be considered for future research with SAV:

1. Research into transplanting SAV to (a) refine specific habitat requirements of individual species of SAV both for long term persistence and/or recolonization and restoration of SAV populations, and (b) quantify rates of revegetation into unvegetated areas.

2. Research to improve our understanding of the relationships between SAV and other important Chesapeake Bay species, in particular waterfowl, fish, and shellfish. In addition, research needs to address the interactions and interrelationships between SAV and other habitats, such as oyster reefs and unvegetated sand flats.

3. Research on the effects of eutrophication, sediment loading, toxics, and natural purturbations on growth and survival of SAV, in particular the lag time, or delay in SAV response, to changes in ambient light regimes. In addition, duration and timing of purturbations needs to be incorporated into these strategies.

4. Research to develop a more complete knowledge of the sources and causes of the various light attenuation components.

5. Research on the epiphyte component of light attenuation, particularly with regard to nutrient enrichments.

6. Research on how loading rates affect the habitat requirements developed in the Technical Synthesis (Batuik *et al.* 1992).

Management

Because SAV are most affected by water quality, management efforts must be directed towards attaining water quality values within their habitat requirements. Point sources of nutrient inputs are the easiest to control but it is critical to understand how loading rates are translated to actual concentrations observed in the field. More difficult is the control of non-point sources, both as direct runoff, but also as atmospheric deposition and groundwater infiltration.

Existing SAV beds should receive the highest protection by all governmental agencies as these represent areas that could serve as sources of propagules for natural and artificial restoration. In addition, potential habitat (habitat that has either historically supported SAV or habitat defined within the 2 meter contour of the bay) should receive protection.

Modeling

Current seagrass models and efforts to use models as a research tool are far from complete relative to understanding the current or historic distribution and abundance of seagrasses. Models that focus on seagrasses (or more generally submersed aquatic vegetation) have not yet been developed and implemented for the explicit purpose of predicting plant response to environmental variables. The

environmental controls of seagrass growth and/or survival at the community level of ecological organization remain for all practical purposes a planning tool for basic research (Kemp *et al.* 1983, Wetzel and Neckles 1986). Other models have been developed that address seagrasses but they have employed conceptual and/or mathematical structures, neither appropriate for nor designed for predicting the environmental effects (e.g. light attenuation, nutrients, and grazing impacts) on the larger issues of community survival and longevity (Short 1980). Other models are published that address community productivity, plant growth, and nutrient interactions, and, in a general sense, the relationships between certain environmental variables, and plant growth and depth distribution (Verhagen and Nienhuis 1983, Zimmerman *et al.* 1987).

Objectives

1. TO EFFECTIVELY PREDICT SAV RESPONSE TO ENVIRONMENTAL PARAMETERS, PARTICULARLY THE WATER QUALITY PARAMETERS USED AS THE SAV INDICATORS OF STRESS.

2. TO DEVELOP COMMUNITY AND ECOSYSTEM LEVEL MODELS TO PREDICT ENVIRONMENTAL EFFECTS ON COMMUNITY SURVIVAL AND LONGEVITY.

3. TO INTEGRATE COMPONENTS OF LIGHT ATTENUATION, EPIPHYTE LIGHT ATTENUATION, AND PLANT/SEDIMENT INTERACTIONS INTO MODELS OF SAV.

Habitat

Because of the ecosystem importance of SAV and their sensitivity to water quality, existing SAV habitat must be protected, as well as restored in those areas that are currently devoid of any SAV. Areas with marginal growth should be enhanced. Restoration targets for species diversity and abundance can be used as a goal to assess the success or failure of efforts to clean up the Chesapeake Bay. A tiered set of SAV distribution restoration targets established in the SAV Technical Synthesis (Batiuk *et al.* in press) gives management agencies a quantitative measure of change in SAV distribution at different levels in response to the implementation of Chesapeake Bay restoration strategies (e.g. reducing nutrients by 40%).

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WETLANDS

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INTRODUCTION

Sandwiched between the low tide line of Chesapeake Bay and the uplands, lies a spectrum of wetland communities which mediate exchanges from one system to the other. These wetland communities can be defined technically in terms of hydrology, soil type and plant species but are generally systems in which the substrate is saturated for a portion of time which creates periodic anaerobic conditions in the root zone. Since comparatively few plants are adapted to low or no oxygen in the root zone, distinctive communities develop depending on the degree and periodicity of soil saturation. Because wetland plants have varying tolerances to anaerobic conditions (and salinity), a range of species can dominate, depending on the micro-climate, but as a whole they harbor a rich diversity of consumer species which are an essential ingredient in the image of a healthy Chesapeake ecosystem.

These animals include an array of migrants from warblers to waterfowl as well as many species of fish (eels, killifish, mummichogs, pipefish, etc.). In addition, there are both conspicuous invertebrates (blue crabs) and inconspicuous ones (amphipods and copepods) which have direct connections with harvestable resources in the open bay. Moreover, a few marsh mammals (muskrat, otter, and deer) have long been important for both commercial hunting and sportsmen. Wetlands are also enjoyed by local residents who go in for "frogging" and/or "turkelling" (hunting turtles–snappers mostly, but terrapins can often be found in large quantities in marsh embayments as well).

In addition to their functions as regards habitat (not to mention water quality, and landscape hydrology discussed later), the wetlands contribute variety and interest as well as an aesthetic character to the rim of the Bay. If for nothing else, these systems need to be protected as essential habitat for the variety of species which use them. Indeed, since they are often the last resort of many species whose habitat was destroyed with the encroachment of development, wetlands were among the first components of the Chesapeake System to receive regulatory protection. Public support for these resources is attested to by legislation afforded them. In Maryland, laws were passed in the early 1970's for protection of tidal marshes and in the late 1980's the non-tidal wetland systems were also included.

REPRESENTATIVE SPECIES

Wetlands can be classified in several ways depending on the issues of concern - floristics, geomorphology, etc. (Stevenson *et al.* 1986). A general scheme which has been used in mapping in the Chesapeake region (and elsewhere) by the U.S. Fish and Wildlife Service to identify long term trends (Tiner 1987) is as follows:

Wetland Type	Representative Plant Species	Current Acreage	% Change
Tidal Flats and Beaches	Occasional *Ulva* & *Zannichellia palustris*	84,500	
Coastal Marshes	High Salinity: *Spartina alterniflora* *Spartina patens* Low Salinity: *Scirpus olneyii* *Spartina cynosuroides* Tidal Fresh: *Pontederia cordata* *Zizania aquatica*	*134,500*	*-8.5*
Freshwater *Emergent Wetlands*	*Scirpus validus* *Bidens cernua* Chelone glabra Cicuta maculata Hypericum virgicum Justicia americana Lycopus virginicus Mimulus ringens Typha latifolia	103,500	
Shrub Wetlands	*Alnus serrulata* *Asimina triloba* *Cephalanthus occidentalis* *Rhododendron viscosum* *Myrica cerifera*	*152,000*	*-6.0*
Forested *Wetlands*	*Acer rubrum* *Chamaecyparis thyoides* *Betula nigra* *Fraxinus pensylvanica* *Larix larcina* *Nyssa sylvatica* *Taxodium distichum*	657,700	
Freshwater Ponds	*Nuphar luteum* *Myriophyllum spicatum* *Lemna minor*	90,700	+170

The cumulative acreage of these systems in the Chesapeake drainage basin (Total= 41 million acres), is estimated at just

less than one and a quarter million acres by the U.S. Fish and Wildlife Service (Tiner 1987), or 3% of the total watershed. However, in all likelihood, due both to underestimation of forested wetlands detectable in the aerial photographs and the expanded definition of non-tidal wetlands (now being debated), a larger percentage (more in the range of 5%) of the watershed is undoubtedly wetlands. The percentage change in the table above is over a thirty year period from the 1950's to the 1980's and reflects considerable loss of wetlands both to apparent sea-level rise and development. The highest amount of loss (8.5%) is in tidal coastal wetlands, but for the same reasons cited above for non-tidal wetlands the percentage loss may be less than 6% cited above.

IMPORTANCE TO THE CHESAPEAKE ECOSYSTEM

There is considerable evidence (Mitsch and Gosselink 1986, LeBaugh 1986, Gehrels and Mulamouttil 1989, Athanas and Stevenson 1991) that a variety of wetland systems can act as significant sinks in the landscape; particularly in regard to nutrients (Boyd 1969) but also in terms of metals which are attached to sediments (Simpson *et al.* 1983). As Gosselink *et al.* (1974) suggest, "detailed analysis of waste assimilation shows that...marshes have a tremendous capacity for tertiary treatment of nutrients, especially phosphorus." In addition, because of the alternating redox conditions in wetland soils, denitrification can cause a release of nitrogen (N) into the atmosphere. When the reduction of nitrate is complete, and mostly N_2 is released, no environmental damage occurs, which greatly enhances their value. However not all of this is positive. If denitrification is incomplete, N_2O emissions can result (Seitzinger 1988) which contributes to the greenhouse effect. This negative contribution might be even more problematic in view of the fact that several wetlands in the Chesapeake region have significant methane production (Harriss *et al.* 1985, Bartlett *et al.* 1987) –another potent greenhouse gas.

On the other hand, coastal marshes, have also been considered as sources of nutrients and energy subsidies for shallower coastal waters (Odum 1961), "outwelling" large quantities of detrital materials. Nutrient exchanges studies in the Chesapeake (e.g. Heinle and Flemer 1976, Stevenson *et al.* 1977, Jordan *et al.* 1983, Wolaver *et al.* 1983) have indicated varying degrees of nutrient transformation, retention and loss in a variety of wetland systems. Jordan *et al.* (1983) have emphasized the primary role of tidal marshes at Rhode River (on the western shore of Chesapeake Bay) was in their ability to transform particulate to dissolved nutrients–rather than nutrient retention and release. Jordan and Correll (1985) have concluded that a little less than half of the nutrient export they observe at Rhode River is due to tidal pumping– seepage of interstitial water out of the sediments at low tide.

In non-tidal wetlands, orthophosphorus (bioavailable phosphorus) has also been shown to be exported during fall; especially in systems which have reached equilibrium (Richardson 1985). Although perhaps not as significant as burial or atmospheric losses; the time delay, which these wetlands offer, still benefits the Bay in that the release of P does not occur in spring and summer to directly fuel algal blooms when temperatures are high.

INDICATORS OF STATUS AND FUNCTION

Physical losses of wetlands remain the largest problem in maintaining the overall buffering capacity of these systems and providing habitat for consumers. Unfortunately, there has been only one comprehensive effort in the Chesapeake watershed thus far to evaluate the changes in the entire system (Tiner 1985). [This was done via aerial photography with minimal sporadic field checking, so that the non-tidal wetlands, especially at the upland edges, were significantly underestimated.] More accurate mapping needs to be carried out for regulatory and planning purposes in the future. There has been more intense scrutiny of tidal marshes where the percentage loss has been greatest. These surveys indicate large changes in acreage due to apparent sea-level rise in the mid-Bay region where marshes are concentrated. However, more regional approaches are needed which should be coupled to emerging geographical information systems (GIS) to monitor change.

Unfortunately, investigations of marsh function in the Chesapeake have been limited to comparatively few sites, and although sediment and nutrient trapping functions have been evaluated, results have been somewhat contradictory. It is now recognized that many of these areas were differentially affected by apparent sea-level rise because of differences in subsidence and external sediment supplies. Some of them are largely erosional (Stevenson *et al.* 1985), while others are depositional (Jordan *et al.* 1983). Modern automated microprocessor-controlled sampling now makes integrated sampling more efficient and additional site analysis possible. Simultaneously, measurements using dating techniques (pollen, diatoms, and radionucleides) at these sites to determine sediment accretion are necessary to assess how well these systems are functioning over longer time periods (decades to centuries) in regard to sea-level and subsidence.

We know less about the functions of non-tidal wetlands which makes it especially perplexing to evaluate various mitigation schemes for alterations and marsh creation (Kusler and Kentula 1991). The role of non-tidal wetlands

in attenuating groundwater inputs is little understood and this function could be important to consider in mitigation strategies.

QUANTITATIVE AND QUALITATIVE TARGETS

Essentially, the quantitative targets for the Chesapeake region are the same as for the nation - "NO NET LOSS." Although this may be potentially achievable for non-tidal wetlands, it remains to be seen how well this goal might be translated into the coastal marshes which are undergoing varying degrees of apparent sea-level rise. In qualitative terms we also need to maintain balanced healthy systems with a diversity of species. Therefore, we need to establish targeted responses to biological problems such as the invasions of *Phragmites*, which can lower diversity, and nutria, which can cause severe eat-outs and subsequent ponding of marshes. Although not severe at present, excessive beaver activity in the non-tidal wetlands can act to reduce tree diversity by causing excessive flooding of diverse forested areas.

RECOMMENDATIONS

Monitoring

Although there are up-to-date manuals for coastal marshes (Silberhorn 1982) and non-tidal wetland plants (Tiner 1988), and detailed mapping of the tidal marshes (McCormick and Somes 1982), wetlands have not had the same attention as other resources in terms of periodic "stock assessment." Although not as difficult a task as estimating finfish or SAV stocks, comparatively little effort has been put into a trend analysis of specific wetlands, with the possible exception of local studies such as Blackwater Marsh (Stevenson *et al.* 1985) and the Lower Nanticoke (Kearney *et al.* 1988) and Chesapeake Bay marsh islands (Kearney and Stevenson 1991). More effort should be made to accurately map non-tidal wetlands and to evaluate changes in coastal wetlands due to sea-level rise and other factors (Kearney and Stevenson in press). Emerging technologies of remote sensing and GIS may be helpful in assessing acreage in the future; but species composition changes need to be monitored in regard to exotics (*Phragmites* and nutria), subsidence, management (e.g. marsh burning and timbering), and hydrologic changes, and in this respect ground truthing can not be ignored.

Research

Despite our general understanding of coastal marsh sediments in relation to carbon content and bulk density (Gosslink *et al.* 1984), we know surprisingly little about processes such as peat deposition and preservation in various marsh systems. An example of where this may be critical at present is at Blackwater National Wildlife Refuge where an arm of the embayment that was once freshwater is extending toward the Little Choptank where much higher salinities exist. It is well known that sulfate reduction can promote oxidation of carbon and, if liberated from the sediments, catastrophic losses may occur in this region - forming an island in southern Dorchester County. Sulfate is a component of agricultural runoff (Sharpley *et al.* 1991). If significant quantities of saline water flow into the Blackwater system, resulting in further enrichment of sulfate, it may cause even more peat degradation than in the past.

Another area that requires more research is in the functions of freshwater wetlands - both non-tidal and tidal (Silberhorn 1982). Although Odum *et al.* (1984) reviewed many of the functional aspects of tidal fresh marshes; and Cahoon and Stevenson (1985) and Weiner and Whigham (1988) have studied aspects of their population dynamics; their function relative to size, configuration and location in the larger landscape is still open to question. Another question involves non-tidal wetlands: how best to mitigate losses in terms of restoring their functional values (Kusler & Kentula 1991)? Although some work has been initiated by the Maryland Department of Natural Resources and the Maryland Highway Administration, more needs to be done to elaborate nutrient exchange capacities, sediment trapping and other functions at different wetland mitigation sites. Special attention needs to be paid to the long term responses of mitigated sites and other constructed wetlands where sediment and nutrient attenuation is an issue (Athanas and Stevenson 1991).

Modeling

One aspect of marsh and wetland research in Chesapeake Bay which is obviously lacking is modeling to predict responses to natural and human change. While carbon flows have been extensively modeled within the Chesapeake Bay (Baird and Ulanowicz 1989) and others have worked on carbon flow in marshes (Day *et al.* 1973, Wiegert *et al.* 1975, Randerson 1986), the connections between wetlands and the Bay have been largely ignored. This is unfortunate, especially since expertise is available at both the University of Maryland and the Virginia Institute of Marine Science. A carbon and/or nutrient model would be beneficial to researchers and managers, enabling them to target key overall processes where more data are necessary, as well as focus on the "big picture" which is often neglected in reductionist studies.

In Louisiana, Costanza *et al.* (1986) have constructed a spatial model which depicts past marsh losses due to regional subsidence, salinity intrusion, canal and levee construction and sea-level rise, and also can project where they will most probably occur in the future. The model

consists of 3,000 interconnected cells representing 1 km^2 of marsh surface (Costanza *et al.* 1986). Most management decisions require both temporal and spatial responses to varying management decisions. It would be advantageous to adapt Costanza's "CELS" model, or its successor - "GEM," to the mid-eastern shore (Lower Dorchester, Western Somerset, Western Wicomico counties) where marshes are likely to be lost in the near future.

Eventually this effort should be expanded into a more comprehensive functional landscape model of major flows of materials and energy between the uplands and the Bay ecosystem. Although the concept of landscape planning is now well established (Marsh 1983), it has not been used effectively in the Chesapeake region due in part to inadequate understanding of all the complex interactions of upland, wetland and open Bay systems. Unfortunately, the watershed modeling that has been developed by the EPA Chesapeake Bay program to date largely neglects the wetland interface (Blalock and Smollen 1990).

Management

Demonstration projects need to be developed to determine the effectiveness of management measures to reverse or slow interior marsh loss on the extensive marshes of the Eastern Shore. If they are designed with a research component, they will be able to answer some of the longer term functional questions raised above. Also, the use of hydrological modifications such as weirs and increasing bed roughness (e.g. Christmas trees, straw bales, snow fencing) needs to be explored to promote sedimentation in sediment starved marshes to enhance retention capacities in shallow ponds.

Another continuing management problem in the marshes is the issue involving *Phragmites* control. A workshop on invasive species should be convened to pool information and experiences involving this issue. Another workshop might be convened to evaluate mosquito control programs which significantly change hydrology by cutting channels and constructing ponds in marshes. Although initial studies (Whigham *et al.* 1982) on the eastern shore of the Chesapeake indicated no significant changes in water quality due to mosquito controls, there were changes in species composition. The long term impacts of these manipulations on marsh survival in relation to sea-level rise are yet to be determined. Finally, more effort needs to be put into nutria control measures, possibly by encouraging trapping via a bounty system.

Habitat Restoration

Zedler and Weller (1991) have emphasized the need for long term evaluation of wetland restoration and creation projects. Support needs to be given to ongoing efforts to create and/or replant marshes for habitat restoration and/or shoreline stabilization by a) funding efforts to monitor and evaluate the success of past and ongoing replanting efforts, b) determining the need to plant or stabilize in specific areas for habitat in the Bay's watershed and along tidal shorelines with the specific goal of prioritization of sites, and c) evaluating techniques of packaging and selling the ideas to landowners.

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