Higher Trophic Level Species

What is the relationship between environmental change and habitat change and the recruitment, growth, and survivorship of higher trophic level species?

Contents

About this report

This report draws its material directly from syntheses compiled for the 2001 Florida Bay Science Conference. The Florida Bay Science Program organizes itself around five central research questions. Topical teams associated with each question consist of modelers and researchers working in the Bay and adjacent marine systems. These teams compiled the original synthesis documents.

In preparation for the 2003 Florida Bay Science Conference, the research teams have modified the existing synthesis documents to bring them up to date and implement a more uniform, common format. In some cases, entirely new documents have been drafted, such as the information here on ecosystem history and on nutrient dynamics. The present report compiles these separate documents into one and provides the reader with summary material as a guide to the contents.

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Introduction

In the context of the Florida Bay Science Program higher trophic level species (HTLs) include zooplankton, benthic invertebrates such as sponges, mollusks, crustaceans (particularly decapods), fishes, marine mammals, marine reptiles, and water birds. Scientific input about HTLs in the Bay is critical to the successful restoration of Florida Bay and associated coastal ecosystems because HTLs are both ecologically and economically important and are viewed as important by the public. Changes in the abundance of HTLs may cascade down the system due to loss of the beneficial services they provide. Performance measures based on HTLs are essential to protecting and restoring Florida Bay in the CERP implementation process.

HTLs integrate the condition of the ecosystem and reflect it in their responses to environmental change. Question 5 investigates how higher trophic level species respond to changes in the characteristics of the ecosystem considered in other chapters (i.e. benthic communities, water quality, circulation and exchange with adjacent ecosystems), and the effect of human activities on these characteristics. Question 5 also investigates how HTLs are affected by fishing. Some HTLs play a critical role in regulating ecosystem functions, so changes due to fishing or other causes, anthropogenic or natural, can have repercussions on the entire Florida Bay ecosystem.

The Higher Trophic Levels component of the Florida Bay Science Program has approached question 5 by addressing the following questions.

A. How do human activities (e.g., water management, fishing) and major natural factors influence biological processes affecting growth, survival, and recruitment of fishery species, protected species, and keystone species in Florida Bay?
B. How do HTL community composition and trophic structure vary in time and space, what factors are responsible, and what processes are affected by the variation?
C. What major processes influence transport of pre-settlement stages of fish and invertebrates to and into Florida Bay, what is their schedule, what parts of the Bay are most affected, and what is their importance to recruitment to fisheries inside and outside of the Bay?
D. What animals affect major ecological processes in the Bay such as primary productivity and nutrient cycling, and what is the magnitude of this role?

Substantial progress has been made on these topics, but much remains to be done. This report synthesizes recent results, examines historical information relevant to the central question, and identifies needed future work.

Description of Higher Trophic Level Species in Florida Bay

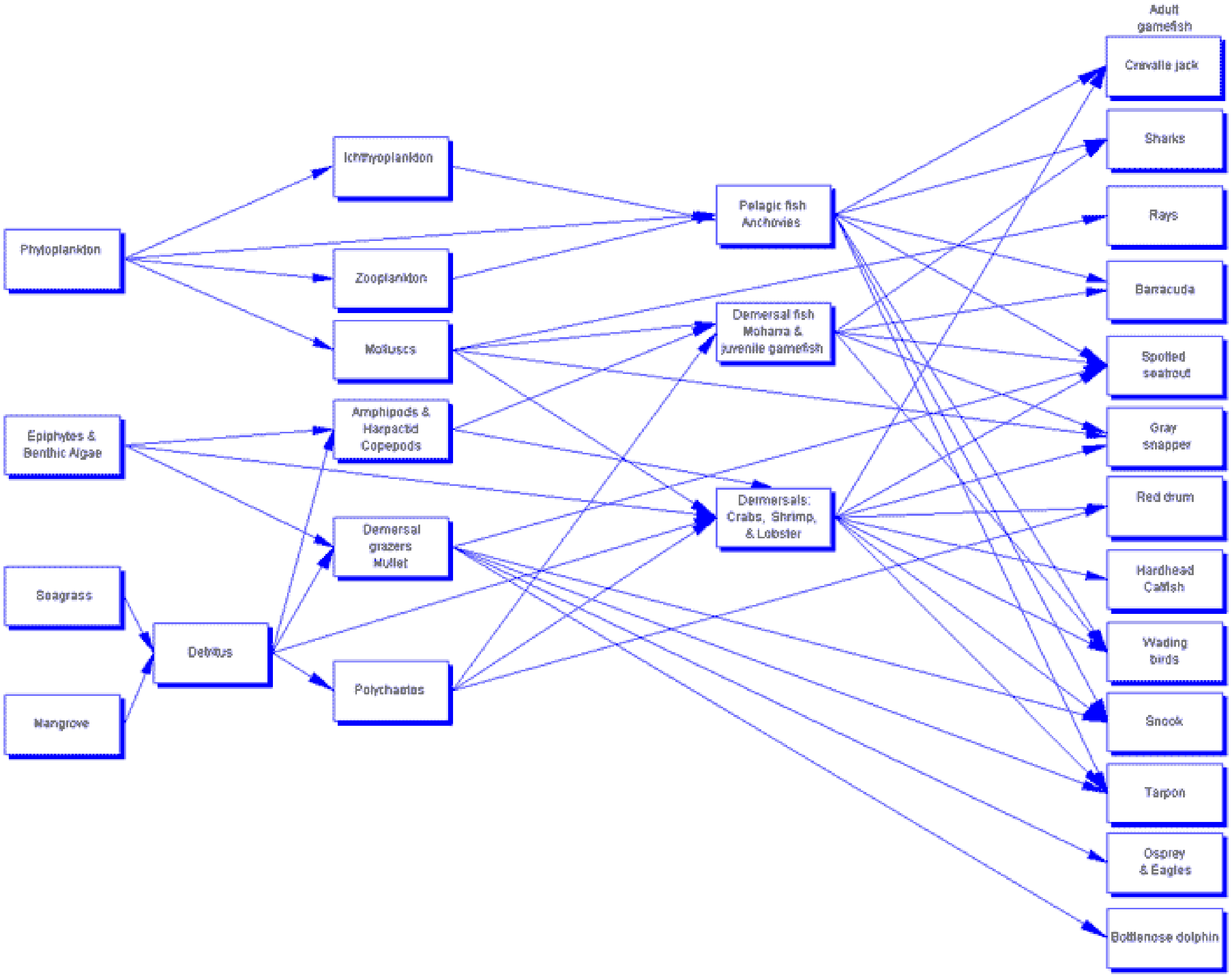
The Higher Trophic Level component of the Florida Bay Science Program encompasses all the animals of the system. Recent work on higher trophic levels in Florida Bay builds on prior research in coastal waters of Everglades National Park (ENP) before or in the 1950s and 1960s (summarized by Tilmant [1989] and Tabb and Roessler [1989]), in the 1970s by Schmidt (1979), in the 1980s by Thayer and Chester (1989), Powell et al. (1989), Sogard et al. (1989), Holmquist et al. 1989, Robblee et al. (1991), and Ley et al. (1994). Over 250 fish species are known to occur in Everglades National Park coastal waters (Loftus 2000). Schmidt (1979) found 128 fish species in Florida Bay. Tabb (1966) concluded that individuals of most species left ENP waters for unknown seaward spawning areas when they reached sexually maturity.

A synthesis of past research for the March 1998, HTL Group Report (Browder et al.1998) organized the animals of the bay into a generalized food web (Fig. 8.1). The primary producers at the food-web base include phytoplankton, epiphytes, benthic algae, seagrass, and mangroves. The Florida Bay fauna is made up of herbivores, detritivores, planktivores, and piscivores at three to four trophic levels. Within the Bay, the food web has two major branches, pelagic (water-column) and benthic (on or near the bottom), which may converge at the highest trophic levels. Most of the following information is summarized from Browder et al. (1998), but new information has been added as cited.

In the pelagic branch, filter-feeding planktonic stages of fishes, crustaceans, mollusks, and other taxa of zooplankton feed on phytoplankton (e.g., diatoms, dinoflagellates, etc.) in the water column and are preyed upon by small schooling pelagic fish such as bay anchovy and hardhead silversides. The benthic branch includes filter feeders (e.g., sponges, bivalve mollusks, ascidians, polychaetes, etc.) and demersal grazers or detritivores such as amphipods, harpacticoid copepods, polychaetes, striped mullet, and post-settlement stages of mollusks and other invertebrates. The next level of benthic consumers includes a host of small demersal fish and macroinvertebrates that feed on small invertebrates. Dominant members of this group include gulf toadfish, goldspotted killifish, rainwater killifish, dwarf seahorse, dusky pipefish, gulf pipefish, spotfin mojarra, silver jenny, white grunt, pigfish, pinfish, and silver perch (Thayer et al. 1999). Pink shrimp and many taxa of small caridean and penaeoidean shrimp also are numerically abundant in the Bay (Holmquist et al. 1989; Robblee pers. comm.). Juvenile spiny lobsters are abundant in the southwest portion of the bay, south of major mud bank barriers (Field and Butler 1994, Herrnkind et al. 1997). The limited work in the Bay and nearby areas suggests that the demersal fish in the Bay are generalists that eat a variety of benthic invertebrates (Zieman 1981, Ley et al. 1994, Schmidt 1993).

Florida Bay supports several highly sought-after game fish, including red drum, spotted seatrout, gray snapper, snook, tarpon, and bonefish (Schmidt et al. 2001, 2002). Sharks are commonly seen on aerial surveys (S. Bass, pers. comm.) and include nurse shark, bonnethead shark, and lemon shark. Rays (e.g., sting rays and manta rays) are commonly seen on aerial surveys. Small fish and macroinvertebrates are the prey of these larger fish. Within the Florida Bay area, gray snapper and red drum eat primarily shrimp and crabs, whereas barracuda, seatrout, and snook eat more fish than crustaceans (Marshall 1954, Croker 1960, Yokel 1966, Fore and Schmidt 1973, Rutherford et al. 1983, Harrigan et al. 1989, Hettler 1989, Schmidt 1989, 1986). Of the abundant forage fish, those that appear to be important in the diet of some piscivorous fishes are gulf toad fish (lemon shark, red drum, and bonefish), pinfish (lemon shark and snook), hardhead silversides (snook), goldspotted killifish (barracuda), and rainwater killifish (barracuda and spotted seatrout) (Schmidt 1986; Schmidt 1989; Crabtree et al. 1998; Koening et al. 2001). In the southern Florida Bay, juvenile lobsters constitute a large fraction of the diets of a variety of fish: nurse shark, bonnethead shark, southern stingray, bonefish, permit, and gulf toadfish (Smith and Herrnkind 1992). Small mollusks are abundant in Florida Bay and probably are fed on by rays and fish such as sheepshead. The pink shrimp *Farfantepenaeus duorarum* is a key component of trophic webs. This species is an important prey of game fish (Croker 1960; Stewart; Yokel 1966; Rutherford et al. 1983; Hettler 1989; Schmidt 1986, 1989) and wading birds (Palmer 1962), linking them to small grazers and detritivores supported by algae and

Figure 8.1: Trophic levels in Florida Bay



seagrass and mangrove detritus (Mumford et al. 1999). The abundant small caridean shrimps are in Florida Bay are the principal prey of juvenile pink shrimp (Schwamborn and Criales 2000).

The many piscivorous water birds that live in the Bay seasonally or year-round also eat small fish and macroinvertebrates such as crabs and shrimps, although this is poorly documented. Piscivorous birds in the Bay include double-crested cormorants, brown pelicans, red-breasted mergansers, laughing gulls, ring-billed gulls, royal terns, and many wading bird species, as well as bald eagles and osprey. The most abundant wading bird species in the Bay seasonally are white ibis and great egrets (Browder and Bass, unpublished data.). The Bay is a major habitat for the great white heron, roseate spoonbill, and reddish egret. All of these species feed in the Bay proper or in shallow ponds on the Bay's islands.

The bottlenose dolphin is another high-level predator in Florida Bay and, based on studies elsewhere in South Florida, probably feeds on fish at several trophic levels. The American crocodiles that occur in the northern Bay and the American alligators that penetrate the northern Bay during wet years also are predators on the Bay's small fish populations.

Two large grazing animals, the West Indian manatee and the adult green sea turtle, may once have been more abundant in Florida Bay than they are today and may have influenced the structure and productivity of seagrasses through their grazing. A review by Thayer et al. (1984) described the dietary importance of seagrass to various herbivores and the influence of herbivory on seagrass systems. Green turtles once were the primary consumers of seagrasses in the Caribbean, but now they are few in number everywhere. In a major feeding area in Nicaragua, *Thalassia testudinum* made up 87% of the diet of green sea turtles and other seagrasses (*Syringodium filiforme* and *Halodule wrightii*) made up another 5%. Grazing by green sea turtles may have profound influences on the seagrass community that are different from the effects of grazing by other herbivores. Green sea turtles may feed on *Thalassia* preferentially. They are known to maintain discrete grazing plots in a *Thalassia* bed and feed repeatedly on the new growth in these plots until food quality deteriorates. It is possible that the presence of grazing sea turtles might prevent the type of high-biomass *Thalassia* monoculture that preceded the seagrass die-off in Florida Bay of the late 1980s. The possible impact of loss of sea turtles on Florida Bay was discussed by Jackson et al. (2001). Grazing by manatees may have a more disruptive effect than that by turtles because the rhizophore is disturbed and might jeopardize recovery (Thayer et al. 1984).

The density of large herbivores in the Bay today is too low for them to have much influence on the present ecosystem. According to a recent Sea Grant report, B. A. Schroeder, B. E. Witherington, and A. M. Foley have found only juvenile green sea turtles and loggerhead turtles in their Florida Bay study. Neither of these is herbivorous. In a recent aerial monthly census 1995-2000) of water birds of the bay, Browder and Bass (pers. comm.) seldom saw manatees.

Seagrass is the main diet of the caridean seagrass shrimp (Schwanborn and Criales 2000). Seagrass is also important in the diet of sea urchins and is reported in the diets of some fishes (Thayer et al. 1984). Even where grazing animals are more abundant, it is likely that more energy travels from seagrass to consumers through the detrital than the grazing food web. In Florida Bay today, only the detrital food web is significant.

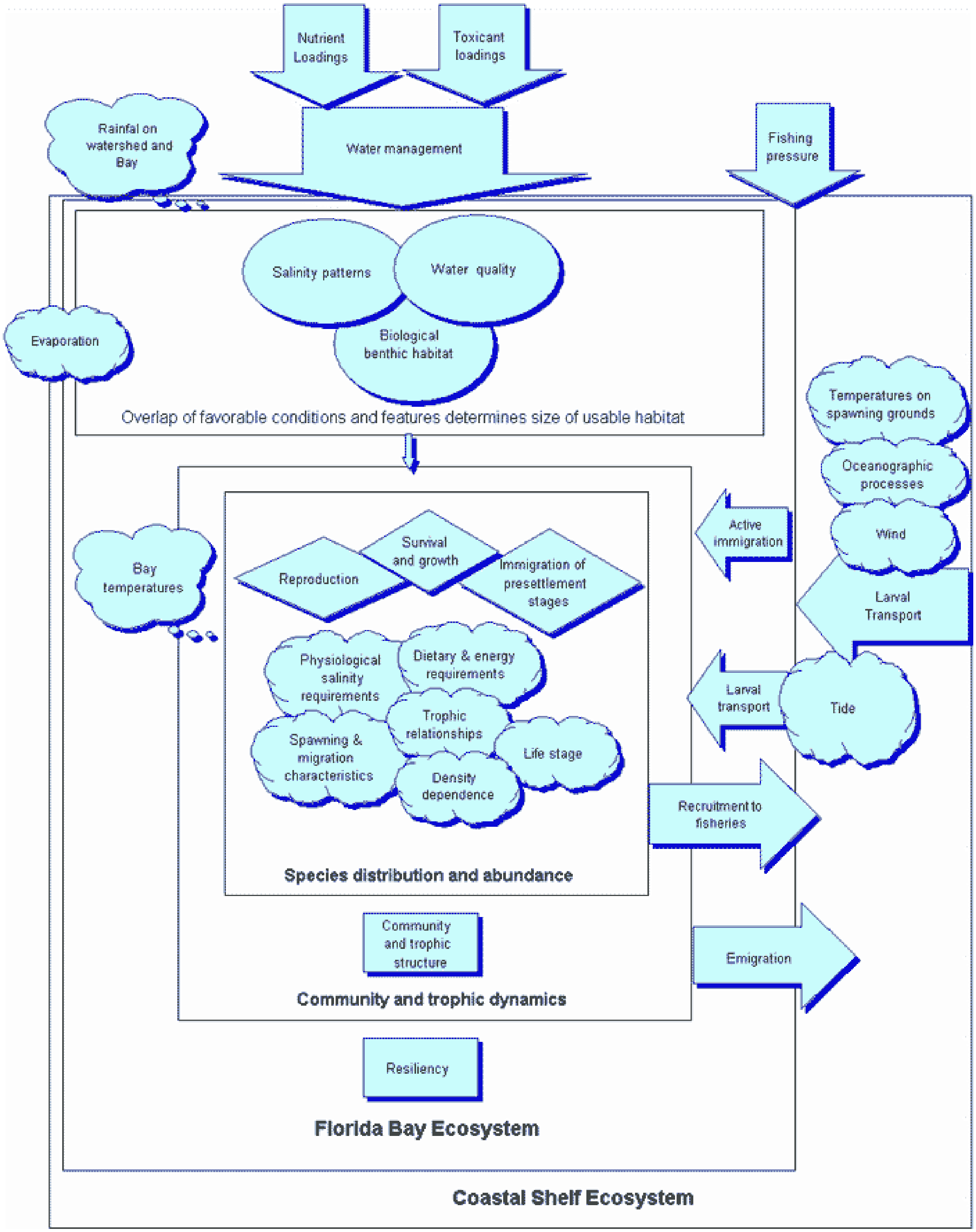
A strategic conceptual model developed to help guide Florida Bay HTL research is shown in Figure 8.2. The model incorporates the following major concepts:

- Critical ecosystem characteristics (i.e. salinity, water quality, and biological benthic habitat) directly influence HTLs at the individual level. Species and community level response represents the aggregate influence of these characteristics integrated over HTLs populations.
- Changes in HTLs at the species and community level occur as the result of driving processes acting on Florida Bay as a whole. These processes influence HTLs by their effect on critical ecosystem characteristics and by controlling the movement of HTLs into and out of Florida Bay.
- At the shelf scale, which includes Florida Bay as a component of a complex of wetland and marine ecosystems, other potentially influencing factors include temperatures on spawning grounds, larval transport processes, and fishing.
- The scope of research on HTLs of Florida Bay must include within-bay, cross boundary, and greater coastal ecosystem processes, and these processes should be examined at time scales from seasons to decades;
- Higher trophic level processes and patterns potentially affected by water management occur at the population, community/trophic, and ecosystem level;
- HTL responses to water management are expected to occur through water management effects on salinity, the area of co-occurrence of biologically favorable salinity and habitat, the condition of biological habitat (e.g., seagrass, sponge, coral), animal movements, and loading of nutrients or toxicants;
- Intrinsic factors potentially influencing responses to water management include physiological salinity requirements, dietary and energy requirements, and trophic relationships, all of which may differ by species, life stage, and spawning and migration characteristics;
- At the bay scale, other potential influencing factors on HTLs include salinity-temperature interactions, toxicant concentrations in freshwater inflow, and fishing;

Processes Driving Change in the Ecosystem

Preceding chapters describe some major ecosystem characteristics that influence higher trophic levels in Florida Bay: salinity, water quality, and benthic habitat. All are subject to change, and an understanding of how they might change is being developed in other parts of the Florida Bay program. Determining how their change might affect higher trophic levels is being determined by HTL research. Relationships between processes driving change, ecosystem characteristics, and characteristic species and communities of Florida Bay are highly relevant to the Comprehensive Everglades Restoration Project (CERP), which will influence the change-driving processes. Defining and quantifying these relationships is crucial to preparing performance measures to restore or protect Florida Bay. Augmenting the descriptions of ecosystem characteristics in the preceding chapters are studies on mercury. These studies are defining previously unknown spatial patterns of mercury and methyl mercury concentrations in Florida Bay waters, sediments, and biota.

Figure 8.2: Conceptual model of factors affecting higher trophic level species in Florida Bay



The quest for answers to Question 5 must extend beyond Florida Bay to include the greater ecosystem that supports the movements of species into and out of the bay and the processes that affect these movements. Animal movements, as well as the flow of water, connect Florida Bay not only to the upstream Everglades and coastal mangrove areas but also to the Florida Keys, the Reef Tract, the southwest Florida shelf, and the Dry Tortugas. Many higher trophic level species range between the Bay and coastal reefs within their life cycle. The processes driving change in the Florida Bay ecosystem extend beyond the bay both upstream and downstream.

The principal human generated processes potentially driving change in the Florida Bay ecosystem are water management, contaminant and anthropogenic nutrient inputs, causeway/bridge construction in the Florida Keys, and fishing. Climatic variation and oceanographic processes are other instruments of change in the Florida Bay ecosystem and may cause year-to-year and long-term variation.

Water Management

By affecting freshwater inflow to Florida Bay, water management can affect Florida Bay's HTLs through the effect of freshwater inflow on salinity patterns and nutrient, organic detritus, and contaminant loads. Salinity directly affects physiological processes that determine growth, survival, and reproduction rates of many higher trophic level species. The area in which a favorable salinity range overlaps with other favorable conditions (i.e., shoreline, depth, or bottom habitat) in areas accessible to appropriate life stages determines the productive capacity of the Bay for a given species. Salinity gradients may provide orientation cues that promote the successful immigration into the Bay of postlarvae spawned offshore that use the Bay as a nursery ground. Nutrients and organic detritus may have positive or negative effects depending on concentration. In excess, they degrade habitat (via reduced water clarity, low dissolved oxygen, etc.).

Effects of water management on salinity patterns and nutrient and contaminant loads are being studied in other parts of the Florida Bay science program. A major emphasis of the HTL science plan is determining the possible effect of changes in salinity on animal species and communities. Water management may affect higher trophic level organisms through effects on important living benthic habitat such as seagrass and sponges (e.g., through salinity, nutrient, turbidity or other effects on the organisms that form living benthic habitat), and these potential effects are also being evaluated through studies of relationships of HTL to living benthic habitat.

Fishing

Major fisheries operate in the coastal waters of South Florida, contributing strongly to the economic base of the area as direct production, "value added", and purchases generated in support industries such as tourism, restaurants, fishing supply stores, and dive shops. Many coastal fisheries have ecological connections to Florida Bay. Especially notable of these are the commercial fishery for pink shrimp and the commercial and recreational fisheries for gray snapper and spiny lobster. These species and others (sparids, grunts, other snapper, and even groupers) found on the Florida Keys Reef Tract and in the waters near the Dry Tortugas spend part of their life cycle in Florida Bay. Reef waters near Marathon in the Middle Keys are an important spawning ground for gray snapper (Rutherford 1989). Shelf waters near the Dry

Tortugas islands are the most important commercial fishing grounds for pink shrimp in Florida, and Florida Bay is the major pink shrimp nursery ground. Florida Bay also contains important spiny lobster nursery habitat, and Everglades National Park is a fishing-free sanctuary for spiny lobster. Nearby areas and parts of Florida Bay outside of ENP support commercial fishing for Spanish mackerel and other species and recreational and commercial fishing for spiny lobster. Recreational fishing is an expanding sport in the Florida Keys, Tortugas waters, and Florida Bay, both within and outside ENP boundaries. The number of fishing trips in ENP in 2001 was the highest ever reported (Schmidt et al. 2002). ENP began phasing out commercial fishing in the bay in the early 1980s when analyses of recreational and commercial fishery data suggested that overfishing might be occurring. Regulations on recreational fishing have since also been strengthened. Later analyses have suggested that environmental factors affect abundance (Tilmant et al. 1989; Schmidt et al. 2002). The ratio of kept fish to total fish caught changed dramatically from the 1980s to the 1990s. This may be an artifact of regulatory changes (legal size limits, bag limits, seasonal closures); however it may be indicative of an increased catch of smaller sizes (below legal size limits). This issue will be addressed in current and future analyses of size-frequency distributions in the creel census data by ENP and the Florida Marine Research Institute.

The growing demand for fish and popularity of fishing have increased the pressure on fishery populations in South Florida. Fishing pressure is especially reflected in declining sizes and densities of snappers and groupers and changes in the trophic structure of fish assemblages on reefs (Ault et al. 1998). These changes are apparent even in the Tortugas area and are consistent with similar changes previously detected in the Florida Keys (Ault et al. 1998; Bohnsack et al. 1999; Schmidt et al. 1999). The observed decline in fish abundance may be due to loss of coral habitat. For example the total area of Caribbean reef-building corals *Acropora palmate* and *Acropora cervicornis* has declined by 93% and 98% respectively since 1983 (Miller et al. 2002).

Oceanographic Processes

The Loop Current/Florida Current and countercurrents, the Tortugas Gyre, and coastal eddies are oceanographic features that may influence the migration of postlarvae to Florida Bay and to the Florida Keys Reef Tract from offshore spawning areas. These processes may affect the timing of abundance peaks and year class strength in fish and macroinvertebrate populations in the Bay and on the Reef Tract.

The Florida Keys Reef Tract extends almost without interruption along the entirety of the Florida Keys and is the core component of the Florida Keys National Marine Sanctuary. Florida Bay is connected to the reef tract through inter-island channels. Regional-scale and local-scale oceanic processes that affect the reef track likely also affect Florida Bay. Reef tract populations are replenished not only by local spawning but also by spawning upstream. The upstream distance limit is primarily determined by current velocity and larval development rate, which ranges from two weeks in some invertebrates and fish to up to 12 months in spiny lobster. Recruitment of some species to the Florida Keys Reef Tract from as far away as the western Caribbean has been postulated. The argument for multiple upstream larval sources for the Florida spiny lobster population is especially strong, given the wide geographic range of the species and its extraordinarily long planktonic larval life (Lyons 1980, Yeung et al. 2000, Yeung and Lee 2002), and is supported by mtDNA analysis (Silberman et al. 1994).

More local sources may be important to most populations. The lower southwest Florida shelf in the vicinity of the Dry Tortugas is one potential source of recruitment to the Florida Keys Reef Tract and Florida Bay. The islands of the Dry Tortugas and surrounding shallow waters, now both a national park and part of the Florida Keys National Marine Sanctuary, lie roughly 150 km (70 miles) west of Key West and are known for remoteness and relatively unspoiled marine richness (Ault et al. 2002; Franklin et al. 2003). The coastal shelf in the vicinity of the Dry Tortugas is the major spawning ground for pink shrimp in Florida. Recent research is uncovering luxuriant, previously unknown and unmapped coral reefs near the Dry Tortugas and near the Marquesas, which lie between the Dry Tortugas and Key West (Miller et al. 2001).

Causeway/Bridge Construction

The flow connecting Florida Bay to the Atlantic Ocean through Lignum Vitae, Indian Key, and Teatable Key Channels was reduced by the construction of the Flagler railroad, which became the Overseas Highway. This construction, which occurred in the early 1900s, partially blocked tidal passages and affected Bay circulation and associated water quality (Healy 1996). By affecting transport between the Bay and Gulf of Mexico and the Atlantic Ocean, the construction areas may also have affected the immigration of postlarvae and early juveniles into Florida Bay. The U.S. Corps of Engineers is leading a study to determine whether Keys passes should be enlarged to restore the health of Florida Bay. The Corps is planning a pilot study of the effect of enlarging passes than have been restricted by the highway. The pilot study will be performed in passes located between Fat Deer (Marathon) and Grassy Key.

Research Approaches

A major focus of Florida Bay HTL research has been to characterize the response of species and species groups to environmental and habitat conditions that vary in space and time. The topic has been approached by modeling, statistical analyses, experiments, and field measurements. Modeling, supported by laboratory experiments, was used to characterize the response of individual organisms and was applied to pink shrimp, spiny lobster, sponges, and spotted seatrout to examine functional responses to salinity and temperature and their consequences for populations. Statistical analysis of historical resource survey data was used to characterize the response of 11 forage species and nine fishery species to environmental variables at the population and community level. Field studies were conducted to characterize the spatial and temporal patterns of immigration of early life stages into Florida Bay from offshore spawning grounds and the density of juveniles on Florida Bay nursery grounds. Most work has included an examination of the possible effects of salinity because salinity is a likely variable to be affected by water management.

A more recent focus of Florida Bay HTL research has been to examine the effect of HTLs on critical ecosystem characteristics, such as water quality and benthic habitat, that determine habitat quality and define distinct communities. In this regard, sponges are a major interest because of the recent decline in sponge biomass in the Bay. Sponges are capable of regulating water clarity through their filter feeding. The volume of water filtered is largely determined by sponge biomass density and has declined substantially.

Field sampling and comparative analysis of data from fished and unfished areas provided information on the effect of fishing on individual species and species composition.

Comparative studies provided evidence that fishing in ENP affects size distribution within species (gray snapper) and the species composition of communities. Underwater visual resource surveys on the reef tract and near the Dry Tortugas have found signs of overfishing of fish species that occur both on the reef tract and in Florida Bay.

One approach to examining the effect of water management on higher trophic level species has been through statistical analyses relating fishery catch or catch-per-unit-of-effort to indices of freshwater inflow to Florida Bay and nearby southwest Florida coastal waters. Another approach, already mentioned above, has been to examine the effect of salinity on processes that affect the abundance of these species.

Summary of Recent Results

The following summary of recent results, presented as bullets, is organized under specific research questions (subsets of the four topic questions identified above) to provide an overview of progress. Table 8.1 organizes research activities into specific topic categories. These topics provide a general framework for a series of sections synthesizing recent results and conclusions, by specific research topic, which follows the table.

Does salinity affect survival and growth, do salinity patterns affect faunal abundance and distributions, and will changes in salinity patterns affect the bay's nursery function?

- Five species of sponges found in Florida Bay experience high mortality rates at low salinity. None survived at 15‰. (laboratory experiments)
- Pink shrimp from Florida Bay are more sensitive to low salinity than to high salinity. The salinity of maximum physiological survival varies with temperature. Pink shrimp are more tolerant of high salinity at high temperature and low salinity at low temperature. Acclimation improves survival at high salinity (55‰) but not at low salinity (5-10‰). Growth of pink shrimp is optimal at a salinity of 30‰. (laboratory)
- A salinity optimum of 35‰ is reported for postlarval Caribbean spiny lobster. The extreme salinities that sometimes occur in portions of Florida Bay are lethal to lobster postlarvae. (laboratory experiments)
- Larval and juvenile seatrout survival and growth are low at salinity >45‰. (laboratory)
- Temperature and salinity have an interactive effect on the metabolic rate of young spotted seatrout. Their metabolic rate in relation to size is bi-phasic and changes isometrically with body mass in early stages, approximating an exponential relationship near unity, but changes isometrically thereafter. (laboratory)
- Spotted seatrout catch rates in the recreational fishery are negatively related to indices of freshwater inputs to Florida Bay. (analyses of creel census data)
- Western Florida Bay is a major nursery ground for spotted seatrout (field study). The high density of planktonic postlarvae suggests that Central Florida Bay may also be a major nursery ground when conditions allow. Salinities > 45‰ have frequently occurred in Central Florida Bay in the past, which may limit this area's nursery value.

- Pink shrimp recruitment from Florida Bay could differ among years, seasons, and regions of the Bay solely due to observed salinity and temperature variation. (simulation model).
- Observed salinity during a wet and a dry year caused a predicted decline in lobster recruitment of ~25% in the area of Florida Bay directly affected by salinity variation. (individual based model).
- Habitat, tidal amplitude, freshwater inflow to Florida Bay, and salinity were the most widely influential variables explaining density in 11 forage species in a meta-analysis of data from historical surveys. Seagrass density and tidal amplitude each were significant for 10 species, seagrass type and freshwater inflow each were significant for nine species, and salinity was significant for seven species. (statistical analyses of combined data sets)

Does water management affect the productive capacity of Florida Bay?

- When used in alternative testing to select the preferred plan for CERP, a statistical model relating an abundance index of pink shrimp in the Tortugas fishery to freshwater inflow to ENP at the Tamiami Trail during certain months predicted that “natural system” flows (as compared to 1995 base case or any alternative) consistently produced highest shrimp abundance over a 31-yr period. The selected alternative was predicted to lead to abundances intermediate between predictions for the natural system and 1995 base case.
- Remnant molluscan fauna in cores suggest that molluscan faunal diversity and absolute abundance in eastern and central Florida Bay began a decline in the 1960s or earlier and reached a low in the 1970s. The low diversity and increased abundance of *Brachidontes exustus* are evidence of a system under stress.
- Fish density in the wet season is positively related to water depth in coastal marshes and the length of time during which water depths are greater than 12.5 cm. Maximum concentration (to roughly twice dry-down density) in low spots (e.g., creeks and shallow pans) occurs when water depths decline below 12.5 cm in adjacent marshes. Successful Roseate Spoonbill nesting occurred in past years during dry season when mean water levels in the coastal marshes were less than 12.5 cm. Nesting failures in recent years can be explained by out-of-season water releases from the C111 Canal.

What affects the balance between benthic and pelagic trophic networks in Florida Bay?

- The seagrass die-off was a suspected cause because bay anchovy abundance was much greater in 1995 than in 1984-1985. Recent findings discount this possible cause. The abundance of bay anchovy in the western Bay has fluctuated since it reached a maximum in 1995. The diversity and overall abundance of canopy-dwelling fauna has increased since 1995 without a return to the original Thalassia-dominated seagrass canopy.
- Bay anchovy abundance may be related to the presence of salinity fronts. Bay anchovy abundance was negatively correlated with salinity and positively correlated with salinity standard deviation, chlorophyll, and an index of freshwater inflow in an analysis of historic data. A study in the Manatee River associated low mean salinity and high salinity standard deviation with the presence of fronts and found a relationship between anchovy egg abundance and these indicators of fronts.
- Seagrass diversity may determine faunal density. A Principal Components analysis suggested that faunal species have affinities to certain seagrass types, *Thalassia, Halodule, Syringodium*, or macroalgae. Seagrass type was a significant explaining

variable in a metanalysis of faunal density in Florida Bay, and faunal density in relation to seagrass type varied differently depending on faunal species. No species was favored by pure *Thalassia*.

Does bottom and shoreline habitat affect abundance and community composition?

- Mangrove prop-root habitat in northeastern Florida Bay had significantly more fish larvae than nearby open water sites or nearshore areas without mangroves but a lower density and diversity of both forage fish and juvenile predator fishes than found in similar habitat in the Bahamas, Puerto Rico, leading to the hypothesis that the low densities were caused by isolation from offshore sources of larvae or juveniles.
- Seagrass density was a significant explaining variable for density for 10 out of 11 key forage species examined, and seagrass type was a significant explaining variable for density of 9 out of the 11 species.

Does fishing affect fish populations?

- Recreational fishing in Everglades National Park affects the size structure of gray snapper, according to a comparison of the length frequency distribution inside and outside of an area in the park protected from fishing.
- Evidence of overfishing is seen in gray snapper and other species on the reef tract.

Is spatial variation in influencing factors (e.g., freshwater inflow, tidal mixing) reflected in distinct regional patterns in species distributions and community and trophic composition in Florida Bay?

- Peak concentrations of postlarval pink shrimp are roughly an order of magnitude greater in passes leading into western Florida Bay than in channels to Florida Bay through the Florida Keys. Movement into the Bay occurs on the flood tide. The timing of high immigrations rates is more predictable from the west than from the east.
- Based on stable isotope analyses, the central Bay has a strongly seagrass-based trophic structure, whereas the western Bay has a more plankton dominated trophic structure. The eastern Bay has a non-seagrass-based diet base (likely more water-column based). The trophic structure of the southwestern Bay is based on macroalgae.
- Northern Florida Bay probably is not a significant nursery area for red drum

Is temporal variation in recruitment strength of spiny lobster, snapper, and pink shrimp related to oceanographic processes, especially the Tortugas gyres?

- Spiny lobster postlarvae that recruit throughout the year had peaks of influx into the Bay at the Middle Keys coinciding with the presence of eddy and countercurrent conditions.
- Larval duration of snapper varied from one year to the next and, within the first year, ranged from 35.50 to 41.45 days
- Peak abundance of snapper larvae in Florida Keys channels occurred in summer, 1997, and was coincident with a well-developed Loop Current (high latitudinal extent) favoring gyre formation off the Dry Tortugas, where snapper spawning aggregations occur.
- Temporal variability was observed in the influx of pink shrimp postlarvae through two channels in the Middle Keys and may be related to the position of the leading edge of the

cyclonic eddies relative to the channels. Pink shrimp larvae at the spawning grounds also seem to be retained by the circulation of the Tortugas gyre.

Are urban and agricultural sources, carried by the C111 Canal, responsible for high methymercury in Florida Bay and its biota?

- Sources of elevated mercury concentrations in fish from northeastern Florida Bay include (1) methylmercury in runoff from the Everglades and (2) *in situ* mercury methylation in sediments from both the mangrove transition zone and the open bay itself.
- Mercury concentrations seem to be higher along a Taylor River/Little Madeira Bay sampling transect than along a C-111 canal/Joe Bay transect, suggesting that the urban and agricultural runoff that more strongly influences the C111 canal/Joe Bay transect is not the most important source of mercury to the Bay and its biota.

Did the former density of sponges in Florida Bay influence water quality to the extent that the sponge die-off that followed seagrass die-off led to water-quality conditions that impeded the recovery of seagrass?

- At pre-dieoff (pre 1992) densities, sponges in Florida Bay may have been capable of filtering the entire water column in 24 hours. Recovery of the largest and most abundant species has been extremely slow. At present densities, filtering takes an estimated 4 days. Sponges are efficient filters of small (< 5 µm) planktonic particles. Loss of sponges may have reduced water clarity and affected seagrass recovery.

Do predators seek areas of higher prey abundance?

- Bottlenose dolphin were found in areas of highest density of potential prey, supporting the working hypothesis that they search out feeding areas with higher prey concentrations. Higher dolphin and prey densities occur in the east-central and south-central Bay than in the northeastern Bay, but densities of both dolphin and prey and prey density are low in the east-central and south-central Bay compared to other coastal areas.

Table 8.1: Research topics defined by Question 5 (cells in the matrix) and key references to the associated research.

Research Topic	***Population Level* - Species Abundance and Community and Trophic Structure** Read et al. 2001, Limouzy-Paris et al. 1997, Robblee et al. 1991, Costello et al. 1986, Thayer & Chester 1989, Powell et al. 1989, Chester & Thayer 1990, Thayer et al. 1999, Powell 2002, Powell in press, Powell in review, Schwamborn & Criales 2000.	***Individual Level* - Growth and Survival** Powell et al. in review, Settle, in prep.
Salinity Pattern *(see Question 1)*	Schmidt 2001, Browder et al. 1999, in press; Brewster-Wingard et al. 2001, Matheson et al. 2001, Field and Butler 1994, Lorenz 2001a	Browder et al. 2001, Browder et al. 1999, Butler et al. 2001, Butler et al. in press, Field and Butler 1994, Wuenschel 2001, Richards and DeAngelis 2001
Water Quality (see Question 2)	**Water quality effect on HTLs:** (no results reported)	**Water quality effects on contaminants and humans, piscivorous birds, mammals, and reptiles:** Evans and Crumley, in review; Sepulveda et al. 1998 **Effects on invertebrates:** Scott et al. 2002)
	HTLs effect on water quality: Stevely and Sweat 2001, Peterson 2001	
Biological Benthic Habitat (see Question 4), Stevely and Sweat 2001	**Habitat effect on HTLs:** Dennis and Sulak 2001, Robblee et al. 2001, Matheson et al. 2001, Powell et al. 2001, Ortner et al. 2001, Robblee et al. 2001, Chanton et al. 2001, Hernkind and Butler 1994, Field and Butler 1994, Butler et al. 1995, Butler et al. in press, Koening et al. 2001	**Habitat effect on HTLs:** Butler et al. 1995, Butler et al. in press
	HTLs effect on habitat: Rose et al. 2001, Peterson and Fourqurean 2001	
Coastal Transport (Larval) Processes (see Question 1 for regional circulation),	Field & Butler 1994, Yeung et al. 2001, Yeung & Lee 2002, Jones et al. 2001, Browder et al. 2001, Browder et al. 2002, Butler et al. 2001, Criales et al. 2003	Settle 2001 & in prep.., Yeung and Lee (2002.), Acosta and Butler 1997, Criales and Lee 1995, Criales and McGowan 1993, 1994, Jones et al. 2001, Jones 1978, Tabb et al. 1962, Yokel 1969, Smith 2000, Butler et al. 2001
Water Management and Hydrology (see Question 1 for regional hydrology)	Browder 1985, Sheridan 1996, Browder 1999, Johnson et al. 2002a	Lorenz 2001a, 2001b
Fishing Schmidt et al. 2001	Faunce et al. 2002, Bohnsack et al. 2001	

Distribution of Species and Patterns of Abundance

Spatial variation in the influence of environmental and physical factors shaping Florida Bay, especially substrate, freshwater inflow, degree of mixing with waters of the Atlantic and the Gulf of Mexico, have led to substantial regional differences in animal distributions within the bay. For example, the southern bay is prime habitat for juvenile spiny lobster, which are found in few other parts of the bay. On the other hand, juvenile pink shrimp occur most densely in the western bay. Animal distributions have been used to define distinct sub-regions of the bay beginning with Turney and Perkins' (1972) delineations based on mollusks. Sub-regional delineations based on animals roughly correspond to those based on seagrasses (Zieman et al. 1989) and water quality (Boyer 1997). Short-term and long-term temporal variation in environmental variables accentuates regional differences in bay habitat (for example, the northeastern bay has the most seasonally variable salinities). Temporal variation also undermines efforts to better describe and understand regional differences (for example, the northcentral bay can be hypersaline one summer and mesohaline another, creating an entirely different environment for animals in the same time of year). Recent research has expanded our understanding of how animal distributions vary spatially and temporally and the most likely reasons for the variation. Results of studies that address spatial and temporal variation follow under a number of topics. A few field studies addressing spatial patterns follow directly below.

Field studies have expanded the knowledge of spawning areas and spawning periods. Powell and colleagues (Powell et al. 2001; Powell et al. in press; Powell et al. 2002) determined that spotted seatrout spawning occurs primarily in western Florida Bay. Spawning at Bradley and Palm Key had been observed historically, but spawning at Whipray Basin and Little Madeira Bay was determined for the first time in 1994-1995 sampling. Based on collections and hatch-date estimates from 1995 collections, they determined that spawning occurred primarily during the summer with spawning peaks in May and June. Larvae were collected over a wide range of bottom types with and without seagrass, in waters with temperatures between 20 and 35°C (majority 26-34 °C), and salinities between 12 and 41‰ (majority 25-40‰). Consistently high densities of larvae were collected at Whipray Basin, which is located in the central portion of the bay and is a valuable juvenile nursery area despite low seagrass above-ground standing crop and occasional (two occasions during sampling—40 and 41‰) hypersaline conditions in 1998 and 1999.

Nursery grounds of several other gamefish species that occur in Florida Bay as adults are not yet documented in Florida Bay. Recently Powell et al. (2002) attempted to locate Florida Bay nursery grounds of red drum, which occur in Florida Bay and spawn in the nearby Gulf of Mexico. Based on results of intensive sampling for juveniles in northern Florida Bay, the only part of the Bay with suitable habitat, Powell et al. (2002) concluded that this area was not a nursery ground for red drum. They suggested that limitations on transport of postlarvae into the Bay's interior might limit the use of otherwise suitable sites in the northern Bay as nursery habitat for offshore spawning species such as red drum. Red drum nursery habitat was characterized by Peters and McMichael (1987) with work in Tampa Bay.

Read et al. (2001) studied bottlenose dolphin in the eastern half of Florida Bay and found that densities of prey organisms were higher in areas where bottlenose dolphin had been feeding than elsewhere that trawl samples were taken. This supported their hypothesis that dolphin seek out feeding areas with higher prey concentrations. These investigators found a greater abundance of dolphin in the east-central and south-central parts of the Bay than in the northeastern Bay. (Their study did not include the western Bay.) They suggested that the low abundance of dolphin in the northeastern Bay might be related to the lower fish densities that have been reported there by other investigators. In 20 surveys conducted in all four seasons, they encountered 23 groups of bottlenose dolphin, consisting of 133 individuals. They concluded that the entire Bay area they surveyed contains relatively few dolphin, corresponding to the low density and diversity of potential prey items overall. In all seasons and areas, their trawl catches were dominated by mojarras (family Gerreidae).

Effect of Ecosystem Characteristics on Growth and Survival

Work on this topic addresses the major question: How do growth and survival of individuals in each HTLs vary through the range of environmental conditions defined by salinity, water quality and benthic habitat found in Florida Bay? Major working hypotheses are as follows:

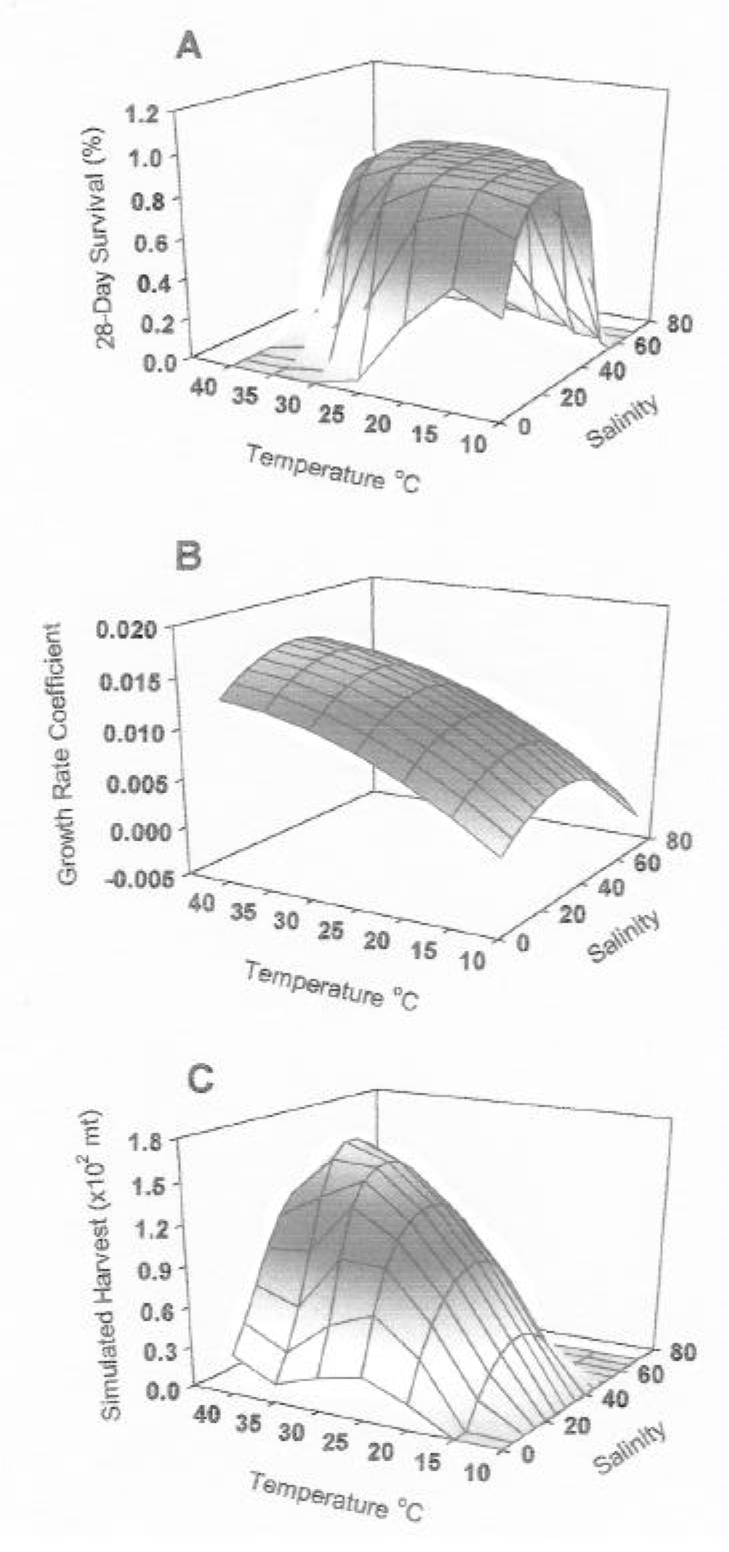
1. Salinity directly affects the growth and survival of HTLs;
2. The carrying capacity of Florida Bay nursery areas is related to the overlap of favorable salinity and favorable bottom or shoreline habitat.

Effect of Salinity on Growth and Survival

Simulation models and associated experimental trials suggest that several Florida Bay species, each with optimal habitat in a different part of the Bay, can be affected by changes in freshwater inflow and resultant changes in salinity patterns. Both pink shrimp and spiny lobster could be negatively affected by the extreme high salinity that often occurs in the north central part of the Bay and sometimes spreads westward into optimal shrimp nursery habitat and southward into optimal lobster habitat. Lobster and shrimp could both be negatively affected by low salinity conditions when it occurs in otherwise suitable habitat and locations.

The effect of salinity and temperature on the growth, survival, and subsequent recruitment and harvest of pink shrimp (*Farfantepenaeus duorarum*) was examined with laboratory experiments and a simulation model (Browder et al. 2002). The pink shrimp is an ecologically and economically important species that has major nursery grounds in Florida Bay. Experiments were conducted to determine the response of juvenile growth and survival to temperature (15 to 33°C) and salinity (2 to 55‰), and results were used to refine an existing model (Browder et al. 1999). Results of these experiments (Fig. 8.3, a and b)(Browder et al. 2002) indicated that juvenile pink shrimp have a broad salinity tolerance range at their optimal temperature, but the salinity tolerance range narrows with distance from the optimal temperature range, 20-25°C. Acclimation improved survival at extreme high salinity (55‰), but not at extreme low salinity (i.e., 5, 10 ‰). Growth rate increases with temperature until tolerance is exceeded beyond about 35°C. Growth is optimal in the mid-range of salinity (30‰), and decreases as salinity increases or decreases. Potential recruitment and harvests from regions of Florida Bay were simulated based on local observed daily temperature and salinity. The simulations predicted that potential harvests might differ among years, seasons, and regions of the bay solely on the basis of observed temperature and salinity. Results indicated that harvests on the Tortugas grounds could be affected by spatial extent, location relative to suitable bottom habitat, and duration within a favorable salinity range.

Figure 8.3: Response curves of survival, growth, and potential offshore harvest of pink shrimp in relation to salinity and temperature (Browder et al.. in press).



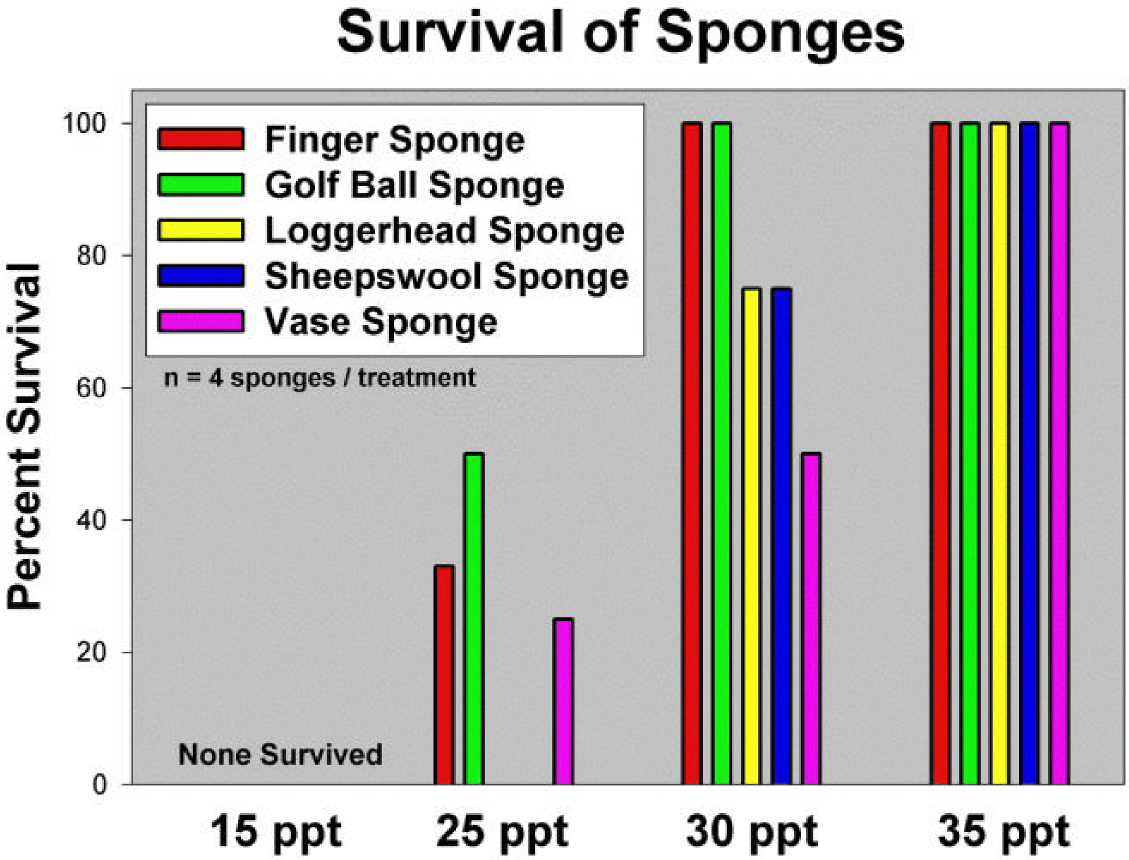
Butler et al. (2001) explored the impact of changing salinity on lobster and hard-bottom habitat, especially as it might relate to lobster microhabitat (i.e., various species of sponge and octocoral. Salinity experiments at winter temperatures have recently been completed for several sponge species (Fig. 8.4) and indicate reduced survival for an increasing number of species as salinity decreases (Butler et al. 2001). None of the five species tested survived at 15‰. Field and Butler's (1994) reported results concerning salinity and temperature effects on postlarval lobsters, which suggested a salinity optimum of 35‰. Survival at other salinities other than 35‰ was low below 18°C and above 33°C.

Powell et al. (in review) examined spatial and temporal variation in growth and survival of spotted seatrout. They looked at variation among areas and months and examined variation in relation to temperature. They found a strong parabolic relationship of temperature with the growth of juveniles (22 d-60 d) but no significant relationship with the growth of larvae. They did not have an appropriate distribution of samples to look at variation in relation to salinity.

In a laboratory experiment, Wuenschel (2001, 2002) found a significant interactive effect of temperature and salinity (within the range found in Florida Bay) on routine metabolic rate of spotted seatrout. He found a bi-phasic metabolic rate that changed isometrically with body mass in early stages of larval growth, approximating the exponential relationship near unity proposed in previous studies, and changed allometrically thereafter. Response surfaces describing the effects of temperature and salinity on maximum consumption and growth rates were also developed from laboratory experiments (Wuenschel 2001, 2002).

The optimal salinity for spotted seatrout may differ by life stage and process. Schmidt et al. 2001, 2002) found a negative correlation of annual average spotted seatrout catch rates with indices of freshwater inputs to the Bay. Johnson et al. (2002a) found a low but significant negative correlation of spotted seatrout catch rates with Bay salinity, but thought it might be the spurious result of fish concentrating during hypersaline events in more limited favorable habitat with increased vulnerability to fishing. There is indirect evidence that hypersaline conditions reduce survival of spotted seatrout in the early-settlement stage. Although larval concentrations suggest that Central Florida Bay is a major spawning ground for spotted seatrout (Powell, in press), juvenile spotted seatrout appeared to extend their range into the central portion of the Bay when hypersaline conditions were absent (Thayer et al. 1999, Powell, pers. comm.), but this has to be tested more rigorously. Citing other published work, Powell (2002) noted that spotted seatrout eggs do not float at salinities <15‰, therefore egg survival might be virtually zero percent at 0-15‰. On the other hand, laboratory experiments of spotted seatrout in Texas suggest that the species does not spawn at salinity > 30‰ (Wakeman and Wolschlag 1977, Taniguchi 1980).

Figure 8.4: Survival of five sponge species at four salinities at winter water temperatures for four weeks (Butler et al. 2001).



Effect of Water Quality on Growth and Survival

Everglades National Park maintains a record of fish kills in Florida Bay (Schmidt 1993, Schmidt and Robblee 1994). These deaths are believed to occur due to low dissolved oxygen in the water column. The mass mortalities usually are reported in the Snake Bight area, where episodic low dissolved oxygen may be caused by a combination of extremely shallow water, high summer temperature, poor tidal and wind mixing, and high respiration rates. High ammonia levels recently reported by Boyer (pers. comm.) are another possible source of mortality.

Contaminants in Florida Bay biota have previously been investigated. Tissues of fish, macroinvertebrates, and birds were analyzed for concentrations of heavy metals, pesticides, and PCBs in fish, macroinvertebrates (Ogden et al. 1974). Concentrations of DDT, arsenic, and methylmercury in marine animals were high enough to warrant further investigation and led to later air quality studies in ENP. As part of a larger study of the possible effects of mosquito control in Monroe County, the Environmental Protection Agency (EPA 1980) examined fish and shellfish tissues and water for concentrations of certain pesticides, including Naled and Batex. They found negligible amounts in fish and shellfish; however oysters accumulated an average of 0.007 ppb of Naled. Batex was not found in detectable amounts. Results may have been biased on the low side by the dry season conditions that prevailed.

A multi-year study in the C-111 canal and associated sites in Florida Bay was undertaken in order to determine other potential contaminant risks that exist in South Florida (Scott *et al.*, 2002). According to extensive surface water data, as well as results from analyses of sediment, tissue, and semi-permeable membrane devices (SPMDs), canal contamination seems to be derived from the extensive agricultural production that drains into the C-111 canal. The results of this study indicate that runoff from agricultural fields led to quantifiable pesticide residues found in both canal and bay surface water, at levels that occasionally exceeded current water quality criteria. The major pesticide of concern was endosulfan, which was detected at 100% of the sites sampled. The decision to alter the C-111 canal flow and allow increased freshwater flow into the adjacent Everglades may result in discharges of pesticides through Everglades National Park and then into Florida Bay. Endosulfan concentrations are highest in the northeastern part of Florida Bay where the special sensitivity of pink shrimp could cause mortalities. Low pink shrimp densities in northeastern Florida Bay have been documented since at least the 1960s (Costello et al. 1986). Other factors (e.g., extreme and variable salinities, absence of broad banks, sparse seagrass coverage) may limit the presence of pink shrimp in the northeastern Bay, however no investigation of the possible effect of endosulfan on pink shrimp in the Bay has been made.

Health advisories are now posted in eastern Florida Bay warning of elevated levels of mercury in some higher trophic level fish. Thirty percent of spotted seatrout sampled from eastern Florida Bay exceed Florida no consumption advisory level of 1.5 :g g^{-1} (Evans and Crumley, in review). The jack crevalle contain comparably high mercury concentrations (Evans, pers. comm..). Other species of gamefish and forage fish, although not as high in mercury as these two species, nevertheless have concentrations several times those found in the western bay or elsewhere in Florida. These high concentrations may put humans, other mammals, birds, and reptiles at risk. Reduction in body burdens of mercury in top carnivores is one of the success criteria listed by the South Florida Ecosystem Restoration Task Force. Work is underway by Marnie Billie at FIU to assess the ecological risk of consumption of Florida Bay fish by piscivorous ospreys in the bay. Planned restoration activities in the Everglades will change freshwater deliveries to Florida Bay. These deliveries could alter the existing high levels of mercury in some Florida Bay gamefish through enhanced mercury fluxes as well as altered productivity and food web structure, which influence mercury bioaccumulation.

Effect of Benthic Habitat on Growth and Survival

This issue has generally been approached by relating benthic habitat to animal density, which implies survival and growth, rather than measuring habitat effects on growth and survival directly. The fact that faunal densities are correlated with certain benthic habitat suggests that growth and survival are highest in the appropriate habitat. See section on effect of benthic habitat on abundance.

Immigration, growth and survival of offshore-spawning fishes that use Florida Bay as a nursery.

In an effort to understand spatial and temporal patterns of variability in immigration, growth and survivorship of upper trophic level fishes Settle (in prep.) examined these life history attributes in several important species in the Bay. Juvenile great barracuda using the Bay as nursery habitat are the product of protracted spawning centered during the summer but with nearly 15% originating from late-fall and winter months. Spawning during these later periods has not been previously reported in South Florida and may suggest that either some spawning does occur in the region during those times or that some barracuda in the bay originate from elsewhere in the species distribution. The northwestern Caribbean is a possibility since it has been demonstrated that transport times from the vicinity of the Yucatan Channel to the Florida Keys are on the order of one month, which coincides with the age of the youngest barracuda in the bay. The youngest individuals are found in the Atlantic Transition, Gulf Transition and Western sub-regions suggesting ingress from both the Atlantic channels and the open Gulf of Mexico. Cohort-specific growth rates of young fish (age 30-150 d) ranged from 1.44 to 2.65 mm d^{-1} during the 1990's. Over the same period, growth was significantly slower in two faunally depauperate sub regions, the Eastern and the turbid Western bay. Relative condition of this species over the period 1973 to 2000 declined during the early to mid-1990's and appears to be returning to values observed during the 1970s and mid-1980s. The overall instantaneous natural mortality rate was 0.02656. Average survival was 97.38 % d^{-1}. Cohort-specific growth rates of juvenile lane snapper (age 30-242 d), which primarily inhabit the Gulf Transition and Western sub-regions, showed significant intra- and inter-annual variation. Growth rates ranged from 0.59 to 0.93 mm d^{-1}. Snappers spawned during the spring and summer grew faster than those spawned during fall and winter and fish spawned during 1998 grew faster than those spawned in 1997. Instantaneous natural mortality both years was 0.03636 and average survival was 96.43 % d^{-1}.

Effect of Ecosystem Characteristics on Species Distribution and Community and Trophic Structure

Work on this topic addresses the major question: Do HTL community composition or trophic structure in Florida Bay vary in time and space, what factors are responsible for this variation, and what processes are affected? Major working hypotheses are as follows:

(1) The abundance of HTLs is low in the northeast portion of Florida Bay because of high amplitude variation in salinity, low density of seagrass, lack of extensive banks, restrictions on the immigration of postlarvae, or a combination of all of these factors;
(2) Changes in community composition are related to changes in salinity, which can be influenced by water management, although the effect of benthic habitat, tidal exposure, rainfall, and oceanographic events may need to be filtered out to see these effects;
(3) Changes have occurred in the species composition of mollusks, foraminifera, and other sessile species in Florida Bay, and these changes reflect changes in salinity, water quality, and the cover and composition of benthic vegetation;
(4) Spatial and temporal patterns in trophic pathways vary depending on salinity, water quality and abundance and type of benthic vegetation;
(5) Widespread sponge mortalities may affect both hard-bottom and seagrass communities;
(6) Fishing reduces the number and size of some apex predators, causing shifts in community structure; and
(7) Changes in community composition are related directly to changes in benthic habitat.

Effect of Salinity on Species Abundance and Community Structure

Several studies suggest that hypersalinity affects the benthic fauna of Florida Bay. Schmidt (1977) reported lower forage fish diversity, biomass, and numbers in northcentral Florida Bay in salinities greater than 45 ‰. Johnson et al. (2002) noted that “evenness” (an index of community structure) among 11 dominant species, as estimated from statistical model predictions, was lower in 1990, a year of extreme high salinity in the bay, than in 1995, a wet year. Lyons (1999) observed fewer species in the molluscan community in the hypersaline part of Florida Bay. A simulation model based on experimental data (Browder et al. 2002) predicted lower juvenile pink shrimp densities and fewer potential recruits to the Tortugas fisheries from the hypersaline central part of Florida Bay. Based on relative concentrations of smallest stage seatrout postlarvae, Powell (in press) determined that Central Florida Bay is a major spawning ground for spotted seatrout; however, there is evidence that at salinities >45‰, survival and growth of larval and juvenile spotted seatrout could be diminished (Wuenschel 2002). The frequency and duration of hypersaline events in the Central Bay might, therefore, affect survival and growth of young seatrout and, consequently, the abundance of this species. Powell (2002) noted that densities of the postlarvae of many species collected with an epibenthic sled were higher in the Central Bay, so many species may be disproportionately exposed to hypersaline conditions in an otherwise favorable nursery area. Previously, Sogard et al. (1989) found lower species richness of both epibenthic and water column fishes, and Holmquist et al. (1989) found a lower species richness of macroinvertebrates in the Central Bay, characterized by a low tidal range and, during their studies, hypersaline conditions. They concluded that water circulation and salinity patterns were influential in structuring Florida Bay’s epibenthic faunal communities.

Historic Distributions as Indicators of Past Salinity Patterns

Historical records of salinity and bottom vegetation were reconstructed based on molluscan assemblages in shallow sediment cores. An analysis by Brewster-Wingard et al. (2001) suggests that molluscan assemblages in Florida Bay have undergone distinctive changes over the last 100-200 years. *Brachidontes exustus*, a euryhaline species tolerant of diminished water quality and a wide range of salinities, comprises >80% of the molluscan fauna in the upper portions of six cores. Four cores from central and eastern Florida Bay and one from Featherbed Bank in

Biscayne Bay suggest decreases in molluscan faunal diversity and absolute abundance perhaps starting in the 1960's or earlier and reaching a low in the early 1970's (Fig. 8.5).

The dominance of *Brachidontes* and the decreases in faunal richness and abundance are indicative of a system under stress. Interestingly, the transition zone cores from the mouth of Taylor Creek and in Manatee Bay do not show the decline in faunal diversity and absolute abundance exhibited in the other cores. Based on their analysis of molluscan epiphytic species within the cores, Brewster-Wingard et al. (2001) concluded that common factors are affecting the faunas and their associated bottom vegetation across eastern and central Florida Bay, despite the isolation of some of the basins.

Effect of Water Quality on Species Abundance and Community Structure

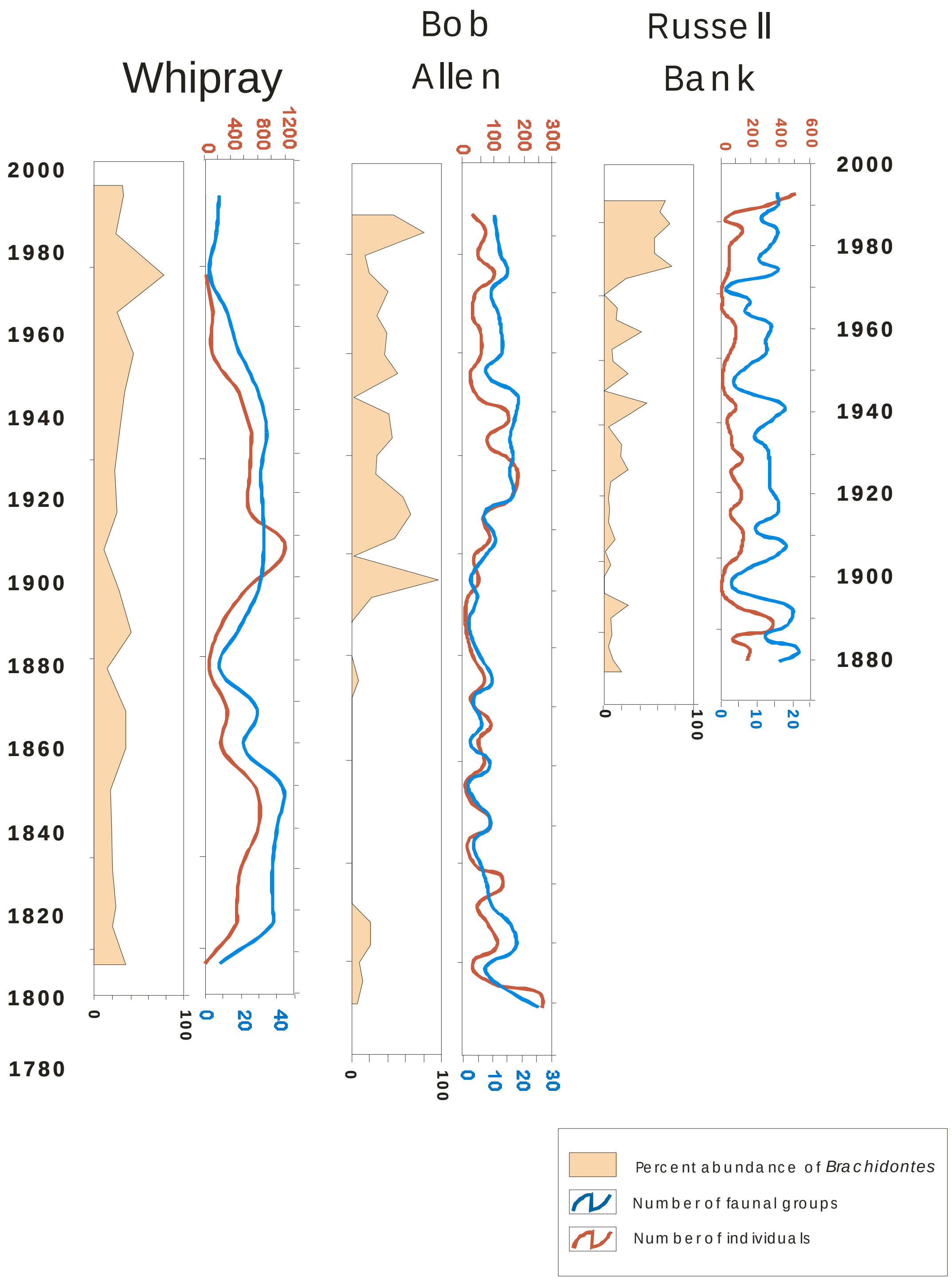
Ortner et al. (2002), who examined possible relationships among chlorophyll, zooplankton, and anchovy from January 1994 through January 1999, found no evidence that phytoplankton blooms were causing a fundamental shift in community structure and trophic dynamics in Florida Bay. Copepod concentrations were not related to chlorophyll concentrations, and anchovy density was not related to copepod concentrations. On the other hand, Johnson et al. (2002a) found a significant relationship between bay anchovy density and chlorophyll a concentrations. Intermittent high anchovy densities might be due to the attraction of anchovies to unvegetated bottoms and high turbidity (Patillo et al. 1997). Peebles' (2002) study of bay anchovy egg densities in the Manatee River suggests that structured, spatially and temporally intensive sampling of bay anchovy eggs may reveal relationships with prey abundance, salinity fronts, and freshwater inflow not obvious from previous sampling in Florida Bay.

Effect of Benthic Habitat on Species Abundance and Community Structure

Fish distributions patterns in mangrove prop-root habitat

Dennis and Sulak (2001) found that prop root sites in northeastern Florida Bay had significantly more fish larvae than nearby open water sites or near shore areas without mangroves; however the density of both forage fish and juvenile predator fishes was low in mangrove prop root habitat of Little Madeira Bay, Trout Cove, and Manatee Bay in comparison to that in the Bahamas and Puerto Rico. They proposed that isolation from offshore sources of larvae or juveniles was the reason for the low densities. In support of this conclusion, they found that the concentration of larval fish was much greater on the leeward side of Key Largo than at their northeastern Florida Bay mangrove prop root sites. Fish density and biomass were greater in mangrove prop root habitat than in adjacent fringing seagrass areas in a previous study by Thayer et al. (1987), who determined that mangrove prop root habitat in Florida Bay and nearby areas was occupied by a distinct faunal assemblage.

Figure 8.5: Historical view of the dominance of a molluscan water quality indicator in the molluscan fauna (Brewster-Wingard et al. 2001) at three Florida Bay locations. Brachidontes tolerates conditions that exclude other mollusks. Experiments are underway to better define the conditions tolerated by *Brachidontes*.



Canopy-dwelling fish and macroinvertebrate assemblages in relation to seagrass

Densities of many macroinvertebrate and fish species in Florida Bay are higher inside seagrass beds than outside them (Sogard et al. 1989, Holmquist et al. 1989, Thayer and Chester 1989, Thayer et al. 1999, and Matheson et al. 2001). Johnson et al. (2002a) analyzed the combined data of six field studies (including those cited above) and quantified the relationship between animal density and seagrass density for 11 key forage species (Fig. 8.4). They found that, of the 10 species whose densities were significantly related to seagrass, five were densest in dense seagrass, four were densest in moderately dense seagrass, and one was densest in sparse seagrass. Bottom/seagrass type was a significant explaining variable for 10 forage species. Three species were densest in *Syringodium*, three were densest in *Halodule*, two were densest in mixed grasses with *Syringodium*, and one was densest in mixed grasses with *Thalassia*. One, bay anchovy, was densest in areas without seagrass.

Shifts Between Benthic and Pelagic Zooplanktivores

A prevailing hypothesis has been that the seagrass die-offs and phytoplankton blooms experienced beginning in the late 1980s provoked a trophic shift in western Florida Bay from a system based primarily on benthic production to one based primarily on water column production. This hypothesis grew out of comparisons of fish and macroinvertebrate community composition in 1984-1985 to that in 1994-1995. Thayer et al. (1999) compared fish assemblages of 1984-1985 to those of 1994-1995 in three regions of the Bay and found that canopy dwelling species had declined and pelagic zooplanktovores dominated the fauna. Robblee et al. (2001) compared benthic vegetation and fish and macroinvertebrates in Johnson Key Basin in 1985 and 1995. They found a decrease in *Thalassia* and *Syringodium* and an increase in *Halodule* and bare bottom. They found a decrease in *Farfantepenaeus duorarum* (pink shrimp), seagrass-associated caridean shrimps (-65%), and seagrass-associated fishes (-81%) and concluded that the decline in seagrass-associated species was a result of seagrass die-off.

The hypothesis of a trophic shift associated with loss of seagrass lost credence with sampling results beyond 1995. The juvenile and small resident fish assemblage in collections of Powell et al. (2001) from 1996-2000 (especially 1998) differed markedly from that in 1994-1995 and resembled the assemblage observed in 1984-1985. The change from canopy-dwelling to pelagic zooplanktivores from 1984-1985 to 1994-1995 was followed by a change back to canopy dwellers in 1998-1999. The investigators concluded that the recovery of an assemblage of fish species dominated by seagrass canopy dwellers cannot be wholly explained by recovery of seagrasses because there is no evidence of seagrass recovery on a subdivision wide basis in 1999-2000 relative to 1994-1995. In fact, seagrass densities in 1999-2000 were much lower than in 1984-1985 (Powell et al. 2001).

Ortner et al. (2001) also refuted the hypothesis of a trophic shift related to loss of seagrass coverage and an increase in phytoplankton blooms. They concluded that the recent history (1994-2000) of phytoplankton, zooplankton, and planktivorous fish abundance provides little or no support for the concept of a fundamental persistent shift from a demersal benthic based food web to a pelagic water-column based food web. Furthermore, there seems to be no clear relationship between plankton bloom incidence or intensity and the abundance of zooplankton herbivores. Neither is there a relationship between the abundance of the bay anchovy and its preferred copepod prey.

An alternative hypothesis for the observed fluctuation in dominance between demersal and water column species might be that the density of the small juvenile and small resident canopy-dwelling fish assemblage is influenced by the sporadic dominance of pelagic zoolplanktivorous clupeiforms that might be related to water column chlorophyll a concentrations (Powell et al. 2001).

Another alternative hypothesis is that the establishment of a more heterogeneous bottom habitat, occupied by *Halodule* and *Syringodium* as well as some *Thalassia*, might be responsible for the recovery of canopy associated species after 1995 (Robblee, pers. comm.) An exploratory Principal Component analysis revealed four PCs, each of which could be interpreted to relate to a vegetation component, *Thalassia* (PC1), *Halodule* (PC2), *Syringodium* (PC3), and macroalgae (PC4) (Robblee et al. 2001). Pink shrimp correlated with PC2 and PC3. The rainwater killifish was correlated with PC1. Affinities of various species to certain types of seagrass habitat might lead to greater overall abundance with increased seagrass habitat diversity. This is supported by the work of Johnson et al. (2002a), who found that densities of various species varied by seagrass type, and no species was found at highest density in pure *Thalassia* beds. This result is especially valuable because Somerfield et al. (2002) concluded that even large faunal effects of seagrass habitat heterogeneity might be difficult to detect. This hypothesis might explain the recovery of canopy-dwelling species after 1995 but not the fluctuations in bay anchovy density.

Peeble's (2002) study of bay anchovy egg abundance in the Manatee River provides insight on the bay anchovy fluctuations in Florida Bay. Using a spatially and temporally intense sampling strategy, Peebles' (2002) found that nighttime bay anchovy egg abundance in Manatee Bay was positively related to *Acartia tonsa* abundance the previous day. Bay anchovy appeared to spawn immediately upstream from salinity fronts (which he defined as a change of 1‰/km) that concentrated their prey. The effect of freshwater inflow on bay anchovy egg abundance was non-linear. Peak abundance occurred when salinity fronts formed near the river mouth. Egg abundance declined when these fronts advanced seaward of the river mouth, but was lowest when fronts were weak or absent during low-flow periods. The presence of a salinity front was associated with relatively low mean salinity and high standard deviation in salinity. In their analysis of a combined data set from several studies, Johnson et al. (2002a) found a significant relationship of bay anchovy density with salinity (negative relationship), standard deviation in salinity (positive relationship), and a freshwater inflow index (positive relationship) in Florida Bay. Peeble's (2002) study might explain the mechanisms behind these relationships.

Effects of Macroalgae on Animal Abundance

The pattern of settlement of spiny lobster postlarvae in southwestern Florida Bay may be highly dependent on the location of red macroalgae (*Laurencia*), crevice shelters, and planktonic postlarval abundance (Herrnkind and Butler 1994). Mud banks that restrict transport, inappropriate salinity, and scarcity of hard-bottom settlement habitat may severely restrict the presence of spiny lobster in the interior Bay (Field and Butler 1994).

Effect of Sponges on Juvenile Spiny Lobster

Butler et al. (1995) documented widespread sponge mortality coinciding with months long, extensive cyanobacteria blooms in the south-central part of Florida Bay in the early 1990s (1991, 1992, 1994). They showed with field experiments that the loss of sponges affected the distribution of spiny lobster juveniles, which use crevices beneath sponges as nursery habitat. Use of artificial shelters increased following the sponge decline. Juvenile spiny lobster abundance declined 23% at sites without artificial substrates and increased 76% at sites with artificial substrates. The long-term effect of sponge mortality on lobster abundance is not known, but shelter such as that provided by sponges reduces the risk of predation (Herrnkind and Butler 1994). Based on their results, the authors suggested that loss of shelter might lead to increased predation on animals that remain in areas without shelter or are in search of shelter. Loss of area with shelter may cause crowding and resource limitation in areas of remaining shelter (Butler et al. 1995). Other animals that use sponge habitat include stone crabs (*Menippe mercenaria*), spider crabs (*Mithrax* spp.), toadfish (*Opsanus beta*), octopus and (*Octopus* spp.).

Spatial Variability in Trophic Relationships

The relative importance of seagrass and phytoplankton in food webs differs across the Bay, and neither is important in certain parts of the Bay. Chanton et al.'s (2001) evaluation of stable carbon, nitrogen and sulfur ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$) data for producers and consumers in Florida Bay indicates that the interior of the Bay has a strongly seagrass-based trophic structure, whereas the Gulf (outer or western) sites in the Bay shift toward a more plankton-dominated trophic system (Figure 8.6). It is not yet certain whether the shift in Figure 8.6 reflects natural spatial variation or a temporal trend forced by changing environmental conditions in the Bay. Stable carbon, nitrogen, and sulfur data in Figure 8.7 from Evans and Crumley (in review) confirm Chanton et al.'s (2001) description of the trophic structure of the interior and western Bay. In addition, the Evans and Crumley (in review) data suggest a non-seagrass-based diet (likely a more pelagic, or water-column, based food web) in the eastern Bay.

Predominant food webs in the hard-bottom communities of Florida Bay (mainly the southwestern Bay) and bayside hard-bottom communities in the Florida Keys are based on macroalgae rather than seagrass, according to stable-isotope analyses (C, N, and S) conducted by Butler et al. (2001). They sampled macroalgae, seagrass, suspended POM, sediment POM, sponges gastropods, holothuroidians, bivalves, and spiny lobster. With the exception of suspension feeders, the hard-bottom animals were trophically independent of seagrass.

Koening et al. (2001) found spatial, temporal, and ontogenetic dietary shifts in the major prey of red drum. They speculated that the differences were due to differences in prey availability. This is consistent with observations about the abundance of various prey, which differs by region. They were not able to detect spatial or seasonal differences in the diet of snook, possibly because of the lower resolution of the snook diet data.

Figure 8.6: Consumer sulfur and carbon stable isotopic composition (Chanton et. al 2001). A shift from benthic (lower right) to water-column (upper left) production is reflected in enrichment in d^{34}S and depletion of d^{13}C. Florida Bay samples grade from a more benthic signal (similar to Biscayne Bay control site) for interior sites to a more planktonic signal for western Gulf sites.

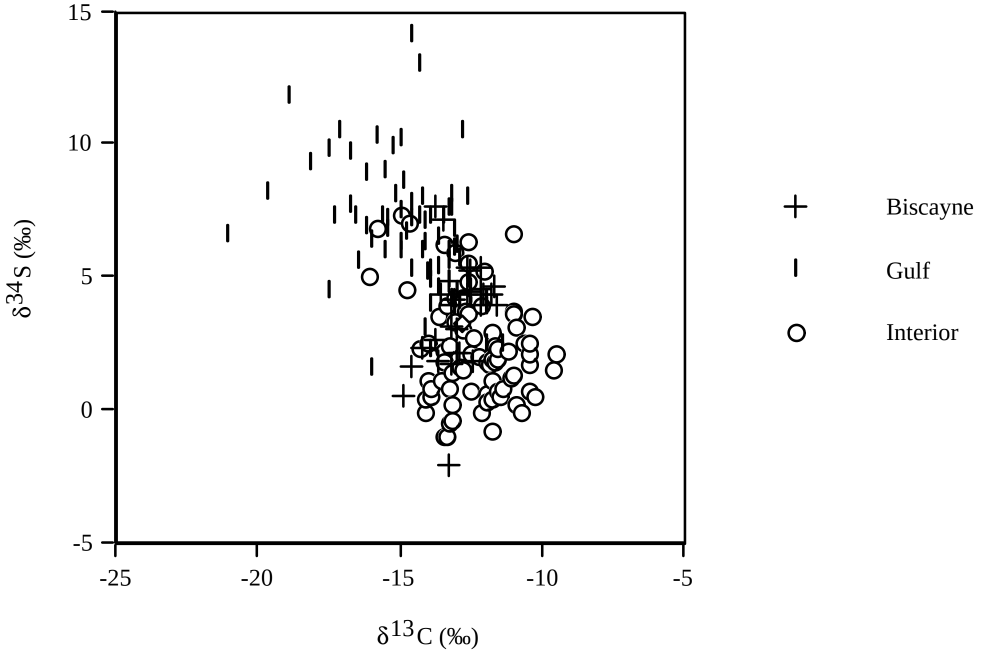
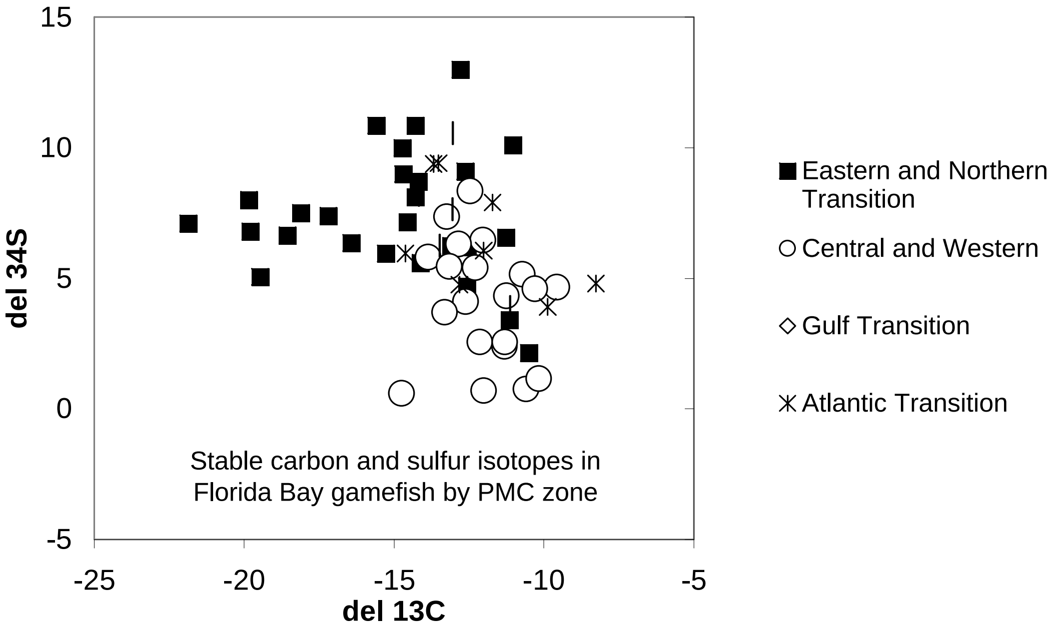


Figure 8.7: Stable isotope analysis of Florida Bay gamefish to support methylmercury studies in Florida Bay (Evans et al.) The analysis complements the view of the Bay in the previous figure by adding information on the Bay's eastern and northern Transition Zones.



Variation in Ecosystem Characteristics

Effects of Animals on the Ecosystem

Specific questions being addressed by this research are as follows: (1) how do animals affect their ecosystem, and what are the consequences of change in animal abundance or distribution for the rest of the system? (2) What is the ecological role of sponges in the ecosystem, and what does the loss of sponges in southwestern Florida Bay and an increasing fishery for some sponge species portend? The principal hypothesis is that water filtering by sponges removes phytoplankton from the water column, moderating algal blooms and improving water clarity. At exceptionally high concentrations, certain animals (e.g., the sea urchin, *Lytechinus variegatus*) can sometimes have negative impacts on seagrass ecosystems.

Effects of Animals on Benthic Habitat

Benthic grazing animals in exceptionally high densities can negatively impact benthic vegetation in Florida Bay. A dense aggregation of the variegated sea urchin (*Lytechinus variegatus*) caused severe localized defoliation of a seagrass bed in outer Florida Bay during 1997-98 (Rose et al. 1999). The population dynamics of this aggregation has been described, and the short-term effect of this aggregation on the benthic community has been assessed (Macia & Lirman 1999; Rose et al. 1999). Subsequent monitoring of the aggregation during 1998-99 revealed that urchin densities progressively declined, as did their impact on seagrass biomass. However, as of 2002, seagrass biomass in the area of the meadow that underwent the most severe defoliation remained drastically reduced compared to areas that had not been damaged by urchins (W. Sharp, pers. comm..).

Role of Sponges in Regulating Water Quality

The working hypothesis is that the large-scale loss of suspension feeding sponges may have rendered the Florida Bay ecosystem susceptible to recurring phytoplankton blooms (Peterson and Fourqurean 2001). Sponges are capable of filtering large volumes of water in their feeding. Widespread sponge mortalities occurred in Florida Bay from 1992 to 1994. By 1995, total sponge biomass was a fraction of its former level. There had been a 70% decline in the Long Key area and an 84.6% decline in the Marathon area (Stevely and Sweat 2001). Loss of sponge biomass in Florida Bay may be having major ecological impacts on water quality (Stevely and Sweat 2001; Peterson and Fourqurean 2001)

Sponges are a particularly dominant structural feature of Florida Bay seagrass and hard-bottom habitats, functioning as efficient filters of small (< 5 µm) planktonic particles. Previous studies have illustrated that the grazing pressure of filter feeding bivalves may control phytoplankton abundance. If the presence of sponges increases light availability to the benthic plant communities, then sponges may reduce the shading effects of phytoplankton blooms, and the loss of this organism in Florida Bay may have cascading effects on the associated seagrass community (Peterson and Fourqurean 2001).

Since the initial seagrass die-off in the late 1980s, blooms have swept over extensive portions of the Bay north of the middle Keys and have persisted for months. The proliferation of the cyanobacterium *Synechococcus* and diatom *Rhizosolenia* blooms has caused widespread concern among scientists and water managers. These blooms have the potential for disrupting the ecology of the Bay through associated anoxia, toxin production, and the reduction of light availability for benthic plant communities. Some regions of Florida Bay exhibit high levels of algal and/or non-algal suspended solids resulting in low light penetration. While phytoplankton blooms were not likely the cause of the initial seagrass die-off, the reduction in light availability caused by high phytoplankton standing crops may have contributed to poor seagrass recovery and more recent seagrass die-offs.

Prior to the widespread sponge mortalities that occurred from 1992 to 1994, Stevely and Sweat (2001) collected data on the abundance of commercial sponges (*Spongia* and *Hippospongia*) and the entire sponge community at 15 locations in the Middle and Upper Keys (four locations were within Everglades National Park). They have been evaluating the recovery of the sponge community annually since 1994, and have identified to family, genus, or species level approximately 95% of the sponges counted. In general, recovery of the largest and most abundant sponge species (in the genera *Spheciospongia*, *Ircinia*) has been extremely slow. The first significant indication of recovery of these species was found at Marathon in 1999 and 2000, but was still not apparent at Long Key by April of 2001. These species represented 70% of the sponge community biomass prior to the mortalities.

Based on their data prior to the 1992-1994 mortalities, Stevely and Sweat (2001) estimate that the mean sponge numerical abundance was 0.725 sponges/m^2 and mean sponge biomass volume was 364ml/m^2. Based on a sponge pumping rate of 10,000 x sponge volume per day (Reiswig, pers. com; Reiswig, 1974), the sponge biomass could therefore pump 3,640 liters of seawater per square meter per day. Since the water column in the study area was approximately three meters deep, sponge biomass could be expected to pump the equivalent of the entire water column in 24 hours (Stevely and Sweat 2001). The loss of 75% of sponge biomass might be expected to lengthen the time required to pump the water column from 1 day to 4 days.

Peterson and Fourqurean (2001) speculate that system-wide trophic dysfunction caused by the sponge die-off has potentially contributed to the magnitude of the nuisance phytoplankton blooms, and that the loss of these organisms can explain why this system remains susceptible to recurrent blooms of phytoplankton and cyanobacteria.

Oceanographic Effects on Larval Transport and Recruitment

Major questions related to this topic are (1) what processes are involved in the transport of pre-settlement stages of fish and invertebrates to the boundaries of Florida Bay, and what are their schedules? and (2) What pathways do early life stages of offshore spawned HTLs use to enter Florida Bay, what is the relative importance and extent of penetration into the Bay’s interior by these pathways, and what factors influence transport and settlement?

Many species associated with the reef tract and the southwest Florida shelf spend some part of their life cycle in Florida Bay. For example, Florida Bay is a major nursery ground for pink shrimp that are harvested in waters off the Dry Tortugas, the most economically important pink shrimp fishing ground in the State. Florida Bay also contains important spiny lobster nursery habitat, and Everglades National Park is a fishing-free sanctuary for spiny lobster. Water flows and animal movements connect Florida Bay not only to the upstream Everglades and coastal mangrove areas but also to the Florida Keys, the Reef Tract, the southwest Florida shelf, and the

Dry Tortugas. Many higher trophic level species range between the Bay and coastal reefs within their life cycle. The development of scientific knowledge about HTLs of the Bay, therefore, must extend beyond Florida Bay to address the greater ecosystem that supports these species and the processes that affect their movements. These include the Loop Current/Florida Current and countercurrents, the Tortugas Gyre, and coastal eddies. The effect of these processes on larval transport and the distribution and abundance of HTLs in the Bay must be addressed to improve the ability to distinguish effects of changes in freshwater inflow.

Florida Bay lies between the Atlantic Ocean and the Gulf of Mexico and is connected to both of these bodies through regional-scale circulation and exchange processes and the oceanic boundary currents that influence these processes. The southwest Florida Shelf to the west and the Keys coastal zone to the east and south of Florida Bay interact with each other and the Bay through the tidal channels between the Keys and also by means of their boundary currents (Herrnkind and Butler 1994, Lee et al. 2000). A dominant process potentially affecting water transport and the transport of eggs and larvae to Florida Bay is the strong coherent response to alongshore wind forcing, coupled with seasonal stratification in response to variation in wind-mixing, air-sea exchange, and river runoff along the near shore western shelf. Boundary current dynamics and eddy processes are also critical larval transport mechanisms that operate both on the regional and local scales. Transport response to prevailing easterly winds may vary along the Florida Keys as a result of the curvature of the coastline (Lee et al. 2000), Easterly winds are expected to favor onshore larval transport between the Lower Keys and the Dry Tortugas where the coastline is east-west oriented. Onshore convergence of the Florida Current can also facilitate transport into the coastal zone of the Keys, and this occurs mainly in the upper Keys where the shelf narrows and curves northwards (Yeung and Lee 2002).

The area of the Dry Tortugas is an important spawning site for penaeid shrimps, spiny lobsters, and some species of snappers and groupers (Limouzy-Paris et al. 1997). The Tortugas gyre provides a retention mechanism for periods of weeks to up to 3 months. Pink shrimp larvae were retained by the Tortugas gyre circulation for a period of 2 weeks (Criales and Lee 1995). Coastal eddies originating from the Dry Tortugas and propagating downstream may be a mechanism to deliver pre-settlement stages from spawning site to nursery sites on the reef tract and in Florida Bay (Yeung et al. 2001). The lower southwest shelf in the vicinity of the Dry Tortugas is a potential source of recruitment to the Florida Keys Reef Tract and Florida Bay for both reef fish and pink shrimp.

Frontal eddies of the Loop Current in the Gulf of Mexico that propagate southward along the outer edge of the western shelf may be trapped and develop into persistent gyres off the Dry Tortugas (Fratantoni et al. 1998) (see Yeung and Lee [2002] for other references). The subsequent arrival of another frontal eddy or the abrupt retreat of the Loop Current may dislodge the gyre, which then moves eastward along the southeastern shelf off the Florida Keys in the form of a transient coastal eddy. The Tortugas gyre provides a retention mechanism for periods of weeks to up to 3 months.

Eddies and Gyres

Working hypotheses relative to transport to the boundaries of the Bay are as follows: (1) Transport and detrainment of pre-settlement stages into the coastal zone of the Florida Keys are caused by coastal eddies; (2) Spawning and nursery sites for pink shrimp, spiny lobsters, and some snappers are linked through the evolution of the coastal eddies from the Tortugas gyre; (3) The formation of the Tortugas gyre is enhanced by a well-developed Loop Current (high latitudinal intrusion) whose dynamics may be modulated by climatic shift; (4) Snapper larvae entering Florida Bay originate from spawning stocks that form seasonal aggregations off the Dry Tortugas; (5) Year class strength of six snapper species is enhanced by increased larval retention and nutrient-enrichment of the pelagic larval habitat via gyre-induced upwelling during spawning season off the Dry Tortugas (Yeung and Lee 2002, Yeung et al. 2001, Criales and Lee 1995, Jones et al. 2001, Criales and McGowan 1994).

Supply of early-life-stage recruits is a major limiting factor of the year-class strength of aquatic species. Pre-settlement stages of the spiny lobster, snapper, and pink shrimp that utilize Florida Bay as juveniles and/or adults enter the Bay from the ocean through inter-island channels.

The eddy hypothesis of regional recruitment has important implications over larger temporal and spatial scales. Since coastal eddies originate from the Dry Tortugas, they may constitute the essential transport link between the spawning and nursery grounds. Moreover, eddy formation at the Dry Tortugas is associated with Loop Current frontal dynamics, which are in turn modulated by long-term climatic variability (Yeung et al. 2001; Yeung and Lee 2002).

Observed larval distribution patterns of some crustaceans in the Florida Keys coastal zone corroborate many of the predictions based on key coastal transport processes. Early-stage phyllosomata (<2-month old) were concentrated within or at the boundaries of a gyre, in the pattern hypothesized for passive drifters (Yeung and Lee 2002). The abundance of strong swimming spiny lobster postlarvae was not highly correlated with wind-driven currents that can affect the coastal transport of more passive drifters (Acosta and Butler 1997). High concentrations of pink shrimp larvae were found in the Tortugas Gyre in late spring-early summer (Criales and Lee 1995). High densities of larvae and postlarvae of 10 different shrimp families were found off Looe Key during the presence of a gyre (Criales and McGowan 1993, 1994).

Variability in the supply of larvae may be related to the development of mesoscale eddies and their associated countercurrents on the ocean-side of the channels. Peak influx of spiny lobster postlarvae into the Bay at the Middle Keys coincided with the presence of eddy and countercurrent conditions (Fig. 8.8 and 8.9) (Yeung et al. 2001; Yeung and Lee 2002).

Temporal and spatial variability in the supply of spiny lobster postlarvae to Florida Bay nursery grounds may interact with local nursery habitat structure to influence recruitment and year-class strength. Butler et al. (2001) used an individual-based model to address this question. They tested eight scenarios of variability describing postlarval supply (Uniform, Volumetric, Gradient, Broken Stick-Static, Broken Stick-Variable, Pulsed, Aggregated, and Random). Their results indicated that random variation in the arrival of postlarvae among regions of the Florida Keys leads to the highest recruitment, whereas persistently patchy settlement (i.e., pulsed and aggregated scenarios) yields the lowest. Analysis of field data suggested that the Random arrival was the most realistic scenario. Field data were based on artificial collectors positioned at eight sites in the Florida Keys.

Figure 8.8: Monthly mean influx density of spiny lobster postlarvae observed at Long Key and the predicted density ($density_{LK}$) using an index of countercurrent magnitude in a simple regression model ($r^2=0.50$, $F_{1,16} = 17.90$, $p<.0006$) (Yeung et al. 2001). The index is the average magnitude of the countercurrent component for the period two-week prior and three days during sampling, taken at a current meter moored at Tennessee Reef in the Middle Keys. Satellite imagery confirmed that in most cases enhanced coastal countercurrents coincided with the presence of a cyclonic mesoscale eddy in the vicinity.

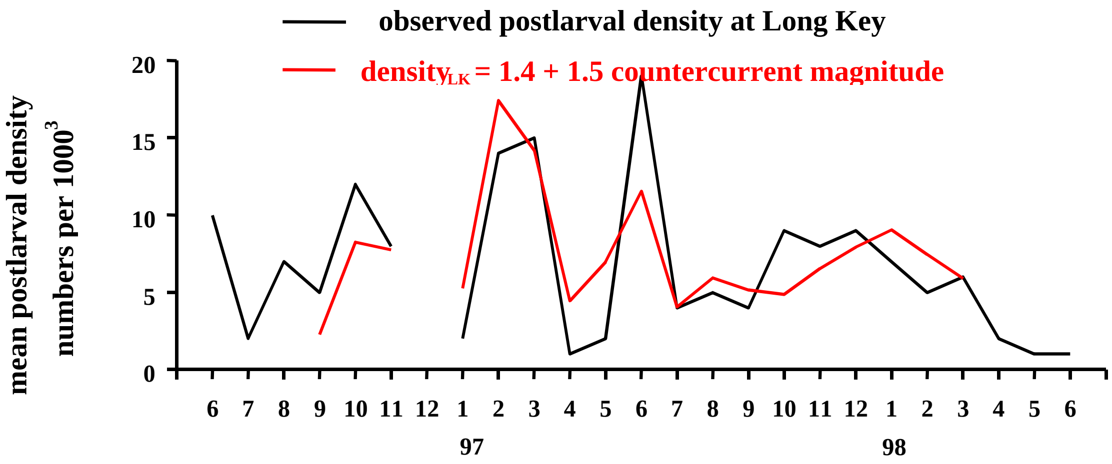
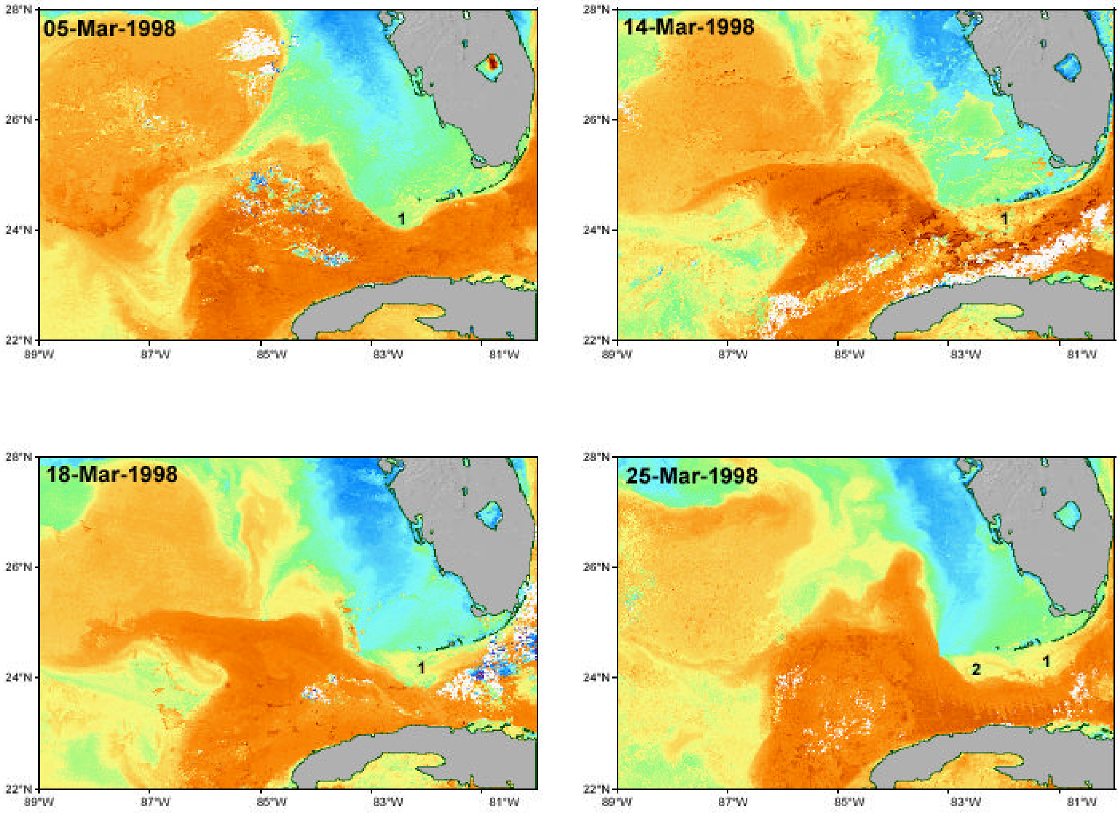


Figure 8.9: Example of a sequence of satellite SST images used to infer gyre displacement and progression down the Straits of Florida (Yeung et al.2001). Warmer waters are red, cooler waters are blue. The centers of each of two gyres present during this period (1 and 2) are indicated. On March 5 a gyre (1) was centered off the Dry Tortugas, by March 14 it began moving downstream, and by March 25 the upstream frontal eddy (2) responsible for its displacement is clearly evident.



Eddy transport processes may also affect supply and nutritional condition of pink shrimp and snapper pre-settlement stages entering Florida Bay through the Florida Keys. .Influx of early-life-stage recruits was monitored monthly on the new moon for 2 years at two tidal channels on opposite ends of the Middle Keys, Whale Harbor (east end), and Long Key Channel (west end). Back-counted birth dates based on daily otolith increment counts suggested that snapper larval duration during the first year varied across species and ranged from 35.50 to 41.45 days (Jones et al. 2001). Preliminary analyses of Year-2 samples suggested that larval durations differed from those of Year 1. Peak abundance of snapper larvae in the channels occurred in the summer of 1997 and was coincident with a well-developed Loop Current (high latitudinal extent) favoring gyre formation off the Dry Tortugas, where snapper spawning aggregations occur. Criales et al. (2001) showed that the temporal pattern of immigration of postlarval pink shrimp differed substantially between Long Key Channel and Whale Harbor Channel (Fig. 8.10). The influx of postlarvae at Long Key was lower in magnitude but steadier than at Whale Harbor. Long Key showed the highest postlarval influx in late spring-summer while the postlarval influx through Whale Harbor (downstream from Long Key in terms of the Gulf Stream and associated shelf gyre processes) showed both spring-summer and winter peak. The winter peaks may be associated with the countercurrent generated by eddies (Fig. 8.10). This high variability over small spatial scales suggests the influence of mesoscale processes.

Movement into and within Florida Bay

Other working hypotheses that relate primarily to movement of postlarvae into the Bay are as follows: (1) Pink shrimp postlarvae enter Florida Bay from two directions--west (across the southwest shelf) and southeast (through the Lower Keys)--whose pathways vary in importance and are affected differently by physical oceanographic factors and tides; (2) Sufficient pink shrimp larvae enter the Bay’s interior for the interior Bay to be a significant nursery ground and source of recruits to the fishery during years of favorable conditions; (3) Snappers settle outside Florida Bay but near the boundary and enter Florida Bay as juveniles; and (4) The abundance of Bay-dependent species that are spawned offshore is lower in northeastern Florida Bay because of weak transport across the Bay.

Transport across the Lower and Middle Keys has previously been the most recognized pathway of larval transport to Florida Bay because of studies (Criales and McGowan 1994; Yeung 2001) that showed the that local winds, Florida Current flow, and coastal eddies interact to influence the onshore transport and recirculation of larvae in the Florida Keys. Now new work, based on synchronized sampling of postlarvae on both sides of Florida Bay, indicates that the dominant pathway of influx of postlarval pink shrimp into Florida Bay is from the west (Browder et al. 2002). Peak concentrations of pink shrimp postlarvae in water moving into the Bay from the west (through Sandy Key and Middle Ground Channels) were substantially larger than in water moving into the Bay from the southeast (Whale Harbor Channel). The temporal pattern from the west consisted of one large, sustained summer peak (Fig. 8.11). In contrast, peak concentrations at Whale Harbor were observed in February, May, and July and were smaller (Fig. 8.11). Prior studies examined the influx of pink shrimp postlarvae from the southeast (Allen et al. 1980) and west (Tabb et al. 1962; Yokel 1969, Robblee et al. 1991), however these studies were not designed to make comparisons.

Figure 8.10: Mean monthly postlarval influx has different temporal patterns in channels of the Middle Florida Keys (Criales et al. 2003). At Long Key Channel (the two upper graphs), larval concentrations are associated with surface temperature and the offshore wind stress (+Ji) that usually enhances countercurrent transport. At Whale Harbor Channel, larval concentrations were associated with the coastal countercurrent flow (-<).

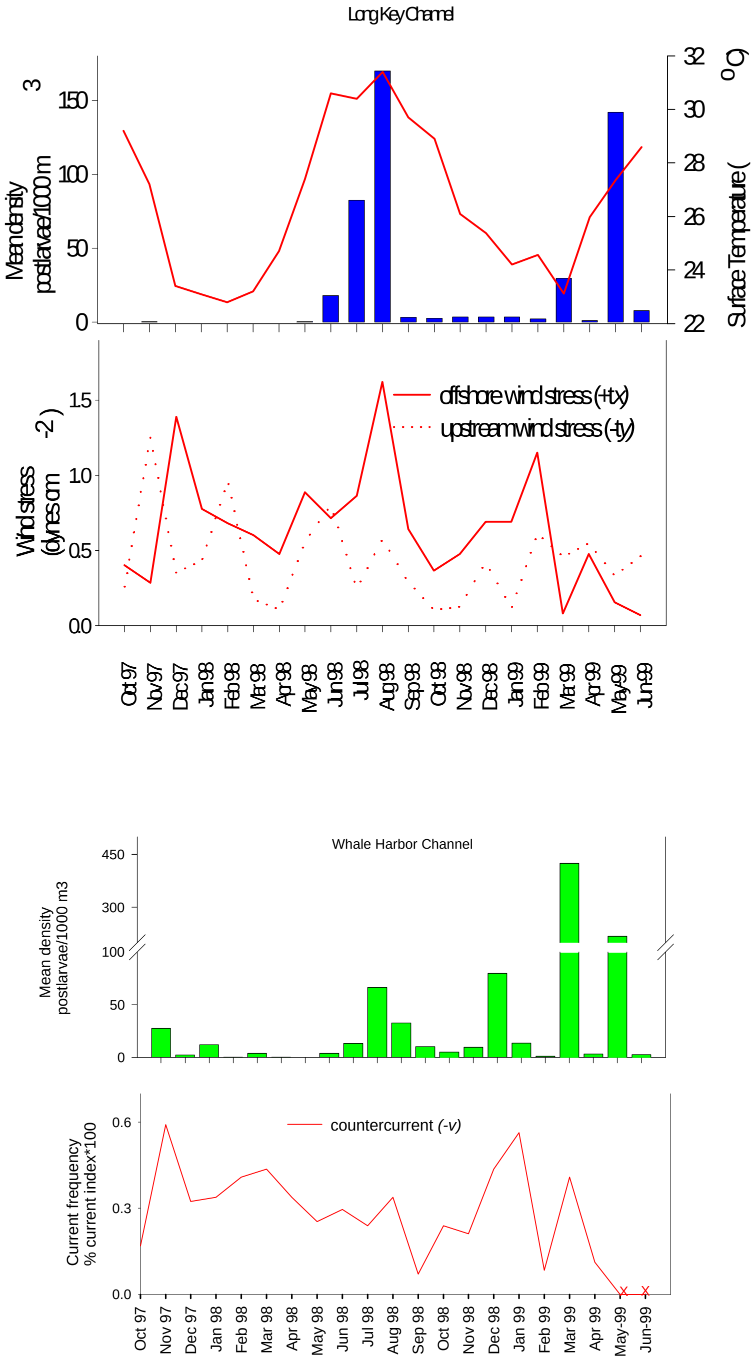
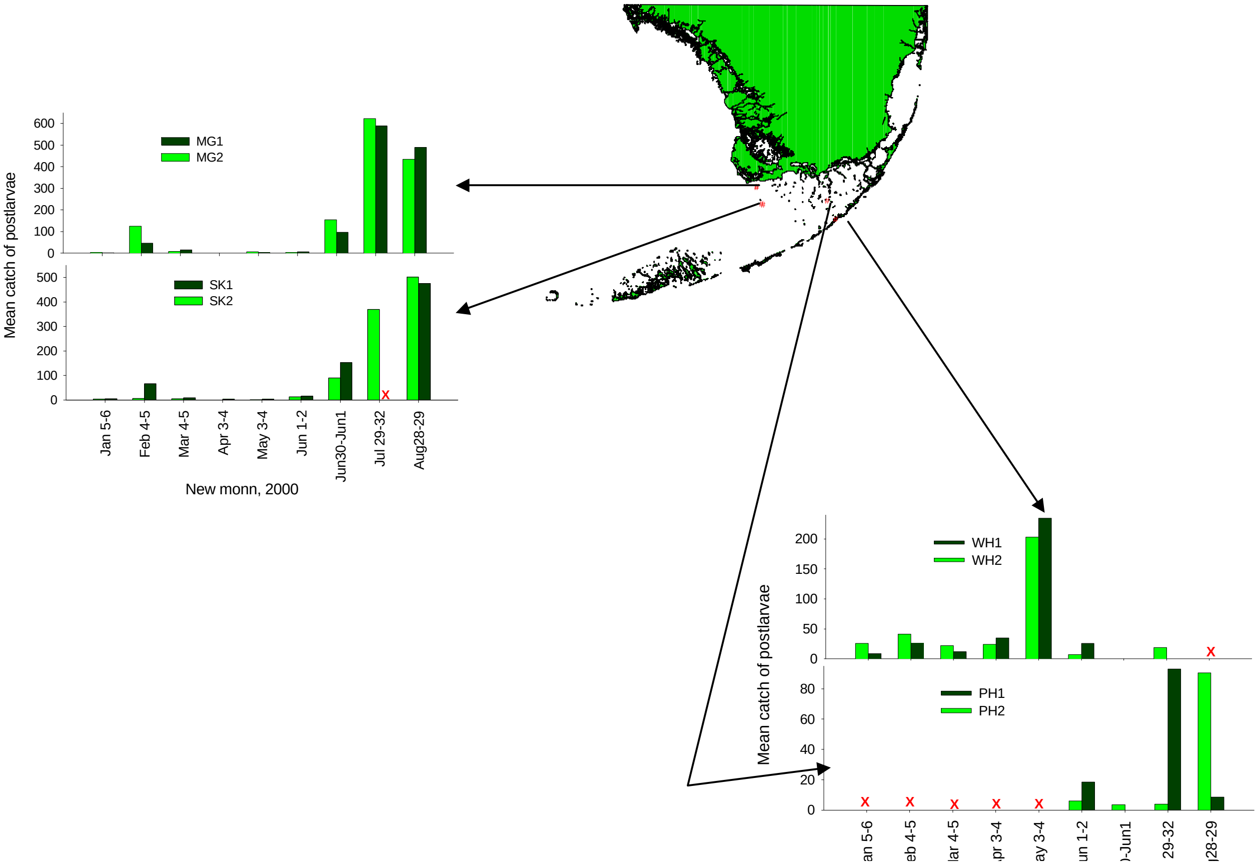


Figure 8.11: The temporal pattern of monthly pink shrimp postlarval influx on the western side of the Bay (upper graphs) differs from that at Whale Harbor (lower graphs) during the same period, but is similar to that at Long Key Channel the two previous years (Figure 10, upper graphs (Criales et al. 2003).



Pink shrimp nursery grounds are on the western side of the Bay (Robblee et al. 1991), not in the east (Costello et al. (1986). The larvae spawned north of the Dry Tortugas on the relatively shallow shelf may escape from the strong flow of the Florida Current and move northeast toward the Bay with the winds and tidal currents.

Effect of Human Activities

This topic was approached by addressing three major questions:

(1) What are the potential effects of water management and other human activities on recruitment, growth, and survivorship of higher trophic level species?
(2) What is the potential effect of water management on bioaccumulation of mercury?
(3) How does fishing, both within the Bay and outside the Bay, affect fishery populations and our ability to detect effects of water management on recruitment, growth, and survival?

Some critical working hypotheses relative to these questions were as follows:

(1) The timing and amount of freshwater releases to coastal wetlands adjacent to Florida Bay affects the nesting success of wading birds in northeastern Florida Bay;
(2) Changes in water management that affect the spatial coverage, intensity, and duration of hypersalinity affect shrimp, lobster, and other species;
(3) Abrupt and out-of-season releases of large volumes of freshwater into Florida Bay and coastal waters negatively affect benthic fauna and fish, shrimp, and lobster recruitment;
(4) Increased freshwater inflow to northeastern Florida Bay will increase the load of mercury entering the Bay and the body burden of mercury in Bay HTLs;
(5) Fishing on the reef tract, in the Tortugas, and throughout the Bay affects the population structure and abundance of predator fish species in Florida Bay.

(Note: Investigation of hypotheses 2 and 3 is hindered by lack of quantitative information about the sensitivity of the salinity regime and water quality to changes in freshwater flow resulting from water management activities.)

Water Management/Wading Bird Nesting Success

Linkages of water management, fish production, and Roseate Spoonbill nesting success in wetlands adjacent to northern Florida Bay have been quantified in studies by Lorenz (2001a, 2001b). Other investigators have proposed that fish availability to wading birds during their nesting season in South Florida is influenced by two main factors: the extent to which water covers wetlands during the wet season and the consistency of the decrease in water depth and water coverage the following dry season. Lorenz (2001b) demonstrated the effectiveness of the process of expansion and contraction of water area in enhancing prey availability to wading birds in the coastal marshes immediately north of eastern Florida Bay. He determined that fish density during the wet season is positively related to water depth in the marsh and the length of time in which depths in the marsh are greater than 12.5 cm. He found that concentration in topographic lows occurs—and reaches roughly twice dry-down density—when water depths in the adjacent marsh decline below 12.5 cm. Roseate Spoonbills that nest on islands in northeastern Florida Bay feed in these coastal marshes during the nesting season, which coincides with the usual dry season. Lorenz (2001b) examined their nesting record in relation to water level data and determined that, in general, mean water levels at his fish sampling sites in the coastal marshes were lower than 12.5 cm during successful Roseate Spoonbill nesting periods and higher than 12.5 cm during failed nesting periods. Furthermore, prey availability at the sites during successful nesting periods was twice that during failed nesting periods. On the other hand, nesting failure occurred in several recent years that might have been expected to support successful nesting. This may be explained by out-of-season water releases from the nearby C-111 Canal. These releases have been shown to raise water levels in the coastal wetlands. Such releases during spoonbill nesting periods could cause prey to become dispersed and result in nesting failure.

The coastal marshes north of Florida Bay were primarily oligohaline prior to the extensive drainage and water diversion that occurred with water management (Egler 1952). Since the time that hydrologic modification was begun, mangroves have encroached inland and there are other indications that the coastal marshes have become more saline (Ross et al. 2000). Lorenz's (2001a) multi-year study of coastal fish populations demonstrated that fish densities were substantially greater and community composition in the coastal wetlands immediately north of northeastern Florida Bay resembled that of an oligohaline marsh in recent years of exceptionally high rainfall, when conditions approximated pre-drainage conditions. Fish densities were substantially greater in the years of oligohaline conditions. The Lorenz study demonstrated the magnitude of loss of coastal wetland fish production and support for nesting wading birds caused by current management practices. This study demonstrated the potential to regain wetland productivity with restoration of more natural hydrologic responses to rainfall.

Several time series are being developed for birds in Florida Bay. The database on nesting activity in Bald Eagles extends back to the late 1950s and continues. The Osprey database is also lengthy, although interrupted, and continues. Monthly data on the abundance and activity of water birds in Florida Bay is five years in length and still growing. These databases provide the opportunity to analyze bird activity in the Bay in relation to freshwater inflow and other conditions that might these birds' food supply. This information also is available to use in trophic network models. Information on the diet of water birds in Florida Bay is very limited and largely anecdotal.

Effects of Water Releases on Recruitment and Benthic Fauna

Some statistical studies have directly connected abundance indices from fishery data to indices of freshwater flow to Florida Bay and the southwest coast. These freshwater flows are affected by water releases to ENP at the Tamiami Trail and the management of water levels and releases in the South Dade Conveyance system on the eastern border of ENP. Change in catch rates in fisheries can provide a rough index of change in relative abundance. In an analysis of ENP catch and effort data, Schmidt et al. (2001) found that an index of freshwater runoff to Florida Bay and adjacent coastal waters was positively related to snook catch rates but negatively related to spotted seatrout catch rates. Change in harvests can provide a rough index of abundance when change in effort is taken into account. Browder (1985) found a positive relationship between pink shrimp harvests in the Tortugas fishery and a freshwater inflow index (water levels at P35 in ENP). Analyses by Browder (1999) and Sheridan (1996) suggested that freshwater inputs as either rainfall or runoff influence pink shrimp catch rates. Browder's (1985, 1999) work suggested that the timing of freshwater inputs affects harvests and catch rates. Johnson et al.

(2002) found that water releases at the Tamiami Trail were a significant variable explaining the density of nine of 11 dominant species in Florida Bay's forage fish assemblage (Table 7.1).

Spatial Patterns of Mercury and Methymercury

Widespread patterns of elevated mercury concentrations in game fish and forage fish have been observed in eastern Florida Bay (Evans and Crumley, in review). Within this region, highest concentrations of both methylmercury and total mercury have been observed in water and sediments in the mangrove transition zone near the inflows of Everglades freshwater through Joe Bay and Little Madeira Bay (Rumbold *et al.*, 2003). Incubation studies with stable mercury isotopes revealed substantial *in situ* methylation in open water bay sediments as well. Inputs of bioavailable Hg(II) may be a critical determining factor in driving this methylation. Concurrent seasonal variations in both methylmercury and total mercury concentrations were observed in sediment, water and forage fish, with peak concentrations occurring during the warm rainy season near the coast where Everglades runoff enters the bay. No significant long-term temporal trends in mercury levels in gamefish can be observed as yet for the period 1996-2001. From these results, it has been concluded that the sources of elevated mercury concentrations in fish from northeastern Florida Bay include (1) methylmercury in runoff from the Everglades and (2) *in situ* mercury methylation in sediments from both the mangrove transition zone and the open bay itself. Mercury concentrations seem to be higher along a Taylor River/Little Madeira Bay sampling transect than along a C-111 canal/Joe Bay transect, suggesting that the urban and agricultural runoff that more strongly influences the C111 canal/Joe Bay transect is not the most important source of mercury to the Bay and its biota. All of these processes could change with restored Everglades freshwater flows and might be further altered by changes in nutrient inputs and trophic processing.

Effect of fishing on age structure and abundance of predators

Faunce et al. (2002) provide evidence that fishing in areas of northern Florida Bay open to recreational fishing affects target fish populations there. The modal length of gray snapper (*Lutjanus griseus*) along mangrove shorelines is substantially larger in the Crocodile Sanctuary of Everglades National Park, where fishing has been excluded since 1980, than in other parts of Florida Bay in Everglades National Park and the nearby Biscayne National Park, where fishing is allowed. Modal lengths were 25-30 cm TL in the Crocodile Sanctuary vs. 15-20 cm TL elsewhere. Future work may be needed to clearly separate effects of fishing from effects of differences in habitat. Ley et al. (1999) found a similar pattern. Other studies (Bohnsack et al. 2001, Ault et al. 2002a, Ault et al. 2002b) suggest that fishing affects reef fish populations, some of which spend part of their life cycle in Florida Bay. On the other hand, Schmidt et al.'s (2001, 2002) recent analyses of Everglades National Park creel census data shows that catch rates were positively correlated with fishing rates for four target species, spotted seatrout, red drum, snook, and gray snapper, suggesting that fishing pressure was not affecting overall abundance.

Modeling Change in Higher Trophic Level Species

Two types of models have thus far been applied to HTLs research in Florida Bay. Empirical, statistical models have been used to explore data for patterns that suggest the major processes driving variation in species abundance and community structure. Complementing these models are simulation models, often incorporating population dynamics, to examine the sensitivity of individual organisms to varying characteristics of their habitat, such as bottom cover and salinity.

Statistical Models

Exploratory General Additive Models

Johnson et al. (2001, 2002a, 2002b) assembled a database for Florida Bay that integrated six independent forage fish/macro-invertebrate studies conducted between 1974-1997. The database was used to examine the dynamics of 11 key forage species. General additive models were used to determine which major forcing functions and habitat factors control their abundance and distribution.. The most widely influential explaining variables were seagrass density, habitat, and tidal amplitude, which were significant variables for 10 species, followed by seagrass type and freshwater inflow to the Bay (9 species), salinity (7 species), and temperature and month (6 species). Depth, wind, rainfall (4 species) and sea level (2) were less important variables in predicting the abundances of forage species (Table 8.2). The U-shaped relationships of three species (*Gobiosoma robustum, Floridichthys carpio,* and *Lucania parva*) to salinity suggested they might be adapted to extreme conditions (high and low salinities). The majority of species were positively correlated with seagrass density with the exception of the pelagic bay anchovy (*Anchoa mitchilli*), *F. carpio,* the toadfish (*Opsanus beta*), and the gobies, *Microgobius gulosus* and *G. robustum*, which were more abundant in sparse seagrass. The type of bottom cover was important for seven animal species, as follows: *Syringodium* (*M. gulosus, Lagodon rhomboides, Hippocampus zosterae*, and *L. parva)*, Halodule (pink shrimp, *Syngnathus scovelli*), *Thalassia* (*G. robustum*), and no seagrass (*A. mitchilli*). Three species (pink shrimp, *L. rhomboides*, and *Eucinostomus spp.*) that spawned outside of the Bay showed relationships with tidal amplitude, sea level, and/or wind, which suggests transport mechanisms may affect abundance. Hindcasts of density distributions across the Bay were made with these models and used to compare density, biomass, and evenness in wet seasons and dry seasons of a representative wet (1995) and dry (1991) year.

Forecasts of the Tortugas Shrimp Fishery

Several empirical statistical models have been used to relate Tortugas catches or catch rates to indices of freshwater inputs to Florida Bay. Browder (1985) found a statistical relationship between quarterly Tortugas catches and the average water level in ENP monitoring well P35. Later Sheridan (1996) developed a statistical model that related annual Tortugas catches to Everglades well and rainfall data, as well as air temperature and Key West sea level, the previous spring and summer. The Sheridan model, which was updated every year with new data, successfully predicted Tortugas catches for the upcoming year for a number of years.

More recently, Browder (2000) developed a statistical model relating annual average Tortugas catch rates to the rainfall of several prior months. Two models were developed, one for recruits to the fishery (assumed to be shrimp in the 68-count per pound category) and another for larger shrimp. These models were designed to make rainfall-based predictions of catch rates that could be compared with observed catch rates to separate effects of South Florida's highly variable rainfall from effects of change in water management. Modeling results suggested that timing as well as quantity of rainfall influence catch rates. The rainfall-based models, which were based on data for biological years (July-June) 1964-1965 through 1994-1995, had high r^2 (0.89 and 0.76 respectively), but predictions differed greatly from observations in five subsequent years when few if any water management changes had occurred (Browder, 2001, unpublished report).

A second empirical model was prepared (Browder 2000) to test alternative configurations of the water management system proposed in the "Restudy" that developed the Comprehensive Everglades Restoration Project. This model related Tortugas catch rates of recently recruited shrimp to releases of fresh water into Everglades National Park at its northern boundary immediately downstream from the leveed Everglades Water Conservation Areas. The model, based on data for the period 1964-1965 through 1994-1995, explained 92% of the variation in average annual catch rate. Total monthly water releases for several months of the year explained over 57% of variation in catch rate. The rest of the explained variance was due to other variables. These included large shrimp catch rates the previous year and monthly average Key West air temperature (as a proxy for water temperature) for several months. The relationship between catch rate and water flow was positive for some months and negative for others, suggesting that timing as well as volume is important. When used in alternative testing, the model predicted consistently higher annual catch rates for the "Natural System" than for the "1995 base case" or any alternative, suggesting that South Florida's pre-drainage hydrologic system provided the best conditions for pink shrimp production. To make these predictions, the output of hydrologic models served as input to the shrimp model.

A later analysis examined pink shrimp recruitment to the Tortugas grounds in relation to observed salinity in the western and central bay (Browder, unpublished). Due to limitations in available salinity data, the time series analyzed was very short compared to that available for relating recruitment to rainfall and water releases to Everglades National Park, so the analyst used monthly rather than annual data. A weak, but significant, relationship was found between monthly recruitment and time-lagged monthly average salinity in both areas.

Simulation Models

A simulation model was developed to predict survival, growth of juvenile pink shrimp cohorts and potential harvests from these cohorts as a function of temperature and salinity in Florida Bay (Browder et al. 1999). The model was recently refined with data from new laboratory experiments (Browder et al. 2002). The model structure consists of three algorithms, which govern (1) physiological survival as a function of temperature and salinity; (2) growth as a function of temperature, salinity, and total length; and (3) survival from predation as a function of total length. The model is driven by observed daily temperature and salinity from specific locations in Florida Bay. The model simulates juvenile densities in that part of the bay and potential recruitment (and related harvests) to the Tortugas fishery from that part of the bay.

A spatially explict individual-based model for Caribbean spiny lobster (Panulirus argus) was developed in 1993 (Butler (1994). Reformulations of the same model have been used to investigate a variety of issues, including (1) the potential effect on lobster recruitment of a massive loss of nursery habitat structure due to a sponge die-off (Butler et al. in press), (2) the

Table 7.1: Summary of forage fish models and significant factors

Species	**Gear**	**Month**	**Temp.**	**Seagrass Type**	**Salinity**	**Seagrass Density**	**Depth**	**Habitat**	**Tidal Amplitude**	**Sea Level**	**Wind**	**Rain**	**Flow**
Transitory species													
Pink Shrimp	Sig	NS	Sig	Sig (grass vs none)	NS Sig>40	Sig	NS	Sig	Sig	Sig-3	NS	NS	NS
Lagodon	NS	Sig	Sig	Sig	NS	Sig	Sig neg	NS	Sig	NS	NS	Sig-1	Sig-1 neg
mojarras	Sig	NS	Sig	Sig (grass vs none)	NS Sig>40	Sig	NS	Sig	Sig	Sig-2	Sig-2	Sig-2	Sig-2 neg
Pelagic species													
Anchoa	Sig	Sig	Sig	Sig	Sig neg	Sig	Sig neg	Sig	Sig	NS	Sig-low wind-2	NS	Sig > 150,000
Resident species													
Opsanus	NS	Sig	Sig	NS	Sig	Sig	NS	Sig	Sig-neg	NS	Sig-3	NS	Sig-3
Gobiosoma	Sig	Sig	NS	Sig	NS	Sig	Sig	Sig	Sig	NS	NS	Sig-2	Sig-1
Floridichthes	Sig-trap higher	NS	NS	NS	Sig neg/pos	NS	NS	Sig	NS neg	NS	Sig-lower wind-3	NS	Sig-2 neg
Syngnathus	Sig	Sig	Sig	Sig	Sig	Sig	Sig	Sig	Sig high/low	NS	NS	NS	Sig-2
Microgobius	Sig	NS	NS Sig>32	Sig	Sig	Sig	NS	Sig	Sig-neg	NS	NS	NS	Sig-2 pos/neg
Lucania	Sig	NS	NS	Sig	Sig neg/pos	Sig	NS	Sig	Sig-neg	NS	NS	Sig-3 neg	NS
Hippocampus	NS	Sig	NS	Sig	Sig	Sig	NS	Sig	Sig high/low	NS	NS	NS	Sig-2
Number of 11 species where factor is significant	8	6	6	9	7	10	4	10	10	2	4	4	9

Sig=Significant; NS=not significant, number = monthly time lag

consequences of temporal and spatial variation in postlarval supply on recruitment (Butler et al. 2001), (3) the effect of nursery habitat structure and geographic specificity on recruitment (Butler et al. 2001), and (4) the direct and indirect consequences of altered salinity on recruitment (M. Butler, pers. comm.). The ecological aspects of recruitment included in this model starts with the arrival of spiny lobster postlarvae in the nearshore nursery and terminate when larger juveniles begin to enter fishermen's traps. The recruitment process is explicitly incorporated into this model by superimposing on the model's spatial landscape the daily ecological processes faced by juvenile spiny lobsters: settlement, growth, shelter, selection, mortality, and movement. The model tracks each hypothetical lobster from settlement until recruitment to 50 mm carapace length. Settlement occurs once every 28 days, corresponding to the lunar cycle. Growth is a discontinuous process involving molts. Daily mortality is a function of various aspects of habitat and lobster-habitat interactions. Simulations with the model were run for observed extreme conditions, a wet year (1995) and a dry year (1993). The direct effects of salinity were limited to ~20% of the lobster nursery area where salinity varies naturally. Simulation results suggested that lobster recruitment during a very wet or dry year would be similar. In both cases, recruitment declined by ~25% in the area directly affected by salinity change, which resulted in ~5% decline in recruitment over the entire Florida Keys region, as compared to control simulations where salinity was stable at 35‰. Other simulations predicted that the lobster population would be surprisingly resilient to sponge die-off. Although nearly the entire sponge community was decimated over ~20% of the nursery area, this loss of habitat was predicted to result in only a 16% decline in lobster recruitment in the perturbed region and a 2% decline over the entire Florida Keys region. The model allowed a follow-up analysis of "why this is so." Apparently the effect was not just because the supply of postlarvae was three times higher in the post die-off year simulated, but mainly because of juvenile lobster movement to nearby unaffected areas and shifts in shelter use on sites impacted by sponge die-off, a response supported by field evidence (Butler et al. 1995, Herrnkind et al. 1997).

Richards (in prep.) examined the relationships between temperature and salinity and growth rate in crocodiles (*Crocodylus acutus*), by tracking 30 radio-tagged hatchlings in the vicinity of the Turkey Point Power Plant for up to several weeks. Water temperatures in habitats in which the hatchlings were tracked were within the range 29-35°C, a range where temperature is not expected to have a detrimental effect on growth (Mazzotti et al., 1986). Richards found no effect of temperature on most measures of growth. Although laboratory work has shown a strong negative effect of salinity on mass in hatchling American crocodiles (Dunson, 1982), field observations suggest that they can survive and grow in highly saline areas (Lang, 1975; Mazzotti, 1983). Richards found of no significant effect of salinity on growth rates, supporting these field observations. Two of the individuals at very high salinities (about 60‰) grew at the same rate as most individuals in low salinity water. In the laboratory, Mazzotti and Dunson (1984) showed that hatchling *C. acutus* maintained in seawater (35‰) grew well if given periodic access to brackish water (4‰). Richards observed hatchlings using hollows in the banks of canals and ponds, and also observed that four individuals on five occasions (sometimes accompanied by other hatchlings) moved out of their low salinity pond and into the hypersaline canal areas at night, and returned to their pond the following day. These observations support the hypothesis that crocodiles may have behavioral adaptations for escaping negative effects of salinity.

Substantial progress has been made in the development of a bioenergetically based individual larval spotted seatrout model to simulate metabolic rate, consumption, and growth as a function of temperature and salinity (Wuenschel 2001). The model follows the basic energy budget equation in which consumption equals the sum of metabolism, excretion, and growth and each component is a function of fish size, temperature, and salinity, where appropriate. The final model will incorporate individual variability for each component, which will enable the modeling of a population of individuals, rather than just the average individual. Laboratory experiments (N=779 SL 4.5-39.5mm) provided the basic information for the model.

A spatially explicit prey-predator model for spotted seatrout and pink shrimp coupled to physical processes was developed for Biscayne Bay (Ault et al. 1999; Ault et al. 2003; Wang et al. 2003). The spotted seatrout component of the model was individual-based.

Ongoing Research

At the time of the 2001 Florida Bay conference, five new (or continuing) HTL projects funded for two years by the NOAA Coastal Oceans Program had barely started. While these studies have made substantial progress to the present date, their results were not presented at the Florida Bay Conference and only a portion of these results were available for this synthesis. Other projects are in progress with funding from the U.S. Department of Interior. They are expected to make substantial progress on the research topics they will address. Other recently funded projects that we do not know about today may address some the needs expressed. NOAA-funded 2-yr projects include “Modeling pink shrimp recruitment from Florida Bay” (continuing work), “Population Studies, Abundance, Habitat Use, Trophic Descriptions, and Reproductive Status of Marine Turtles Inhabiting Florida Bay”, “Reef Fish Community Dynamics and Linkages with Florida Bay”, “Development of Spatially-Explicit Models to Predict Growth-Potential of Age-0 Gray Snapper, *Lutjanus griseus*, in Florida Bay during Restoration of Freshwater Flows”, and “Upstream Larval Supply to Florida Bay—the Dry Tortugas Connection”. The NOAA projects are briefly described below.

Modeling pink shrimp recruitment from Florida Bay

This project continues development of a simulation model and associated performance measure to evaluate the potential impact on Florida Bay of upstream water management changes resulting from efforts to restore the Greater Everglades ecosystem. This work phase seeks to 1) clarify the effect of freshwater inflow and seagrass habitat on Florida Bay’s pink shrimp nursery function, 2) determine the major influences of meteorological and oceanographic processes on postlarval pink shrimp and their ramification on recruitment to the fishery, and 3) improve the ability to predict recruitment to the Tortugas fishery in response to changes in water management. As part of this work, a spatially-explicit recruitment model will be developed from the existing unit model; postlarval immigration pathways, transport rates, and influencing factors will be described and quantified, and historical data on pink shrimp density will be analyzed and used to further refine and verify the model.

Regional Assessment of Sponge Dynamics and Sponge Fishery Impacts

This project is part of a multi-year investigation of the hard-bottom communities of Florida Bay and the Florida Keys. It combines modeling, laboratory, and fieldwork to explore the relationship of spiny lobster population dynamics to spatio-temporal patterns in the structure of bottom habitat and environmental variables. The current project focuses on sponges, but some elements also pertain to spiny lobster and octocorals. The project’s four principal objectives are to (1) describe size-specific population dynamics information (e.g., growth and reproductive status) needed to model and manage commercial sponge species; (2) determine the effects of commercial fishing on sponges and the bycatch of the sponge fishery; (3) experimentally test the tolerance (e.g., survival, susceptibility to disease, changes in behavior, etc.) of selected hard-bottom-dwelling species (e.g., five sponge species, two octocoral species, and three size classes of spiny lobster) to different salinities and periods of exposure at winter (18 C) and summer (28 C) water temperatures; and (4) incorporate new and existing information into a spatially-explicit simulation model to quantitatively compare the impact of potential management strategies on the sustainability of the sponge fishery and its impact on hard-bottom community structure in the Florida Keys National Marine Sanctuary.

Population Studies, Abundance, Habitat Use, Trophic Descriptions, and Reproductive Status of Marine Turtles Inhabiting Florida Bay

Purposes of this study are to 1) capture and tag sea turtles in Florida Bay to continue long-term monitoring of individual growth rates, foraging-site fidelity, residency rates, health status, and trends in abundance; 2) elucidate the trophic role of loggerheads as apex predators in Florida Bay; 3) provide detailed descriptions of loggerhead habitat use and behavior; and 4) examine the sexual maturity and reproductive frequency of adult-sized loggerheads inhabiting Florida Bay. The principal study area is the central-western region.

Reef Fish Community Dynamics and Linkages with Florida Bay

This continuing project will apply a visual sampling strategy to quantify coral reef fish community changes. The project has the following goals: 1) provide intensive and precise spatial and habitat-specific fishery-independent assessment of reef fish communities; 2) document trends in reef fish size and abundance within and outside no-take zones in the Florida Keys reef tract; 3) test specific hypotheses predicting continuing changes in reef fish communities as the result of no-take protection; 4) provide a precise and spatially explicit database for assessing any future reef fish population changes resulting from Everglades restoration actions; 5) provide managers with options for optimizing long-term survey design strategies to identify reef fish population changes; and 6) correlate the linkages between reef fish communities and fishing, habitat, oceanographic, and other physical processes to guide appropriate experimental studies on dynamic mechanisms and to develop predictive models.

Development of Spatially-Explicit Models to Predict Growth-Potential of Age-0 Gray Snapper, Lutjanus griseus, in Florida Bay during Restoration of Freshwater Flows

The general goal is to examine patterns of growth in juvenile gray snapper and develop a bioenergetic model of growth that is a function of temperature, salinity, and fish size. This model will be extended into a spatially explicit calculation of potential fish growth using historical environmental data as well as predicted changes in the environment of Florida Bay under different water management strategies. Specific objectives are 1) to quantify patterns in juvenile gray snapper growth through a retrospective analysis of previously collected samples, 2) to examine the relationship between juvenile gray snapper growth and temperature and salinity using previously collected samples and historical monitoring data, 3) to develop an individual-based bioenergetic model for juvenile gray snapper under a range of temperature and salinity conditions, 4) to decalibrate and validate the bioenergetic model through comparison of predicted growth with observed growth, and 5) to develop a spatially explicit model that predicts growth-potential of young snapper throughout Florida Bay under various freshwater flow regimes.

Upstream Larval Supply to Florida Bay—the Dry Tortugas Connection

This project explores the pathways and enabling transport processes for migration of larval fish, shrimp, and lobster from the Dry Tortugas to Florida Bay. Emphasis is on the role of episodic, mesoscale events, such as those involving eddies and the Tortugas gyre. The hypothesis to be tested is that the presence of a coastal eddy enhances the influx of pre-settlement recruits into Florida Bay. Densities of incoming recruits in the Middle and Lower Keys during the presence and absence of an eddy are being compared. This is a continuation of a previous South Florida

Program project for which substantial progress has been made in relating spiny lobster larval transport to eddies and gyres (Yeung et al. 2001). Planned new work seeks to determine what happens closer to the origin of eddies at the Dry Tortugas and Lower Keys and the importance of the western recruitment pathway in connecting the Dry Tortugas with Florida Bay over the SW Florida shelf. Coordinated sampling at Southwest Channel in the Dry Tortugas and bayside at Northwest Channel will attempt to link the newly spawned snapper larvae to subsequent early settlement stages.

Atlas of Life Histories of Juvenile and Small Resident Species in Florida Bay

The Atlas will include information on the range, reproduction, diet, spatial and temporal abundance and distribution, and length-frequency distributions in the Bay. This work is being conducting with NMFS base funding.

ATLSS Model of Coastal Wetland Fishes

A spatially-explicit model of the resident fishes of the coastal wetlands is being developed by Cline et al. (2001) to further explore the relationships determined by Lorenz (2001a, 2001b). The model utilizes the object-oriented modeling framework provided by the Across Trophic Level System Simulation (ATLSS), which is now being applied to the Everglades. Development of the coastal fish model will extend ATLSS into the coastal marshes and provide a basis for expanding the wading bird elements of ATLSS into the coastal zone.

Unresolved Issues/Questions: Research Needs

Criteria used to propose future research topics were as follows: 1) follow-up of promising recent research expected to sharpen or broaden answers to Question 5; 2) addressing promising new hypotheses that replace failed hypotheses; 3) development of performance measures based on species and communities most likely to be affected by CERP changes; and 4) addressing gaps in the current program where new information suggests higher priority should be assigned. The following series of topic areas fit one or more of these criteria.

Location of Nursery Areas of Major Game Fish Species

Many sought-after gamefish species are found in Florida Bay as pre-adults and adults, but the current nursery grounds of most their populations are not delineated. This includes red drum, snook, tarpon, bonefish, and gray snapper. Recently, Powell (in press) delineated nursery grounds for spotted seatrout in Central and Western Florida Bay. Colvocoresses (unpublished data) found red drum juveniles in Little Madeira Bay at 12‰, however efforts by Powell (2002) to find red drum nursery grounds in northern Florida Bay were unsuccessful, possibly because the appropriate salinity was not present during sampling. Efforts need to be directed at the southwestern mangrove estuaries of Everglades National Park. The type of red drum habitat described by Peters and McMichael (1987) is likely to be found in there. Odum and Heald (1972) collected many red drum juveniles in the Whitewater Bay system (North River), and this system could be a nursery area for red drum found as adults and subadults in Florida Bay. Tabb et al. (1962) found early-settlement-stage bonefish and tarpon in the Buttonwood Canal/Flamingo area. There has been no follow-up to better define the nursery areas of these species. Early settlement stage snook have not been found south of Chokoloskee (T. Schmidt, pers. comm.), although similar habitat appears to occur between Chokoloskee and Cape Sable. The settlement grounds for gray snapper that enter the Bay are not well defined, although

Rutherford et al. (1989) identified mixed seagrass beds of *Syringodium/Thalassia/Halodule* in west Florida Bay as best settling out habitats for juvenile gray snapper. The nursery areas of some of these species are likely to be in the front lines of changes caused by new water management structure and operations. These nursery areas need to be delineated so that the potential effect of water management changes on salinity patterns, nutrient inputs, and other conditions in these areas can be predicted.

Influence of Habitat and Environmental Variables on Species Composition and Trophic Dynamics

The following non-mutually exclusive hypotheses about factors influencing the abundance and relative abundance of water column and seagrass canopy species should be explored.
Hypothesis 1: Density and abundance of bay anchovy is related to salinity fronts.
Hypothesis 2: Density and abundance of canopy species is related to seagrass diversity.

Regional trophic web models should be developed to integrate existing and future information on food webs and trophic structure in Florida Bay. Information on water birds and large marine vertebrates (sharks, rays, bottlenosed dolphin, and sea turtles) should be incorporated into the models. The trophic web models should be viewed as precursors to an ecosystem model to be developed in a subsequent funding phase. The work should include the use of stable isotope analyses, including use of museum specimens (assuming the work to develop methods for processing museum material has been completed).

Statistical analyses of historical resource survey data should be expanded and results used to design and quantify trophic web and ecosystem models. The database assembled by Johnson et al. (2001) provides the opportunity to develop trophic network models for Florida Bay. Separate network models should be prepared for the Bay’s sub regions because of the major differences in the food web base among sub regions suggested by Chanton et al. (2001), Evans and Crumley (in review) (see also Evans et al. [2001]), and Butler et al. (2001). Network models previously prepared for the Bay by R. Ulanowicz (University of Maryland) and A. Acosta (Florida Marine Research Institute) would provide a starting point for a new effort. Acosta (pers. comm.) observed that network modeling suffered from a lack of biomass information on benthic organisms. This is still a serious deficiency, although some data have been gathered on sponge biomass. Molluscan samples collected by W. Lyons and archived at the Florida Marine Research Institute could be used to develop data on molluscan biomass. Analysis and comparison of trophic structure in the various regions of the Bay could be used to organize information about higher trophic level species and assess affects of salinity changes resulting from changes in water management.

Factors Affecting Postlarval Immigration

Immigration into the Bay’s Interior

HTL researchers, building on the work of physical oceanographers, have gained some knowledge about the pathways, mechanisms, and oceanographic factors influencing immigration of offshore-spawned larvae and postlarvae to the eastern edge of Florida Bay. However little information exists on physical processes that influence the immigration of postlarvae onto potential nursery grounds in the Bay’s interior. This information is highly relevant because it would better elucidate the ecological importance and potential economic importance of reducing the frequency, duration, and intensity of hypersaline conditions in the interior of the Bay. To what extent and how much of the interior of the Bay is accessible to offshore-spawned species? What factors cause the accessibility of the inner bay to vary? This information would allow determination of potential benefits of improved conditions to these species. Greater coordination of biological and physical research on the movement of water and early life stages into the Bay's interior is needed. Physical research in the interior of the Bay was initiated last year, opening new opportunities for collaboration.

Immigration to Florida Bay

Recent research suggests that the major pathway for transport of pink shrimp postlarvae from the Tortugas to Florida Bay may be across the southwest Florida shelf. Research on larval immigration to Florida Bay nursery grounds from the west is hampered by a lack of physical oceanographic work that addresses questions biological researchers need to know. For example, what dynamic physical structures might enable early life stages spawned near the Dry Tortugas to reach the Bay from the west? Net flows across a hypothetical boundary of the Bay stretching from Cape Sable to Marathon have been described (Smith 2000), but the flow characteristics along the Bay boundary (boundary of the Bay proper) that stretches from Cape Sable to Long Key are less known. Water movement across this boundary from both the west and the south needs to be studied by oceanographers in integrated studies with biologists studying immigration of early life stages onto Florida Bay nursery grounds.

Effect of Larval Behavior and Freshwater Inflow on Larval Immigration Rates

Freshwater inflow may provide directional cues or otherwise influence the rate of larval immigration from offshore spawning grounds to nearshore nursery grounds. This topic has not been explored with respect to Florida Bay species since Hughes (1969a, 1969b) conducted experiments suggesting that pre-settlement pink shrimp postlarvae move vertically in the water column in response to salinity gradients. He proposed that this behavioral response resulted in net shoreward transport of postlarvae on flood tides. The Hughes results raise questions that have never been addressed regarding the possible role of freshwater inflow in postlarval immigration of pink shrimp and other species. Does the volume and timing of freshwater inflow influence that magnitude of influx of postlarvae to Florida Bay?

Effect of Salinity on Survival and Growth

Integrated studies that might include models, supporting field studies, laboratory experiments, and statistical analyses should be conducted to quantify relationships of survival, growth, and other processes to salinity. This includes continued development and application of lobster, shrimp, gray snapper, and spotted seatrout models. For example, the shrimp model should be applied to assessing potential nursery grounds in the mangrove estuaries of ENP and examining the possible effects of alternative management strategies on the larger Florida Bay system that includes these areas. Another needed application is in interpreting juvenile density data in relation to postlarval immigration and fisheries data. A spotted seatrout individual-based model should be developed to integrate all the recently acquired new information about this species in the bay. Questions about the impact of hypersaline conditions in the Central Bay on year-class strength of spotted seatrout need to be addressed. The lobster model should be expanded to integrate new information on salinity tolerance of lobster and living components of lobster habitat. Following up on modeling results, field experiments should attempt to quantify the effect on growth and survival of movements away from undesirable conditions (i.e., hypersalinity or hyposalinity).

Quantification of Size-Related Predation Mortality

Better quantification of size-related predation mortality is needed to adequately address the effect of salinity on survival through the effect of salinity on growth. This issue is especially pertinent to pink shrimp, spotted seatrout, gray snapper, and lobster. Results are needed to refine and quantify simulation models.

Effect of Water Quality on Survival and Growth

This question has not been specifically addressed in current research in Florida Bay. Effects of both nutrient enrichment and common chemical contaminants on Florida Bay fish and macroinvertebrates may be relevant to determining effects of changes in water management.

Effects of Benthic Habitat on Settlement, Survival, and Growth

What characteristics of habitat lead to initial settlement? How do characteristics of settlement habitat affect survival and growth? How faithful are animals to the location of first settlement? What causes movement and where do animals go? Information on these questions is needed to further refine simulation models.

Identification of Other South Florida Coastal Areas with Enhanced Mercury Bioaccumulation in Fish

Previous work (Rumbold et al. 2003) identified the transitional mangrove ecotone in northeastern Florida Bay as a region of enhanced mercury and methylmercury concentrations in water, sediments, and fish. In unpublished data, Evans found concentrations of mercury in red drum and jack crevalle from Whitewater Bay that were comparable to those found in the same species in northeastern Florida Bay. Whitewater Bay is a mangrove-dominated embayment just north of western Florida Bay that receives some runoff from the Shark River, an area of known mercury contamination in fish. It seems likely that other estuarine recipients of Shark River drainage could support fish with high mercury concentrations. The sensitivity of fish from the mangrove ecotone of the entire Ten-Thousand Islands complex of southwest Florida suggests the need for a monitoring program to establish mercury concentrations in susceptible fish species and a research effort to determine the mercury sources and responses to future CERP changes in the volume and timing of freshwater flows.

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Unpublished Materials

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