ogical Services Program

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PROCEEDINGS OF THE GULF OF MEXICO COASTAL ECOSYSTEMS WORKSHOP:

OFFICE OF ENVIRONMENT, REGION 2, U.S. FISH AND WILDLIFE SERVICE

PORT ARANSAS, TEXAS
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h and Wildlife Service

S. Department of the Interior

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PROCEEDINGS OF THE GULF OF MEXICO COASTAL ECOSYSTEMS WORKSHOP

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Editors

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PREFACE

A workshop on Gulf of Mexico Coastal Ecosystems was conducted from 4 through 7 September 1979 at the University of Texas Marine Science Institute, Port Aransas Marine Laboratory, Port Aransas, Texas. The workshop was co-sponsored by the Office of Biological Services, Coastal Ecosystems Project, and the Office of Environment, U.S. Fish and Wildlife Service, Region 2, Albuquerque, New Mexico. A total of 56 Service personnel attended with the majority coming from the Gulf of Mexico coastal field offices in Region 2 and 4 and other representatives from the Central Office in Washington, D.C. and from the National Coastal Ecosystems Teams, Slidell, Louisiana.

The purpose of this workshop was to provide training for U.S. Fish and Wildlife field personnel on recent developments in our understanding of Gulf coast ecosystems. The workshop focused on presenting and discussing information related to assessing the impact of human activities on fish and wildlife resources in these ecosystems. Fourteen formal presentations were given during three technical sessions by invited scientists and other professionals. These presentations are the papers included in these Proceedings. Two afternoons of the workshop were devoted to field trips to representative coastal habitats of the south Texas region.

Ironically, the timing of the unfortunate IXTOC-I Mexican oil spill (at that time washing ashore on south Texas beaches) provided the participants with a firsthand view of, and in some cases participation in, a potentially catastrophic perturbation to Gulf of Mexico coastal and oceanic ecosystems. A special evening session was devoted to a review of Fish and Wildlife Service responsibilities and procedures in response to this oil spill. Three Service operational representatives from Region 2 gave lively and informative presentations on various aspects of the agency's involvement: Messrs. Jack Woolstenhulme, Assistant Regional Director- Environment and Service's IXTOC-I Oil Spill Coordinator; Charlie Sanchez, Regional Pollution Response Coordinator; and Roy Perez, Field Supervisor, Corpus Christi Field Office.

Administrative assistance for the workshop was provided by the staff of the University of Texas Marine Science Institute, Port Aransas. We wish to acknowledge the fine cooperation and hard work of the staff at the Port Aransas Marine Laboratory in hosting the workshop and making it a success. Special thanks are due: Dr. Warren Pulich, Jr., who served as workshop coordinator and technical writer on the preparation of these Proceedings; Mr. John Thompson, who directed the physical plant and meal arrangements; Ms. Debby Kalke, who handled most of the clerical and typing duties associated with the workshop and the Proceedings; and Mr. Steve Rabalais and Mr. Rick Tinnin for technical assistance. The cover illustration for the Proceedings was drawn by Mrs. Anne Pulich, Sr.

Service planning and liaison for the workshop were provided by Dr. Paul L. Fore, Regional Activity Leader - Coastal Ecosystems, Albuquerque, New Mexico and Mr. Russell D. Peterson, Environmental Specialist, Ecological Services, Galveston, Texas.

Finally, our appreciation is due the 14 scientists who shared their knowledge and ideas with all of us. Their contributions are recorded here for others to use.

Editors

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EFFECTS OF MARSH IMPOUNDMENTS ON COASTAL FISH AND WILDLIFE RESOURCES

Robert H. Chabreck[1]

INTRODUCTION

Marsh impoundments can be categorized on a basis of water level and salinity regimes for descriptive purposes and generally fall into four types: permanently flooded with freshwater, manipulated freshwater, permanently flooded with brackish water, and manipulated brackish water. The effects of impoundments on fish and wildlife resources vary with the resources involved and the type of impoundment. Marsh impoundments are widely used in coastal areas as a means for controlling water levels and salinities to accomplish specific objectives. These objectives include improvement of wildlife habitat, aquaculture, water storage for agricultural irrigation and industrial uses, flooding marshes for mosquito control, and maintaining favorable water depths for navigation.

Although impoundments are usually constructed with a primary objective, secondary values often develop which are incorporated into the management scheme. Several examples are worth mentioning.

Impoundments were constructed on the Rockefeller Wildlife Refuge in Southwestern Louisiana to improve habitat for migratory ducks (Chabreck 1960). Refuge biologists found that the water manipulation system used to produce duck foods in freshwater impoundments could be modified slightly to produce bumper crops of crawfish (*Procambarus clarkii*) without affecting growth of duck foods. Consequently, management of this secondary resource was then included in operational plans (Perry *et al.* 1970), and the impoundments were opened to sport fishing for crawfish during the spring and summer.

A permanently flooded brackish water impoundment on Rockefeller Refuge was managed as a nursery area for shrimp and blue crab (*Callinectes sapidus*) as a secondary objective. Brown shrimp (*Penaeus aztecus*) were introduced in February and white shrimp (*P. setiferus*) were introduced in July by opening water control structures on high tide when post-larval shrimp were present. Sport fishermen were permitted to harvest shrimp with cast nets and blue crabs with hand lines. The annual harvest from the impoundments was estimated to be 60 lb (27 kg) of shrimp and 6 dozen crabs per acre (0.4 ha) over an area of 5,000 ac (2,023.5 ha).

A permanently flooded freshwater impoundment was constructed and managed for waterfowl on the Lacassine National Wildlife Refuge, Louisiana. The

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impoundment received high use by waterfowl, but also developed large crops of sunfishes (Centrarchidae) and was heavily used by fishermen. Sport fishing was included as an important aspect of management plans (Turner 1966).

ENGINEERING AND HYDROLOGY CONSIDERATIONS

Impoundments are constructed in coastal marshes by enclosing an area with a continuous levee system or by using levee systems in conjunction with elevated ridges or uplands to form a closed system. Water control structures are an important part of an impoundment. Spillways are used to remove surplus water associated with heavy rainfall or hurricanes, and stop-log structures serve to maintain a maximum pool level.

Facilities must also be provided for completely draining and flooding impoundments. Gravity drainage may effectively remove water through gated culverts in areas with extreme tidal fluctuation. However, in many areas gravity drainage is inadequate and marsh managers must utilize pumping units to remove water.

Rainfall is the primary water source for most marsh impoundments, particularly freshwater systems. However, if rainfall is not adequate, ample water may not be available in impoundments to meet management requirements. Consequently, pumping units may be installed to add water. Some marsh managers use one pumping system, with appropriate control structures, to either drain or flood an impoundment. Brackish water impoundments may also be flooded by pumping; however, in most areas water can be added by opening control gates on high tides and then closing them as tides fall. This process can be facilitated with structures having flap gates which are automatically opened and closed by water pressure.

Water salinities in impounded marshes more often reflect the historical trends of salinity in an area than do those in non-impounded marshes. Canal dredging and linkage of canals with natural tidal channels has accelerated drainage of marshes in many areas, resulted in saltwater intrusion into many marshes historically free of saltwater, and greatly increased environmental stress on plant and animal populations. Most marsh impoundments have been constructed as an effort to restore traditional salinity regimes and prohibit excessive drainage, thereby creating a stable environment for fish and wildlife. Therefore, in evaluating the effects of marsh impoundments on fish and wildlife resources, it is wise to consider the historical fish and wildlife usage of the particular area, as well as present usage.

HABITAT REQUIREMENTS OF FISH AND WILDLIFE

Coastal marshes and their associated water bodies are among the most productive habitats for fish and wildlife. Some species spend their entire lives in this habitat, while others use the habitat only seasonally or during a portion of their life cycles. The following is a review of the habitat requirements of selected groups which are important because of their commercial, sporting, or recreational qualities. This review will provide basic background information for subsequent discussion on the effects of impoundments in coastal marshes on the various groups of fish and wildlife.

WATERFOWL

Coastal wetlands and waters serve as wintering habitat for a large segment of the continental migratory waterfowl population. Major groups include dabbling ducks, diving ducks, and geese. These groups have different habitat requirements, and considerable variation is even found among species within groups.

Dabbling ducks mostly prefer shallow water areas with depths less than 18 in (46 cm). These birds feed by tipping to reach the bottom of marsh ponds or the surface of flooded marsh. Small species such as blue-winged teal (*Anas discors*) and green-winged teal (*A. crecca*) prefer areas with water less than 6 in (15 cm) deep (Chabreck 1979). Teals, mallards (*Anas platyrhynchos*) and pintails (*A. acuta*) feed mainly on seeds which they pick up on the bottom. Other dabblers, such as gadwalls (*Anas strepera*) and American wigeons (*A. americana*) feed heavily on the leaves and stems of aquatic plants; consequently, they are able to utilize areas with a greater water depth.

Diving ducks, as the name implies, feed by diving and may consume plant or animal materials on reservoir bottoms or aquatic plants growing in the water. Diving ducks may be found in association with dabbling ducks; however, they usually occupy open water areas with depths much greater than those used as feeding areas by dabbling ducks.

The snow goose (*Chen caerulescens*) commonly winters in coastal marshes and prefers areas containing low growing grasses and sedges and having water levels near or below the marsh surface. Snow geese seldom venture into salt marsh. A preferred habitat is brackish marsh containing a dense stand of recently burned three-cornered grass (*Scirpus olneyi*).

COOT, GALLINULES, AND RAILS

The American coot (*Fulica americana*) is a winter resident of coastal wetlands and concentrates in large flocks on ponds and lakes (Lowery 1974a). It is equally at home on a shallow pond with dense growth of aquatic plants for food or a deeper lake with small fishes available as food. The American coot occupies shallow water areas and tolerates widely ranging water salinities, but limits its use of deep water lakes to freshwater systems.

Gallinules and rails are less gregarious than coots and prefer marshes with dense escape cover readily available. The common gallinule (*Gallinula chloropus*) is a year-round resident of Gulf coast marshes, while the purple gallinule (*Porphyrula martinica*) breeds in the area and migrates during winter.

Gallinules occupy freshwater marshes and prefer feeding areas along the shorelines of small ponds.

Several species of rails are present in coastal marshes. The clapper rail (*Rallus longirostris*) occupies saline marshes, and its close relative, the king rail (*R. elegans*), is found in fresh marshes. Rails prefer moist soil conditions and are driven from marshes by prolonged flooding.

WADING BIRDS

This group includes herons, egrets, ibises and similar birds. Wading birds are abundant throughout the coastal area and feed in shallow ponds by slowly walking about capturing fishes and other small animals. Shallow water is an essential part of their habitat, and birds often concentrate around small pools to capture fishes trapped by receding water levels.

FUR ANIMALS

Fur animals are common inhabitants of coastal marshes and waterways and occupy a wide variety of habitat types, ranging from fresh to saline. Major species include muskrat (*Ondatra zibethicus*), nutria (*Myocastor coypus*), raccoon (*Procyon lotor*), mink (*Mustela vison*), and river otter (*Lutra canadensis*). Muskrat and nutria are herbivores and feed on a wide assortment of plants; however, certain plant types will support greater population densities than others (O'Neil 1949; Palmisano 1972).

The raccoon is normally omnivorous but coastal marshes usually lack plant foods used by raccoons; consequently, they are forced to feed largely on animal materials. The mink are carnivores and feed mainly on fishes, crustaceans, small mammals and birds, snakes, and frogs. The river otter is also a carnivore, but feeds heavily on fishes and crustaceans (Lowery 1974b).

The river otter ranges over an area of several square miles and spends a major portion of its time in or near water. Prolonged drought adversely affects the species; however, the impact of drought is less severe if water is available in deeper channels. Likewise, nutria, raccoon, and mink are also affected by excessive marsh drying; but excessive flooding may also force the animals to abandon an area, particularly when protective cover becomes submerged.

ALLIGATOR

The American alligator (*Alligator mississippiensis*) occurs in the southeastern U. S. and occupies coastal marshes and water bodies with salinities ranging from fresh to slightly brackish. Alligators are opportunistic feeders, consuming both vertebrates and invertebrates; and prey size varies with the size of the alligator. Marsh water depths are critical factors limiting populations and affect nesting effort, nest flooding, desiccation mortality, and predation on alligator eggs and young (Nichols *et al.* 1976).

FRESHWATER FISHES

Ponds, lakes, bayous, and canals in freshwater marshes of coastal areas are highly productive habitats for freshwater fishes. Major families found in these habitats include sunfishes (Centrarchidae) and catfishes (Ictaluridae) and contain both foraging and predacious species. Important factors regulating productivity of aquatic habitats are suitable water depths, favorable water quality, adequate nutrients to supply primary producers, and low abundance of undesirable plants, such as water hyacinths (*Eichornia crassipes*).

ESTUARINE FISHES

Estuarine fishes included herein are those species which utilize a brackish marsh environment as a part of their life cycle, mainly during the postlarval and juvenile stages. These include important commercial or sporting species such as Gulf menhaden (*Brevoortia patronus*), Atlantic croaker (*Micropogon undulatus*), white shrimp, and blue crab. In general, these species breed in offshore waters and the young move inland as larval or postlarval forms. Young which reach favorable nursery areas, such as tidal marsh ponds and bayous, grow very rapidly. Favorable nursery areas are those having suitable water salinity and temperature and an abundance of available food. The major food source is derived from detritus or fragments of marsh plants which have been carried into the nursery area by tidal currents. The aquatic forms remain in the marsh systems for several months then gradually make their way to the deeper water, enroute to the sea (Gunter 1967).

CRAWFISH

Crawfish are an important component of freshwater marshes, serve as a major food item for many other species of fishes and wildlife, and provide a commercial and recreational resource for man. Summer drying of freshwater marshes is essential for completion of certain life stages and to reduce predators which would otherwise feed on the crawfish once water is returned to the marsh.

IMPOUNDMENTS AND FISH AND WILDLIFE RESOURCES

The vegetational and hydrological characteristics of coastal wetlands are primary factors regulating their value to fish and wildlife resources. Vegetation produced on wetlands serves as a primary food source and often determines the number of animals that a given area will support. Different species of wildlife have preferences for different species of vegetation; consequently, the plant species composition of an area often governs the animal species in the area. Hydrological characteristics are an important interacting factor, and water depth will affect the ability of many animals to use an area. Hydrological factors such as water salinity and tidal action may affect species tolerance to a particular habitat or regulate the means by which access is gained to the area.

The following is a discussion of the vegetational and hydrological characteristics of each type of impoundment, and the effects of those characteristics on providing the habitat required for selected fish and wildlife resources. The conditions described apply primarily to coastal areas of the south Atlantic and Gulf coastal regions of the United States.

PERMANENTLY FLOODED FRESHWATER IMPOUNDMENTS

Marsh impoundments of this type are usually located inland from the normal influence of tides. In nonimpounded fresh marsh, drainage is usually slow, and as a result, water depths are greater than in tidal marsh. Marshes permanently flooded by impounding usually have even greater water depths. During periods with unusually heavy rainfall, water may be as much as 3 to 4 ft (0.9 to 1.2 m) deep.

Marsh soils typically have high organic matter contents because of the slow decomposition rate in such flooded soils. In permanently flooded freshwater impoundments, organic matter accumulates at an even greater rate and marsh elevations increase above that of natural marsh. Also, scattered floating mats of organic material often develop on the water surface.

Typical vegetation consists of perennial plants adapted to growth in deep water. Plants commonly found are spikerushes (*Eleocharis* spp.), softstem bulrush (*Scirpus validus*), bulltongue (*Sagitarria falcata*) and many species of aquatic and floating leaf plants. Floating mats of organic matter that develop are held together by emergent species such as pennywort (*Hydrocotyle* spp.) and maidencane (*Panicum hemitomon*).

Waterfowl

Permanently flooded freshwater impoundments receive high use by dabbling ducks, particularly gadwalls and American wigeons, which feed on leafy plant materials. Water depths are often too great for bottom feeding by seed-eating dabblers; but where shallow water is present, they find adequate food and often occur in large numbers. Diving ducks, such as ring-necked ducks (*Aythya collaris*), prefer this habitat and concentrate there in large numbers. Permanently flooded impoundments are particularly valuable to ducks during prolonged droughts, when most marshes dry. By maintaining a surplus of water, this habitat is able to survive drought. During the fall of 1968, a severe drought was in progress along the southwestern Louisiana coast when wintering ducks began arriving. Most marsh habitat was dry, but conditions were ideal in permanently flooded freshwater impoundments.

Snow goose use of this type of impoundment is very low; however, white-fronted geese are often found in great numbers in such habitat on the Lacassine National Wildlife Refuge. The birds will feed in nearby harvested rice fields and use the impoundment as a rest area.

Coot, Gallinules, and Rails

The American coot frequents this impoundment type and birds will remain there throughout the winter. Highest quality habitat is provided for gallinules during both the breeding and wintering seasons where floating mats of vegetation are available. Rails also use the area, but to a lesser degree.

Wading Birds

Shallow water must be available for this type of impoundment to attract wading birds. Prey species may be abundant but deep water limits use. Nesting rookeries are often established in this habitat where groups of trees are present on small islands. However, the birds may have to travel several miles from the rookeries to feeding areas.

Fur Animals

Muskrat use is usually limited by excessive water depths that restrict lodge building. Nutria, however, build small resting platforms with emergent vegetation and do very well in this habitat. Plant communities consist largely of species used by nutria as food. Mink and river otter also utilize this habitat when dense vegetative cover is available for denning. River otter may use the habitat and travel great distances to cover. The raccoon prefers areas with shorelines available for feeding; consequently, this impoundment-type is usually less desirable for this species.

Alligator

Excellent feeding conditions and abundant prey species for the alligator occur in habitat provided by this impoundment-type. However, nest sites are usually limited unless islands or spoil deposits are available.

Freshwater Fishes

Permanently flooded freshwater impoundments in coastal marsh provide ideal habitat for freshwater fishes when water depths are adequate. Turner (1966) sampled a 16,000-a impoundment of Lacassine National Wildlife Refuge and found standing crops ranging from 84 to 91 lb (38 to 41 kg) per acre. Largemouth bass (*Micropterus salmoides*), redear sunfish (*Lepomis microlophus*), and warmouth (*Chaenobryttus gulosus*)(all favorites with sport fishermen) were predominant species. Deep canals adjacent to levees and boat trails in the marsh were important as fish travel lanes during drought periods.

Estuarine Fishes

Freshwater marshes, whether impounded or not, are usually unfavorable habitat for estuarine fishes.

Crawfish

This habitat will support populations of crawfish, but breeding habitat may be limited to areas adjacent to levees or islands. Numerous aquatic predators also reduce crawfish numbers.

MANIPULATED FRESHWATER IMPOUNDMENTS

Marsh impoundments of this type are usually located inland from the normal influence of tides. A water manipulation system is usually conducted to affect plant growth. Impoundments managed for ducks are drained during the growing season to encourage germination and growth of annual plants. The major species produced by drying are grasses and sedges, such as wild millet (*Echinochloa walteri*), fall panicum (*Panicum dichotmiflorum*) and fragrant flatsedge (*Cyperus odoratus*)(Chabreck 1960; Baldwin 1967; Carney and Chabreck 1978). Other plants often found in this type are bulltongue, California bulrush (*Scirpus californicus*), and spikerushes. Water depths are usually held at low levels (2 to 18 in or 5 to 46 cm) to make the areas attractive to dabbling ducks. Crawfish are produced in abundance by this management system and provide a food source to many forms of wildlife.

Waterfowl

This type impoundment is usually managed for dabbling ducks; consequently, it is only normal to expect high usage by this group. A study by Chabreck *et al.* (1974) disclosed that dabbling duck use was over four times that of adjacent nonimpounded freshwater marsh. Major use was by seed-eating dabblers. Diving ducks, mainly lesser scaup (*Aythya affinis*), increased as water depths increased in the area, and dabbling duck populations declined under the same conditions. Snow geese often concentrate in this impoundment-type.

Coot, Gallinules, and Rails

Coot and rails use the impoundments quite heavily, but gallinules do not show any particular preference for the type. Rails prefer areas with shallow water depths and remain abundant in the impoundments as long as water depths are favorable and escape cover adequate. Coot numbers increase in late winter when annual plants lodge and large open bodies of water form.

Wading Birds

Wading birds are attracted to the impoundment by shallow water conditions and the abundance of invertebrates, mainly crawfish, available as food. Also, as water is gradually removed during the growing season, shallow isolated pools are created and wading birds flock to the area to feed on stranded aquatic organisms.

Fur Animals

Habitat available in this impoundment-type is highly preferred by most fur animals, particularly species such as mink, raccoon, and river otter, which feed on crawfish. The type is also favorable for nutria, but the muskrat occurs only in small numbers. As available cover diminishes in late winter, fur animal use declines.

Alligator

Freshwater impoundments are heavily used by the American alligator; and, like most other carnivores, the alligator is attracted by the abundance of crawfish. These impoundments also provide good nesting habitat for the alligator; however, removal of water too early in the spring (prior to June) may simulate drought conditions and reduce nesting efforts (Joanen 1969).

Freshwater Fishes

Although a freshwater environment is provided, freshwater fish production is curtailed by the drying process. Freshwater fish habitat is only provided in canals or deep channels not subject to drying.

Estuarine Fishes

Impoundments of this type are normally constructed in freshwater marsh and such marsh is usually considered unfavorable habitat for estuarine fishes.

Crawfish

Manipulated freshwater impoundments are used in aquaculture for growing crawfish (Perry *et al.* 1970). Water is removed in early summer to enhance crawfish reproduction and remove predators of crawfish (mainly fishes). Marshes managed by this process often produce in excess of 500 lb (227 kg) of harvestable crawfish per acre.

PERMANENTLY FLOODED BRACKISH WATER IMPOUNDMENTS

Impoundments of this type are usually managed to produce widgeongrass (*Ruppia maritima*) for the purpose of attracting ducks (Chabreck 1960). A survey of marsh impoundments in South Carolina disclosed that the permanently flooded brackish water impoundment was the type used most often in that state (Morgan *et al.* 1975). Although the impoundments are described as permanently flooded, drainage at 2- to 3-yr intervals is necessary for best widgeongrass growth.

Waterfowl

The impoundments are used heavily by gadwall, American wigeon, and lesser scaup, which are attracted by dense stands of widgeongrass. The type is used to a much lesser extent by other dabbling ducks and use is regulated by water depths. The type does not normally receive use by snow geese.

Coot, Gallinules, and Rails

The impoundments receive high use by coot, and the birds will congregate in dense flocks shortly after fall migration. Concentrations of coot and ducks often become so great that widgeongrass food supplies may be depleted early in the wintering season. Gallinules do not frequent this habitat and rails are often excluded by water depth or lack of protective cover.

Wading Birds

Wading bird use is usually curtailed by excessive water depths. Very often, only impoundment edges are used by the birds. However, Provost (1967) reported that overall bird usage of salt marshes was increased by permanent flooding as part of a mosquito control program in Florida.

Fur Animals

Fur animal populations are usually low because of inadequate protective cover and food supplies. Plants, preferred as food by muskrat and nutria, and prey species, used as food by carnivores, are absent or in very limited supplies.

Alligator

Habitat conditions provided by this impoundment-type are not favorable to the alligator. Water salinities are often above the tolerance levels of small alligators and summer food supplies are usually inadequate for attracting large animals. Brackish marshes, whether impounded or natural, are not preferred habitat for alligators.

Freshwater Fishes

Marshes with high water salinities, whether impounded or not, are unfavorable habitat for freshwater fishes.

Estuarine Fishes

Brackish marshes and associated water bodies serve as a vital nursery area for estuarine fishes, and levee systems used for impoundments block their ingress and egress from tidal channels. Also, organic detritus from marsh plants serves as a primary food source for estuarine fishes, and levee systems block the movement of this material into estuarine waters. However, when brackish water impoundments are drained, detrital material is flushed out and becomes available as a component of the aquatic food chain.

Crawfish

Brackish marshes, whether impounded or not, are unfavorable habitat for crawfish production.

MANIPULATED BRACKISH WATER IMPOUNDMENTS

Impoundments are often constructed in tidal marsh and alternately flooded with brackish water and drained to encourage growth of duck food plants. Brackish water impoundments used for mariculture are also included in this category; however, marsh impoundments have been used only to a very limited extent for mariculture. Impoundments of this type comprised approximately 10% of the total area in marsh impoundments in South Carolina (Morgan *et al.* 1975).

Waterfowl

Neely (1960) described a procedure for growing saltmarsh bulrush (*Scirpus robustus*) in brackish water impoundments in South Carolina that involved flooding and draining the area on a monthly cycle during the growing season. Water was kept at a depth less than 12 in (30 cm) and dabbling ducks, such as mallard, pintail, and black duck (*Anas rubripes*), could easily reach the bottom for feeding. Such impoundments provide excellent dabbling duck habitat and are also used by diving ducks and snow geese. Dwarf spikerush (*Eleocharis parvula*) and widgeongrass grow along the shoreline of ponds or in openings among stands of saltmarsh bulrush and also provide food for waterfowl.

A similar management system is used in Louisiana and involves prolonged drying during the spring and early summer to produce saltmarsh purslane (*Sesuvium maritimum*) and dwarf spikerush. Dabbling duck usage of such impoundments is very high.

Coot, Gallinules, and Rails

Coot are attracted to habitat as provided by this impoundment type. Also, the clapper rails use the shorelines of ponds. Gallinules generally avoid brackish marshes regardless of management practices (Lowery 1974a).

Wading Birds

The cycle of flooding and draining attracts wading birds and conditions for feeding are ideal until mid-summer when vegetation growth becomes very dense. However, water is maintained at shallow depths and shoreline areas remain attractive.

Fur Animals

This impoundment-type provides ideal habitat for fur animals. Abundant cover, food, and feeding conditions are available for both herbivores and carnivores. Impoundments containing saltmarsh bulrush provide better fur animal habitat than those with saltmarsh purslane.

Three-cornered grass (*Scirpus olneyi*), a highly preferred food of muskrat, nutria, and snow geese, is also grown in brackish water impoundments under a system of manipulated water levels. A marsh manager in Louisiana has harvested over 25 muskrat per acre on a 1000-a impoundment containing three-cornered grass.

Alligator

The alligator mostly occupies habitat with low water salinity and its use of brackish impoundments is minimal.

Freshwater Fishes

Brackish marshes, whether impounded or not, are unfavorable habitat for freshwater fishes.

Estuarine Fishes

Water bodies in brackish marshes are important nursery areas for estuarine fishes, and levee systems associated with impoundments block normal ingress and egress. The movement of organic detritus from impounded brackish marsh to estuarine waters is altered by this system of management; however, the system of flooding and draining provides a means by which detritus can be discharged. In fact, plant growth is enhanced by the management procedure and detritus production may actually be increased.

Lunz (1967) described procedures for mariculture in brackish and salt marsh impoundments. The procedures would likely reduce production in natural waters, but the overall production of selected estuarine species can be increased by using controlled environments.

Crawfish

Brackish marshes, whether impounded or not, are usually unfavorable habitat for crawfish.

SUMMARY AND CONCLUSIONS

Marsh impoundments are widely used in coastal regions for improving wildlife habitat, aquaculture, water storage for agricultural irrigation and industrial uses, flooding marshes for mosquito control, and maintaining favorable water depths for navigation. Impoundments can be categorized on a basis of water level and salinity regimes into four types: permanently flooded with freshwater, manipulated freshwater, permanently flooded with brackish water, and manipulated brackish water. Their effects on fish and wildlife resources vary with the resources involved and the type of impoundment.

WATERFOWL

Natural marshes, both fresh and brackish, are used by waterfowl; however, habitat conditions often deteriorate because of canal dredging and subsidence. This has resulted in widely fluctuating water levels and salinities that curtail growth of desirable food plants. Marsh impoundments are constructed as a management practice to improve growth of food plants and ensure proper feeding conditions, particularly for dabbling ducks (Chabreck *et al.* 1974; Morgan *et al.* 1975; Carney and Chabreck 1978). Diving ducks use marsh impoundments with deeper water (2 to 4 ft or 0.6 to 1.2 m). Geese show little response to impoundments managed for ducks; however, marshes which are drained and grazed by cattle are very attractive to geese (Chabreck 1968).

COOT, GALLINULES, AND RAILS

Impounding marshes improves habitat conditions for the coot because of increased food production. Largest populations of gallinules are found in permanently flooded freshwater impoundments. Permanent flooding will reduce rail use of a marsh, but manipulating water levels will increase vegetation density and improve rail habitat.

WADING BIRDS

Wading birds prefer a shallow water environment, and impoundments with manipulated water levels improve habitats for the birds. Freshwater impoundments which produce crawfish are particularly attractive. Usage of impoundments with deeper water is similar to that of nonimpounded marsh.

FUR ANIMALS

Fur animals are greatly affected by cover and food availability. Freshwater impoundments usually contain higher nutria, mink, and river otter populations regardless of water levels. The raccoon favors fluctuating water levels and highest populations occur where food, such as crawfish, is abundant. Muskrat generally do poorly in marsh impoundments managed for ducks; however, impoundments can be managed for muskrat to increase populations.

ALLIGATOR

The American alligator prefers a freshwater environment and marsh impoundments can be managed to maximize alligator production. Freshwater marsh impoundments can be managed for ducks, and still benefit the alligator, by properly timing the dewatering cycle to correspond with alligator nesting. Food production and feeding conditions are improved by impounding.

FRESHWATER FISHES

Production of freshwater fishes is increased in marshes in permanently flooded freshwater impoundments. In nonimpounded marshes, freshwater fishes are limited to deeper channels.

ESTUARINE FISHES

Tidal channels and ponds in brackish marshes are a vital nursery area for estuarine fishes. Levee systems used for impounding brackish marshes block normal ingress and egress of aquatic organisms and reduce the size of nursery areas. A system used on Rockefeller Wildlife Refuge in southwestern Louisiana permits entrance of estuarine fishes and crustaceans (mainly shrimp) by opening water control structures on high tide when postlarval forms are present. Young shrimp grow very rapidly and are harvested by sport fishermen with cast nets several months later as they concentrate at the structures to exit. Other procedures for mariculture in brackish water impoundments were described by Lunz (1967) as a method for increasing production of selected species.

Organic detritus from marsh plants is a basic component of aquatic food chains, and levee systems of impoundments will alter the flow of detritus to tidal waters. If brackish water impoundments are drained periodically, detritus is discharged into tidal channels.

CRAWFISH

Crawfish require a freshwater environment, and marsh impoundments that are drained during the summer and reflooded in fall produce abundant crops of the crustaceans. Crawfish are a major food item of many other species of fish and wildlife and provide a commercial and recreational resource for man. Natural freshwater marshes produce crawfish, but production is maximized in manipulated freshwater impoundments (Perry *et al.* 1970).

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EFFECTS OF ALTERED FRESHWATER INFLOW
ON ESTUARINE SYSTEMS

Neal E. Armstrong[1]

ABSTRACT

Alteration of freshwater inflow to estuaries is of concern to those who study and manage estuaries because of the potential impact of such alterations on the biota, particularly commercially important species. A framework and methodology for estimating these impacts is presented along with examples of previous studies relating freshwater inflows to biological changes in estuaries.

INTRODUCTION

A continuing concern of those who study and manage estuaries is the impact of altered freshwater inflows to these systems. By definition, estuaries are mixtures of salt and freshwater. The ratio of the amounts of these two waters, coming from tidal exchange with the ocean and inflowing fresh water, respectively, and the mixing characteristics of the estuary, determine the salinity patterns of the estuary. Organisms inhabiting an estuary are largely those able to occupy the niches created by prevailing salinities and temperatures. Alterations of freshwater inflows change the salinity width of the niche and may preclude some species, perhaps commercial species, from inhabiting the estuary. This latter effect is of most concern to commercial fisheries management agencies.

Freshwater inflow alterations may be increases or decreases in natural flows, the alteration of temporal inflow patterns, and/or the moderation of maximum and minimum inflows. These alterations may be due to upstream consumption of fresh water during municipal, industrial, and agricultural use, impoundments, or perhaps transfers of water into or out of the drainage basin.

Attention has been given to the problem of freshwater inflow alterations in recent years, notably in studies conducted by the Texas Department of Water Resources along the Texas coast. Recently the U.S. Fish and Wildlife Service sponsored studies, first in Corpus Christi Bay, Texas by Henningson, Durham and Richardson, Inc., and Texas A&M University, and in Matagorda Bay, Texas by Espey, Huston and Associates, Inc. and the University of Texas at Austin. All of these studies are incomplete at present but the procedures used are similar.

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This presentation will include some descriptions of possible approaches to determine the freshwater inflow requirements of estuaries both spatially and temporally. A framework for analysis of this problem will be presented with examples of some of the methods that have been used to date.

FRAMEWORK

ELEMENTS OF FRAMEWORK

The framework for determining the amounts and scheduling of freshwater flows must include the goals to be achieved by meeting freshwater requirements and the competing uses of that freshwater (Figure 1). Assuming that ecological goals for a selected estuary have been established, the first task is to determine the levels of water quality needed to achieve those goals. For estuarine organisms, temperature, salinity, dissolved oxygen, nutrients (primarily carbon, nitrogen and phosphorus), and contaminants are the water quality variables of concern. Tolerance limits (levels of variables above and below which an organism or one of its life stages will not survive and the changes in growth rates over this range), preference levels (levels of these variables which a mobile organism or one of its life stages will select if given a choice) and growth kinetics relationships (growth rates, death rates, substrate utilization rates, yields, productivity, Michaelis constants, food preference, minimum substrate concentrations, and so forth) are ecosystem function properties which are used to determine the required levels of water quality, or water quality criteria (not standards) needed to maintain an organism or a community of organisms. In an estuarine system, this is especially important because of the need for certain communities to function as a unit, not as single parts; for example, the seagrass system or the emergent marsh system must function as subcommunities within the total estuarine community. Therefore, the water quality levels chosen must reflect the needs of the shoalgrass as well as the major class of larval fishes which may inhabit it.

The second task is to determine the spatial and temporal distribution of freshwater flows to the estuary needed to meet these goals and criteria. It is well-known that certain organisms which inhabit estuaries rely on the timing of freshwater flows and the magnitude of these flows for the availability of certain levels of salinity and/or the influx of organic and inorganic materials. These particular salinity and/or food requirements must be met in various geographical areas of the bay system and at the times that the organisms are in those areas. Information about natural inflow rates and occurrence is needed, as well as information which describes the organisms' preference for or reaction to various levels of salinity, temperature, nutrients, and contaminants. A technique is also needed to determine the impacts of these inflows on the water quality of the bay.

Once the freshwater flow needed to maintain ecological goals has been determined, the third task is to formulate the release schedules from existing or proposed upstream reservoirs (Figure 1), the priorities for meeting these needs, and the operational policies of those reservoirs.

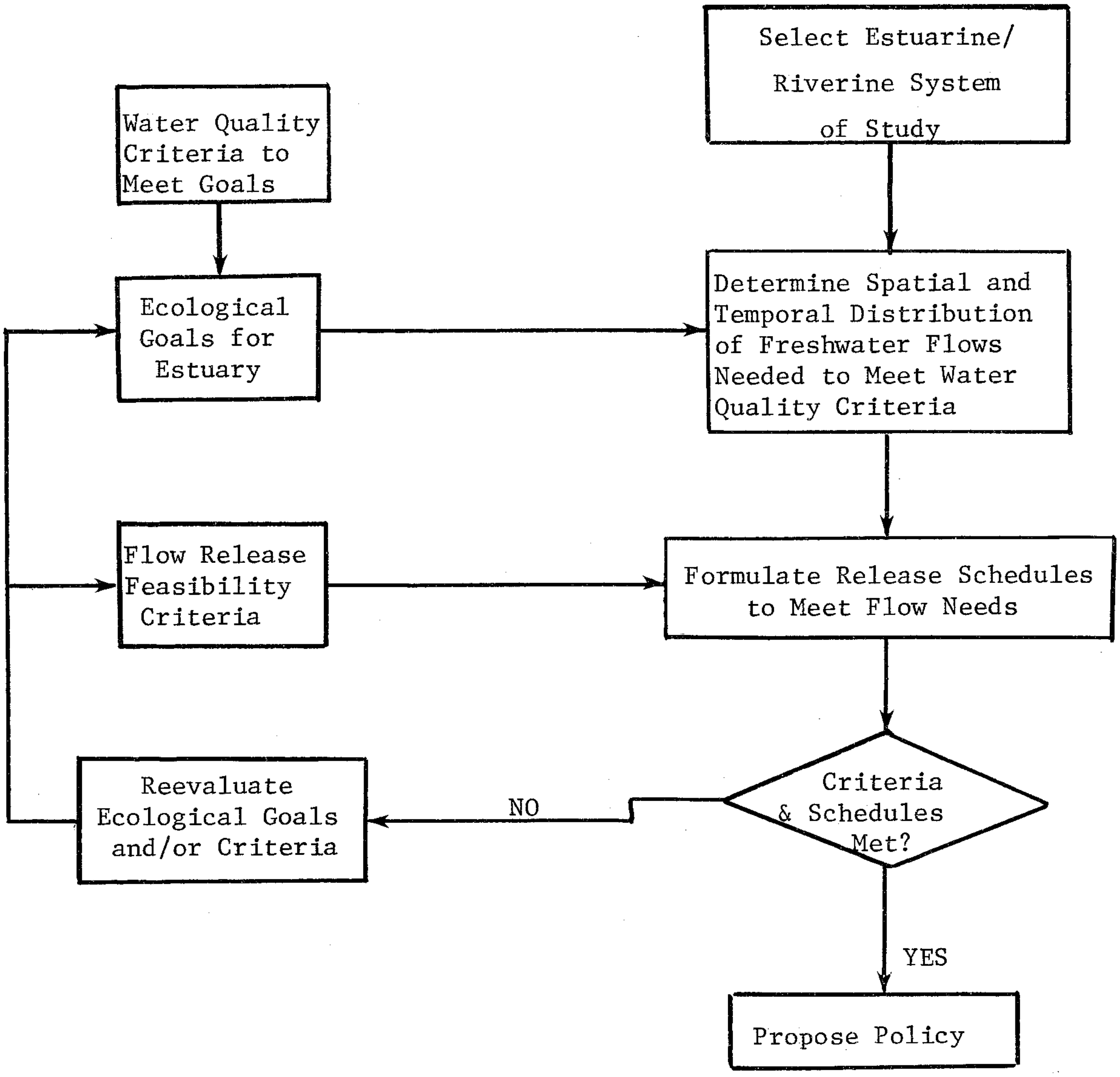

Figure 1. Framework for determining freshwater release schedule policy.

Once the release schedules have been estimated, the fourth task is to determine whether the ecological goals of the estuary and the flow release schedules may be met individually and/or simultaneously. If either the goals or the criteria may not be met, then each or both must be reevaluated and the analysis repeated until they are met. If the goals and criteria are met, then an operational policy may be proposed so that the appropriate government regulatory agency is able to develop a freshwater flow release policy based on a sound scientific rationale.

CRITICAL ELEMENTS

There are three critical elements in this framework for determining freshwater release needs. The first is the determination of appropriate water quality levels needed to sustain the diversity and productivity of the bay system. The second is the process or predictive basis by which the effects of spatial and temporal distributions of freshwater flows are determined. The third is the determination of the quantity and scheduling of the freshwater inflows.

Water Quality Criteria

Appropriate water quality levels or criteria can be determined in several ways. The most immediately useful way is through a literature search and evaluation. Where data are lacking or where it is questionable whether laboratory data can be extrapolated to the field, a second method is the application of various statistical techniques such as regression and ordination to existing data. For example, Copeland and Bechtel (1974) effectively used catch data for fish and shellfish and associated water quality and geographical data to determine environmental limits for salinity, temperature, location (and, in a sense, depth), and dissolved oxygen. Bascom and his staff (SCCRP 1975) used clustering techniques to relate presence and abundance of benthic organisms to sediment quality characteristics. Such techniques can be applied to field data gathered previously or during a study to develop limits specific to some estuary. A third way is through special field studies for: productivity, effects of large amounts of suspended solids from dredging, and effects of thermal wastes. Such studies normally involve gradient analysis examination of community structure and function along a gradient of temperature, salinity, nutrients, dissolved oxygen, or contaminants. A quasi-field technique, the laboratory microcosm, involves placing an intact piece of the natural system in the laboratory for study under controlled conditions. A fourth way is through special laboratory experimental studies such as algal growth bioassays or toxicity bioassays, to derive specific growth function or tolerance limits data. Such tests are costly however.

Mathematical Models

The second critical element incorporates the use of water quality and ecological mathematical models. Mathematical models can be divided into four components (Figure 2). The first component is the source or input data, which normally contain flow and quality information about freshwater, return, and saltwater inflows. The second component is the transport model, which

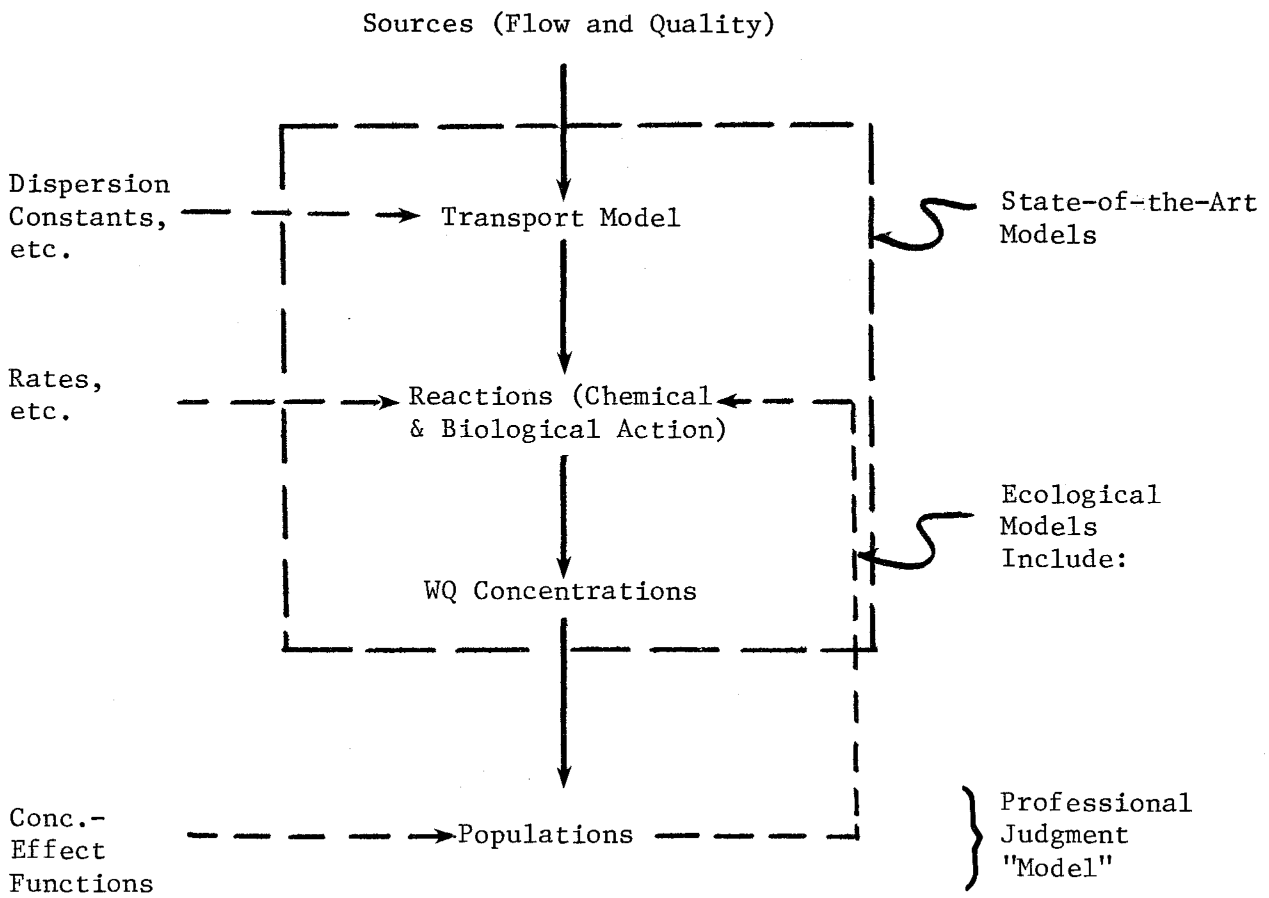

Figure 2. Conceptual components of estuarine models.

incorporates the advective and dispersive transport mechanisms of the aquatic system. The third component includes the reactions by which discharged materials change their chemical form or presence in the water phase due either to physiochemical reactions or to biological action on these materials. (In most mathematical models, the biological action is treated independently of the effects of the materials on the organisms themselves.) The end results of the transport and reaction model are predicted distributions of water quality concentrations. The fourth component of these models is the prediction of the effects of these concentrations on organisms. At the present time, this element of the model is accomplished for the most part by a professional judgement; that is, the predicted water quality concentrations are interpreted by a knowledgeable ecologist as to their effects on the organisms present in the aquatic system, based on the water quality levels or criteria developed above. Some ecological models now incorporate populations (or biomass) of organisms from lower trophic levels within the model itself and the water quality concentrations of materials which affect the growth and survival of the organisms. Thus, the concentration vs. effects relationships are input at the population component. Further, the population information is fed back to the reaction portion of the model so that the transformation of chemicals due to biological action is now a function of the populations of the organisms causing the action, as well as the rate at which the action occurs.

The state-of-the art models, *i.e.* those models whose output may be confidently interpreted, are also delineated in Figure 2. As is evident, they do not include models that incorporate populations of organisms. A number of ecological models have been developed, and with experience the state-of-the-art will extend to them eventually. At present, however, the ecological models which have been successfully verified consider relatively simple trophic interdependencies, *e.g.* planktonic models or models of single species and well-defined fisheries. Ecological models of the complexity capable of treating specific higher-level species in estuaries are in, at least, a formative stage.

In discussing the applicability of a model to a particular problem one frequently refers to the stage of "development" of that model. As any model is an idealization of the complex processes operating in a real estuarine system and is improved as the understanding of each of those processes is improved, any model can be said to be "in development". Whether a model can be considered operable for a particular problem requires that: 1) the basic computer program has been developed and thoroughly tested for satisfactory operation; and 2) the principal natural processes affecting the problem of interest are incorporated in the model formulation and have been tested by comparison with real measurements over a sufficiently wide range of conditions.

The importance of the second criterion, that the model be adequately tested against observation, cannot be overemphasized. This testing, the process of "calibration", is probably the single most important and costly aspect of model development. Though a computer program may be completely operational and yield realistic-appearing calculations (*e.g.* of currents, salinity, etc.), the only satisfactory test of a model's adequacy is by direct comparison with measured data. The spectrum of processes operating in real estuaries and the range of possible interactions are too great to accept a model as operational without direct testing against the real world. "Calibration" is system -specific. The fact that a model is verified for application to one bay does not obviate the need for calibration for any new system to which that model is applied (Espey, Huston, and Associates, Inc. 1978).

By exercising the mathematical models for the aquatic system of concern, freshwater inflows (or saltwater influxes from the ocean) may be correlated with changes in water quality (*e.g.* salinity, temperature, dissolved oxygen, nutrients, contaminants) at any point in the aquatic system. Using this correlation and the water quality criteria, professional ecological judgement is required to determine which salinities are needed in various parts of the bay for the species which inhabit these areas and for the time of inhabitation. In this way, the salinities which determine the presence or absence of these organisms may be related to the freshwater inflows required to maintain those levels. It must be remembered that water quality requirements may vary for different types and life stages of organisms. The freshwater inflows determined by this procedure must be translated into freshwater flow quantities and schedules, and this involves the third critical element of this framework.

Freshwater Inflow Determination

The third critical element, determination of freshwater inflow quantities and schedules, must be established through careful consideration of the natural freshwater flows in the drainage basin of the bay system, any reservoirs or natural lakes which occur in the basin, and the operating criteria for reservoirs if they exist. By using historical records of freshwater flows, or synthesized records as can now be obtained using sophisticated mathematical models, freshwater inflows to the bays may be estimated. Statistical analysis can then be made of the frequencies by which the required freshwater-inflow quantities and timings are achieved to satisfy the water quality requirements of the organisms. This information would then be used by the various regulatory agencies involved to judge whether these flows were adequate for maintaining the species desired, as well as meeting other competing uses of those waters, and to operate the reservoirs to provide these necessary flows. Such an analysis necessarily incorporates the various types of operating policies for the reservoir and various levels of risk of not achieving the required salinities, nutrient levels and temperature for certain species.

In a report from the National Academy of Science to the National Commission on Water Quality (National Commission on Water Quality 1976), for which Parker and Armstrong (1974) prepared an original text, a protocol for examining biological impacts of perturbations, such as altered freshwater inflows, was proposed based on the data available for analysis. The data available in natural systems range from essentially no biological data with minimal water quality data, to systems for which there is a substantial amount of biological structure data with substantial water quality data, to systems for which there are not only biological structure data but also biological function data as well as substantial water quality data. One's ability to assess biological impact then becomes a direct function of data available. For example, with essentially no biological data, one can only compare water quality levels under the influence of a perturbation with general water quality criteria. Perturbations that cause changes in water quality such that these criteria are violated would be considered undesirable. This approach might be entirely satisfactory for some situations, but relies heavily on general water quality criteria, which may not be applicable to the location under consideration.

With a substantial amount of biological structure data, one can refine the water quality criteria as they apply to specific organisms and their tolerance limits (as determined from the literature) for various life stages. Now, one is able to compare the water quality produced by the various perturbations against the water quality requirements for specific organisms and test whether the criteria are violated. While this approach becomes more precise for specific organisms, it does use tolerance limits and this implies an organism is stressed in some way before a level of tolerance is reached. This would imply that the water quality produced by the perturbation may indeed meet water quality requirements but may still be stressful to the populations in a way that could not be measured immediately or noticeably.

To move beyond the tolerance limits constraints requires that one have function data (*i.e.* growth kinetics, productivity, community metabolism, and other similar measures, all as functions of environmental conditions). Function data alone provide one with a measure of the state of the system; but unless they are related to environmental conditions, they may not permit one to predict the future state of that system given some change in environmental conditions. Now, one is able to carry out more sophisticated analyses with increasing data availability. However, the analyses become more complex and interpretation more difficult; and one begins to surpass the present state-of-the-art of biological assessment.

EXAMPLES

COMMUNITY APPROACH

Armstrong and Hinson (1973) examined the freshwater inflow requirements of Galveston Bay as part of a toxicity study. They made use of the data of Copeland (1966), which correlated commercial catch of fish and shellfish in Texas Bays with the previous year's freshwater inflow. Because each of the Texas estuaries examined by Copeland (1966) had different geographic and hydrographic characteristics, it was difficult to compare the correlations of catch vs. freshwater inflow from one bay to another. Armstrong and Hinson (1973) rearranged the data by converting the catch data to catch per unit bay surface area per year and the hydrographic data to hydraulic displacement rate (annual freshwater inflow divided by bay volume at Mean Sea Level). A common graph, with both scales normalized in this fashion, can be drawn (Figure 3). The figure shows that catch increases with increasing displacement rate (or increasing freshwater inflow). However, for each bay there is a peak catch rate which occurs approximately at a displacement rate of 0.5 yr-^{1} for Aransas and

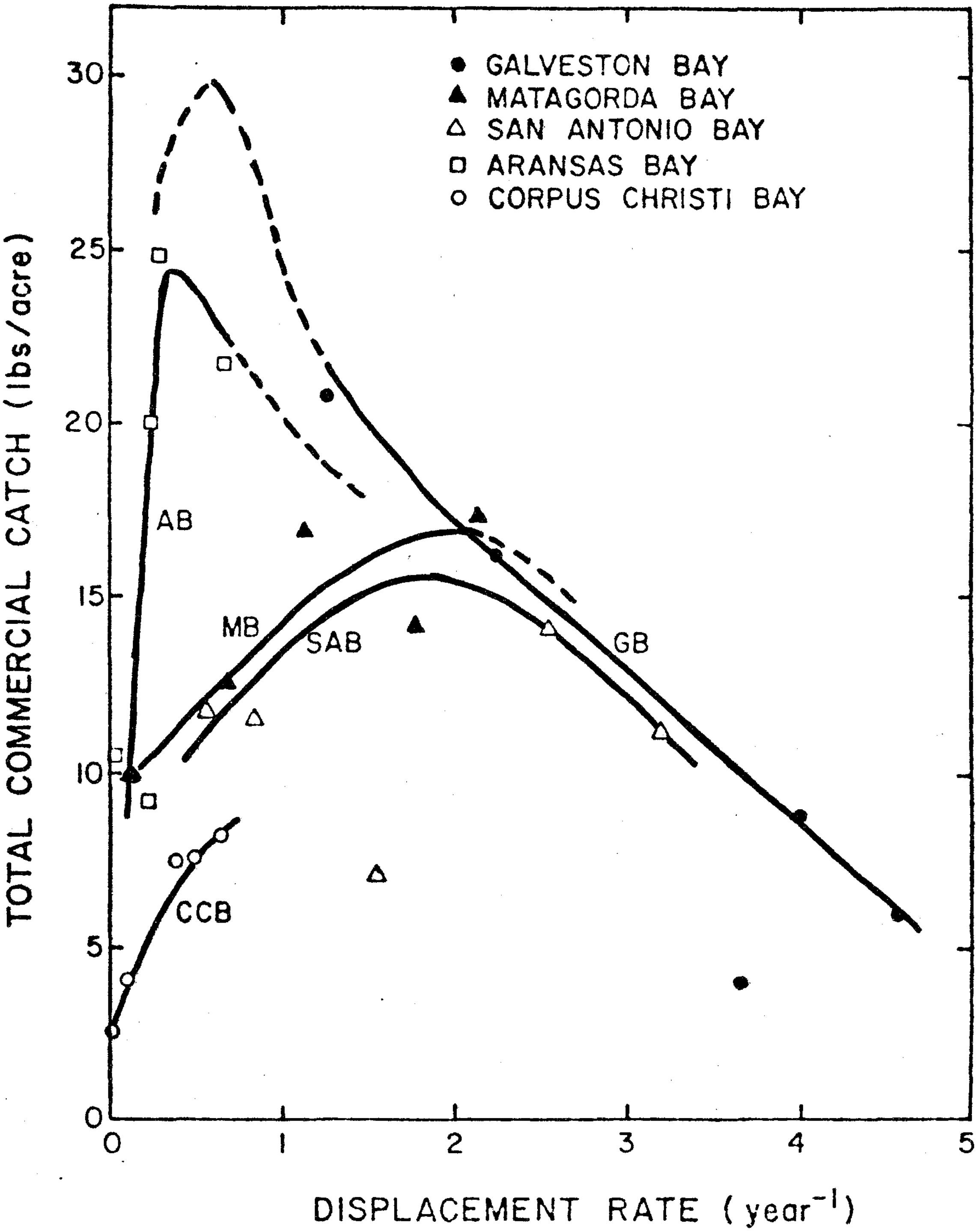

Figure 3. Relation of annual commercial catch with freshwater inflow to Galveston Bay (1959-1964)(Armstrong and Hinson 1973).

Galveston Bays and 2.0 yr^{-1} for Matagorda and San Antonio Bays. Corpus Christi Bay never reached a peak. With increasing displacement rate there is an increase, then a decrease, in annual catch. The increase in annual catch with displacement rate results from (1) the decrease in salinity to a suitable level, (2) the impact of river-borne organic and inorganic nutrients, and (3) perhaps increased nutrient release from sediment deposits due to mixing. The decrease could be due to (1) excessively low salinities during critical times of the life stage of organisms in the estuary, (2) flushing of nutrients needed for larval and juvenile growth out of the bay system, and (3) possibly even the flushing of larvae out of the bay system. Theoretically, a freshwater inflow could be chosen to sustain high catch rates. This approach, while interesting, does not begin to deal with the individual fish and shellfish species in the system and remains a gross, and perhaps inaccurate, example of freshwater inflow effects on estuaries.

Another community approach is that conducted by Cooper and Copeland (1973) using the microcosm technique. A series of five aquaria, interconnected to allow exchange of fresh- and saltwater among them, were operated so that the salinities in the aquaria matched those in Trinity Bay, Texas. These aquaria were seeded with organisms from Trinity Bay and permitted to stabilize. Changes in the ratio of freshwater inflow to saltwater inflow were made to simulate drought conditions. Community metabolism and phytoplankton and zooplankton populations were monitored during this period. Cooper and Copeland (1973) concluded that estuarine systems are reliant to some extent upon freshwater input for their productivity and that the quantity and quality of river inflows must be managed to provide optimum levels.

POPULATION APPROACH

The Texas Department of Water Resources has developed a migration model of the white shrimp (*Penaeus setiferus*) in an attempt to refine a correlation between freshwater inflows and catch data (Texas Department of Water Resources 1978). The description below is summarized from their report.

The migratory organism model was developed from preliminary data analysis and existing knowledge of interactions of environmental conditions, such as inflows, hydrodynamics, and biological processes in San Antonio Bay. This model evaluates the magnitude and seasonal fluctuation of important environmental parameters (*e.g.* freshwater inflow, salinity, and water temperature) and shrimp physiology, and groups them according to an environmental accounting or scoring program. While the scoring is rather complicated, high scores are given for those environmental conditions existing during good shrimping periods and low scores for conditions during poor shrimping years. The model assigns scores to portions of the tolerance limit range of the white shrimp, high scores for the optimal portion, lower scores for non-optimal portions. Through the adjustment of environmental limits, scores, and weighting factors (*i.e.* model coefficients), a "best-fit" curve can be obtained between catch data and scores using data for the 1962-1970 period. An example of the calibrated results obtained for this period are shown in Figure 4 for freshwater inflow.

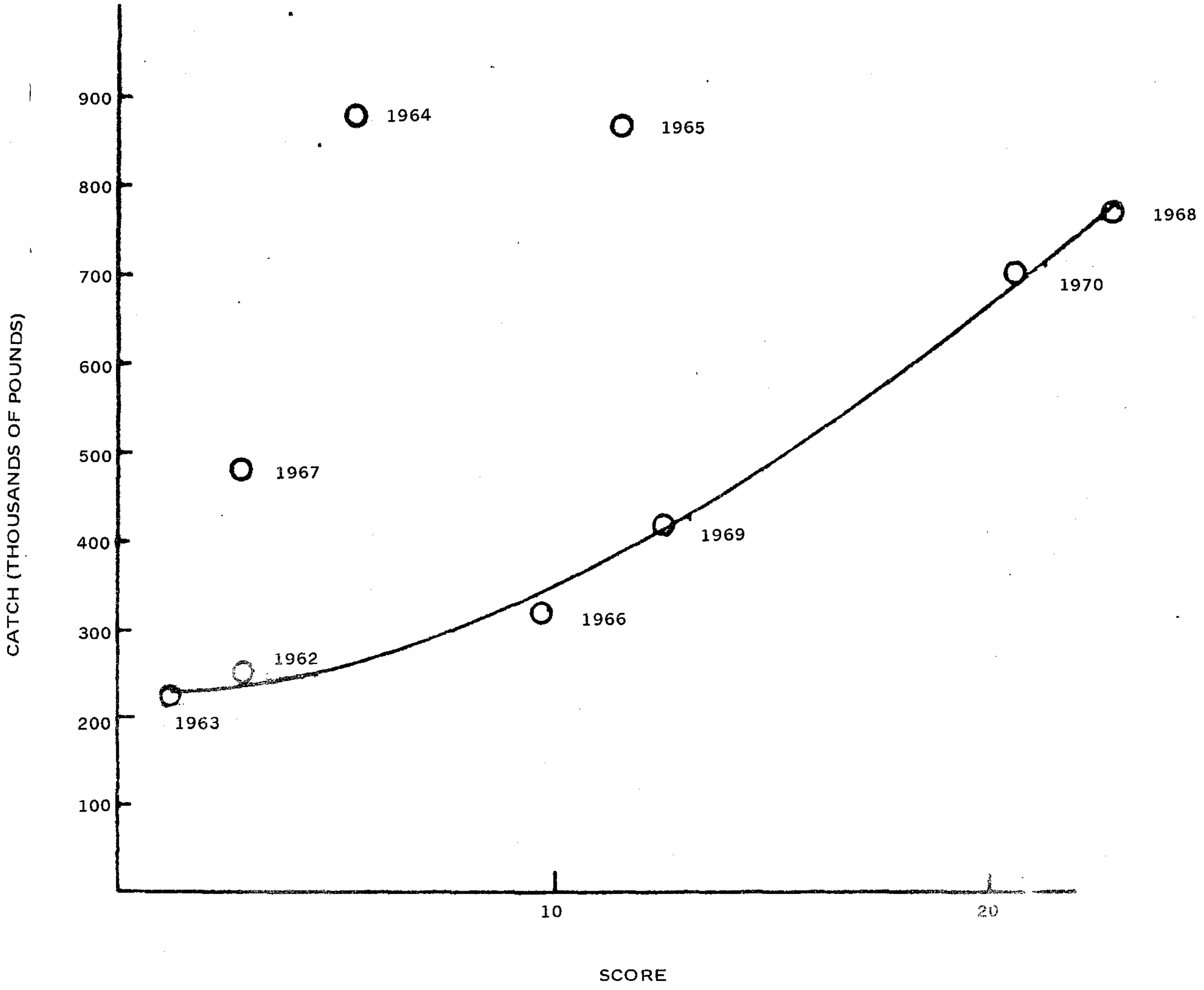

Figure 4. Relation of environmental score of migratory organism model to freshwater inflow for white shrimp in San Antonio Bay (from Texas Dept. of Water Resources 1978).

As illustrated, scores for 1962, 1963, 1966, 1968, 1969, and 1970 lie on a smooth curve, whereas 1964, 1965, 1967 do not relate to the curve. The reasons for the latter years to deviate from the graph were not entirely clear. Again, however, a freshwater inflow pattern could be chosen to enhance the probability of good shrimping years.

INDIVIDUAL APPROACH

An example of the approach using a single individual as an indicator organism is the study performed by Lambert and Fruh (1976). They used the spotted seatrout (*Cynoscion nebulosus*) in Corpus Christi Bay as their example. Basically their study consisted of modeling the hydrology of the Corpus Christi Bay drainage area and determining the freshwater inflows under various drought and flood conditions, reservoir operation regimes, and downstream uses. A two-dimensional mathematical model of Corpus Christi Bay was used to determine the effects of these inflows on salinities throughout the bay. Correlations between salinity, key points (Figure 5) in the bay, and freshwater inflows were developed. Data for a key station in the seagrass beds of Redfish Bay were used to determine the effects of freshwater inflows on the seatrout (Figure 6). The reproduction requirement of 27‰ (parts per thousand) salinity was chosen as the working criterion which should be met between April and September in the grassflat areas of Redfish Bay. Using the graph correlating salinity and freshwater inflow at that location, they determined that a certain freshwater inflow was required to maintain this particular salinity (27‰) at this key location at the appropriate time of year. Based on that single requirement, an operational policy can be proposed for the upstream users of freshwater so that the downstream constraints can be met.

SUMMARY

An overall approach to managing freshwater inflows to estuaries has been presented with specific examples of how this might be done in several estuaries. In reality, the method one chooses is in large part a function of the data available for the analysis.

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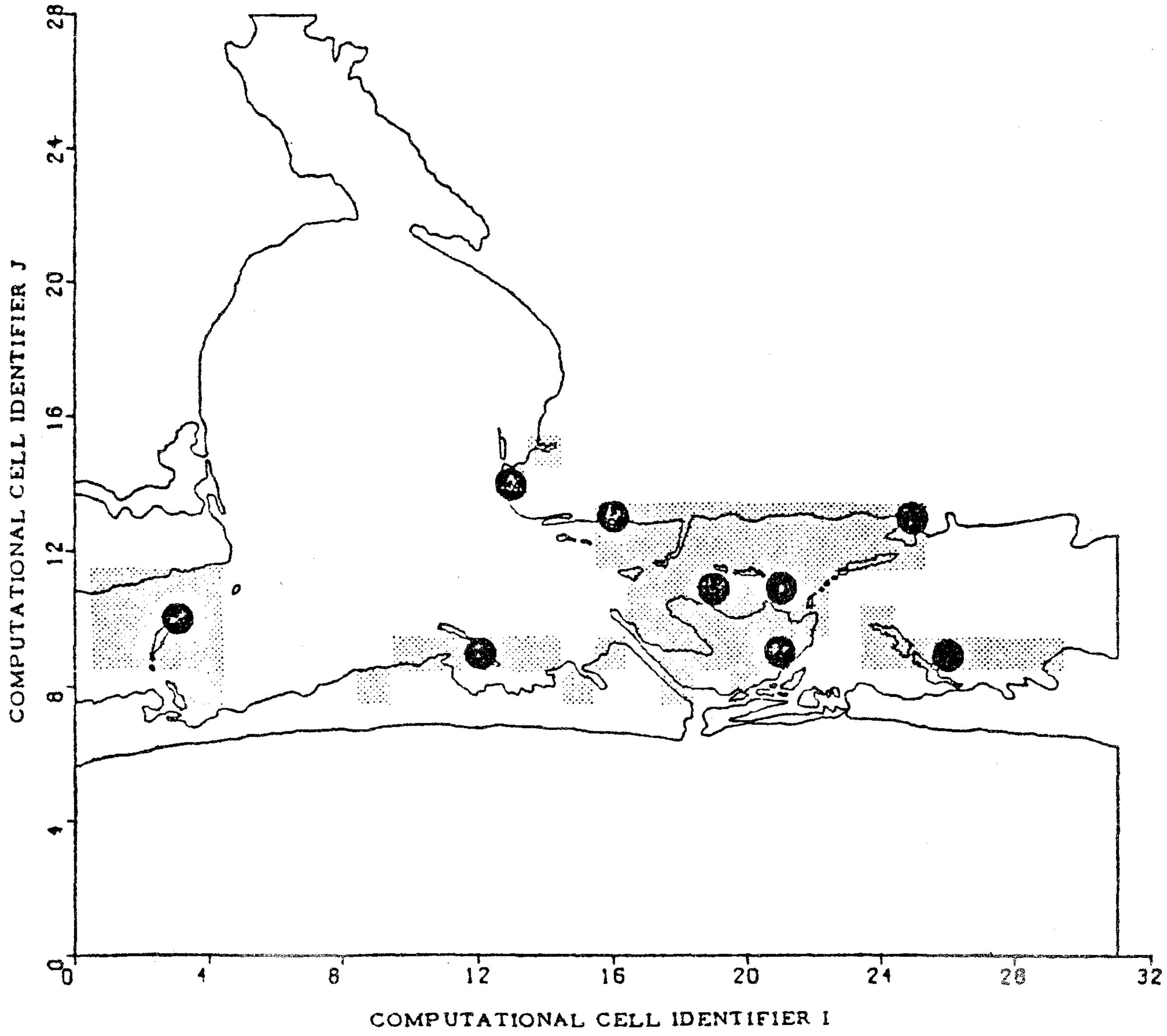

Figure 5. Computational cells (black circles) identified as grassflat areas (shaded) and as indicator cells for the analysis of steady-state computed salinity profiles of the Corpus Christi estuary (from Lambert and Fruh 1976).

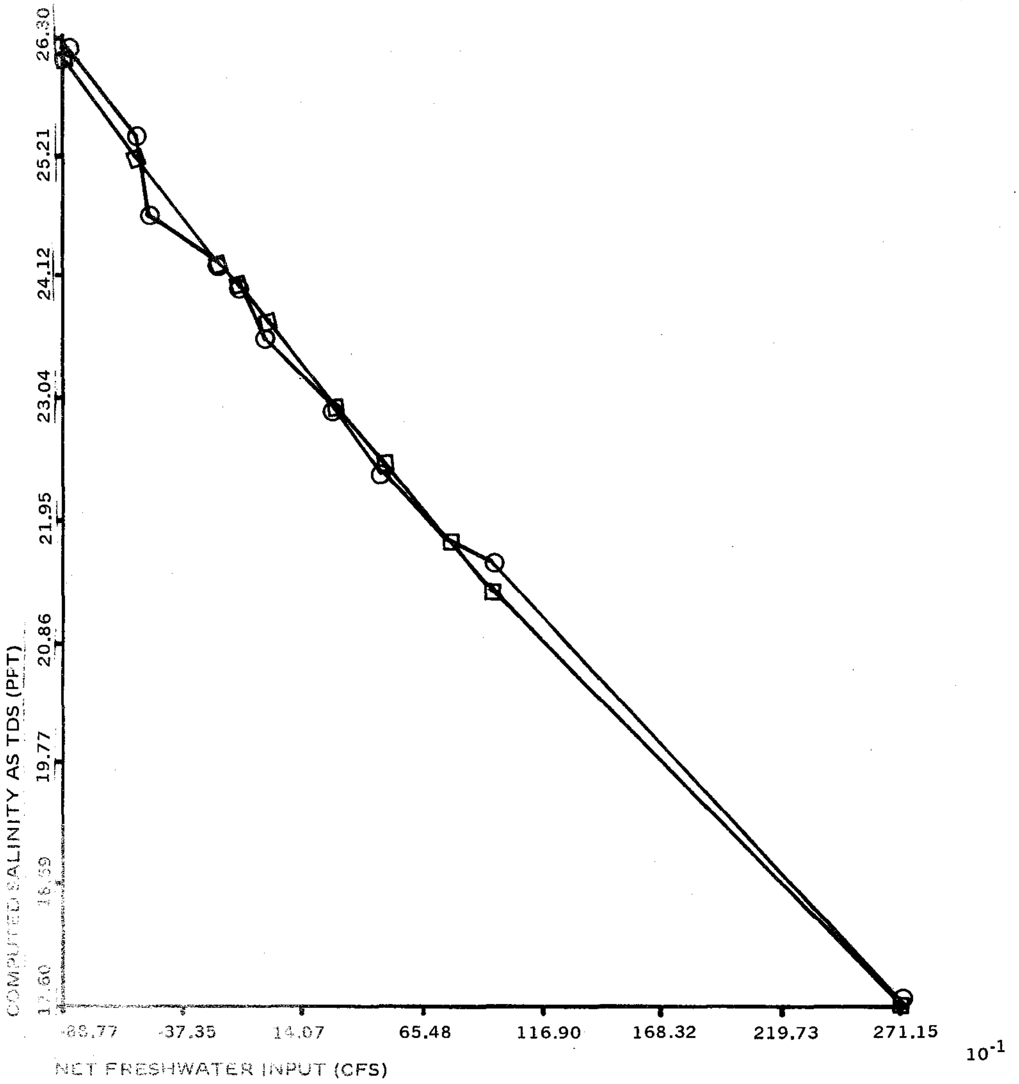

Figure 6. Relationship between total net freshwater inflow and computed steady-state salinity at indicator cell (26, 9), Redfish Bay area, for May, June, and July (from Lambert and Fruh 1976).

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CONTRIBUTION OF WOODED SWAMPS AND BOTTOMLAND FORESTS TO ESTUARINE PRODUCTIVITY

John W. Day Jr., William H. Conner, G. Paul Kemp[1]

INTRODUCTION

Cypress swamps and bottomland forests are important ecosystems in the southeastern United States. Some of the largest are well-known, including the Atchafalaya in Louisiana, the Okeefenoke in Georgia, and the Big Cypress in Florida. However, most rivers have swamps and bottomland forests associated with them, especially in their lower reaches.

The value of these ecosystems for wildlife habitats and water regulation is well-recognized, but studies of the ecology and management of estuaries have rarely taken the role of these freshwater systems into consideration. Recent evidence suggests that in many cases, swamps and bottomlands play an important role in estuarine productivity. Four objectives of this paper are to: 1) review the ecology of swamps and bottomland forests; 2) describe ecological couplings between these systems and estuaries; 3) discuss the impacts of human activities on both swamp ecology and swamp-estuary couplings; and 4) briefly suggest some management approaches.

ECOLOGY OF SWAMPS AND BOTTOMLAND FORESTS

PRODUCTIVITY

Swamp forests of the southeastern United States are highly productive (Conner and Day 1976; Brown *et al.* 1979). This high productivity is related to water flow (Table 1). Odum (1979) hypothesized that both frequency and intensity of flooding is important (Figure 1), with the highest productivity occurring at sites characterized by seasonal flooding. Productivity is lower in areas with less water flow as well as in places with very strong flow. Brown *et al.* (1979) gathered all available data on forested wetlands and reported net productivity that was 40% greater in forested wetlands with flowing water than those with still water.

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Table 1. Comparative swamp productivities for the southeastern United States.

Area	References	Stem growth $g/m^2/yr$	Litterfall $g/m^2/yr$	NPP[a] $g/m^2/yr$
Des Allemands, La. (seasonal flooding)				
Cypress-tupelo	Conner & Day 1976	500	620	1120
Bottomland hardwood	Conner & Day 1976	800	574	1374
Cypress-tupelo	Conner, pers. comm.	538	417	955
Crawfish farm	Conner, pers. comm.	917	549	1466
(stagnant)				
Impounded	Conner, pers. comm.	296	328	624
Lake Pontchartrain	Cramer 1979			
Seasonal flooding		618	473	1091
Continual flooding		376	242	618
Big Cypress Swamp, Fla. (riverine)	Carter *et al.* 1973			
Drained		120	267	387
Undrained-edge strand		485	373	858
Undrained-central strand			756	
Withlacoochee St. Forest, Fla.	Mitsch 1975			
Combined riverine & cypress dome (avg. of 23 sites)				600
Cypress Domes, Fla.	Mitsch 1975			
Drained				416
Undrained (stagnant)				192
Okefenokee Swamp, Ga.	Schlesinger 1978			
Very slowing flowing				692
Tar River, N.C. (seasonal flooding)	Brinson 1977		528-577	
Florida	Mitsch & Ewel 1979			
Cypress-hardwood (riverine)				950
Cypress-tupelo				760

[a] Net primary productivity

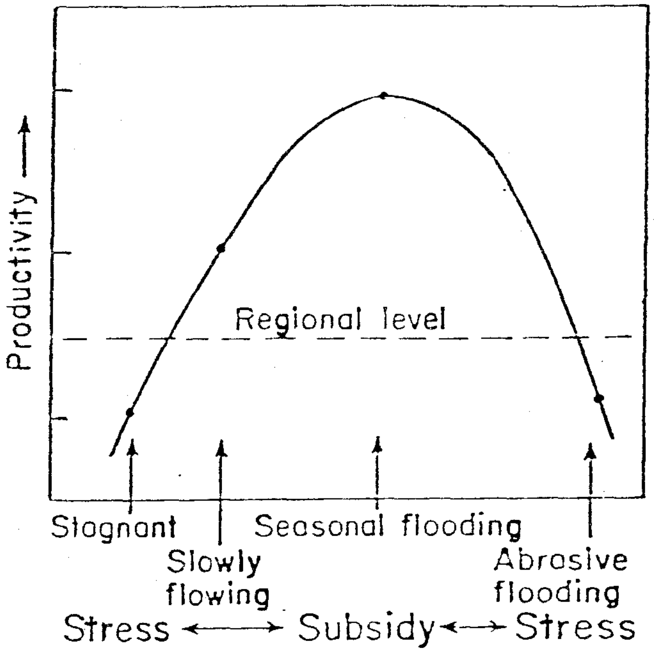

Figure 1. Graphic model (partly data based, partly hypothetical) of swamp subsidy-stress response to flooding (Odum 1979).

Studies in Louisiana support the hypothesis that flowing water and fluctuating water levels are best for the growth of trees. Conner and Day (1976) reported that bottomland forests are very productive (1574 $g/m^2/yr$), even more so than cypress-tupelo swamps (1140 $g/m^2/yr$). The bottomland hardwood forests are flooded each year for a period ranging from a few weeks to months. The rest of the year the water table is near or just below the soil surface. In these areas, cypress trees are present although not in as great a number as in the true swamp forest.

The cypress-tupelo swamps are flooded for many months of the year, sometimes year-round, and thus have a low species diversity. These areas only drain during periods of extremely low rainfall. Since cypress and tupelo only germinate under nonflood conditions, it is during these drought years that new trees become established. This is probably the reason one finds large even-aged stands of these species.

The greatest productivity rates for a Louisiana swamp forest have been measured in an area managed as a crawfish farm, an area flooded from late fall through early spring and drained the rest of the year. While it is flooded, fresh water is constantly being flushed through the area to ensure high oxygen for crawfish. This type of management has proven to be very beneficial to tree growth. Net primary productivity for this area is estimated to be 1755 $g/m^2/yr$ (William Conner, pers. comm., Center for Wetland Resources, Louisiana State University).

In the swamp forests around Lake Pontchartrain, Cramer (1979) studied two different types of swamp forest - one continually flooded and the other with naturally fluctuating water levels. The natural swamp forest was the most productive (1091 $g/m^2/yr$ vs. 618 $g/m^2/yr$).

COMPOSITION

Wetland forests are characterized by standing water for part of the year. Cypress is the most common tree associated with this environment, but depending upon the hydrologic conditions other trees are also found. Bottomland riverine forests which have short hydroperiods tend to be dominated by red maple, ash, box elder, cottonwood, and water oak while cypress and tupelo are scattered throughout. In areas where drainage is poor and the hydroperiod is long, cypress and water tupelo tend to form nearly pure stands. In Louisiana, Conner and Day (1976) found that 52% of the trees in the bottomland forest were ash, box elder, cottonwood and water oak with cypress and tupelo only representing 13% of the total number of trees. In the cypress-tupelo swamp 71% of the overstory was cypress and tupelo. Red maple and pumpkin ash were the most common understory species.

CHEMISTRY

The chemistry of swamp floodwaters is determined by complex biological and geochemical interactions occurring at the sediment-water interface or forest floor. Many of these processes are mediated by such site specific parameters as sediment geology and flooding regime, but a few generalizations may be made. Because of light limitation and the rigor of seasonal flooding, there are few shrubs or grasses in a mature swamp. Thus, the swamp floor is often a bare mud-water interface broken only by the trunks of well-spaced trees. Uptake of nutrients and other constituents, then, by way of the tree roots does not directly affect floodwater concentrations.

Oxygen demand caused by large seasonal inputs of organic matter may strip oxygen completely from the water column during much of the year when low temperatures do not inhibit microbial metabolism (Figure 2). Underlying sediments are almost always reduced.

Swamps act as catchment basins for sediments introduced in upland runoff. There is an initial loss of oxygen and suspended load as water spreads and slows and particles settle out. Thus, swamp drainage waters, while often highly colored by dissolved organic substances, are generally low in suspended matter.

The water spreads over an often reduced sediment interface which is the site of intense anaerobic decomposition. During this stage there are marked changes in the chemical composition of the water due to physical, chemical, and microbial activity, primarily at the mud-water interface. The relative intensity of this alteration is determined by the hydrology of the swamp (*i.e.* the residency time) and by the chemistry of the underlying sediments.

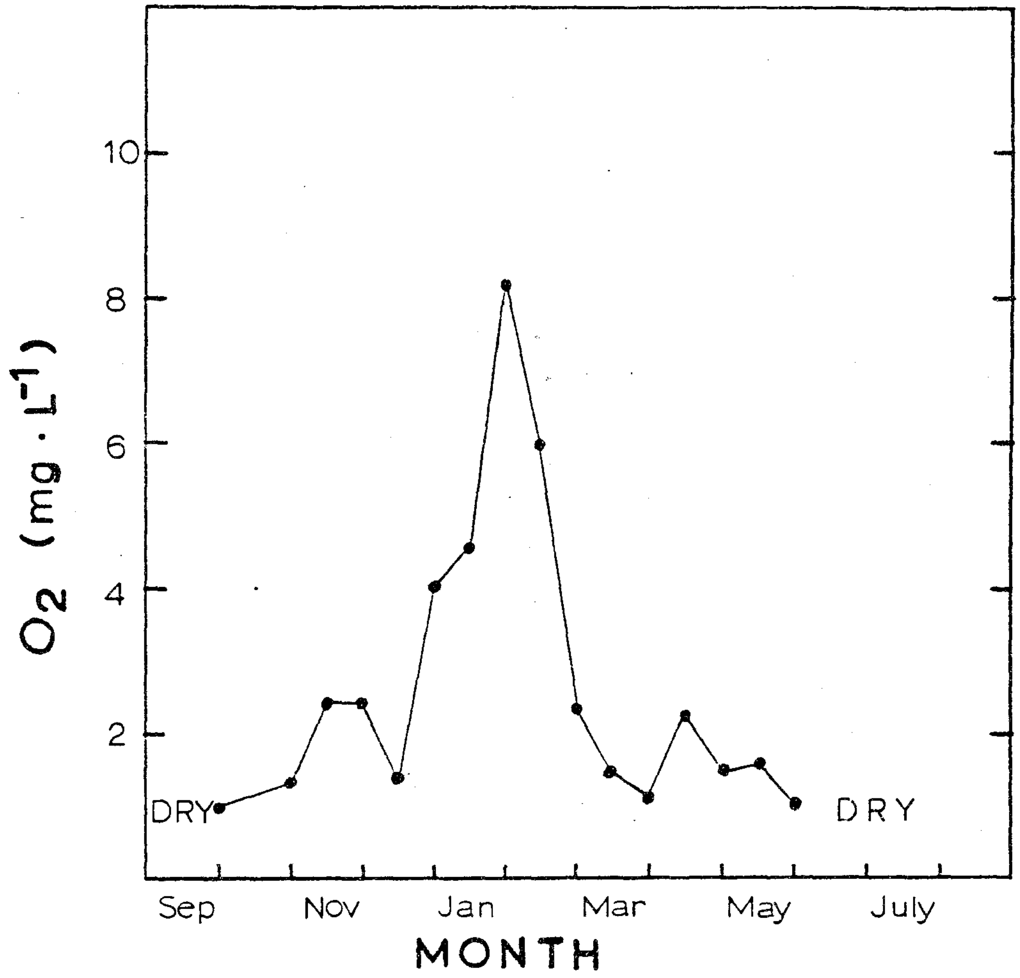

Figure 2. Dissolved oxygen levels in a well-drained Louisiana swamp.

The following discussion will focus mainly on studies of nitrogen and phosphorus dynamics in Louisiana (Butler 1975; Seaton 1979; Kemp 1978). However, much of the information is also true of other floodwater constituents.

Dissolved nutrient concentrations in swamp surface waters are in dynamic balance with concentrations in the sediment pore waters which are, in turn, in equilibrium with the sediments. The magnitude of the labile sediment pool is to some degree fixed by mineralogy and sedimentary history, but it is also strongly influenced by pH and Eh.

The swamp forest in the upper Barataria Basin is an interdistributary swamp formerly subject to overbank flooding from the Mississippi River. Core data indicate an interlayering of peat deposits with alluvial silts and clays. The surface sediments are highly organic peats (carbon 17%), rich in both nitrogen and phosphorus (1.1% and 0.1%, respectively).

The swamp is poorly drained and much of it is generally inundated at least 10 mo of the year. Floodwater pH is stable at neutrality. Dissolved oxygen is generally less than 1 ppm except during January and February when it may approach saturation (~8 ppm). Sediments are strongly reducing at a depth of 2 cm.

Concentrations of dissolved nitrogen and phosphorus are generally high when considered relative to other aquatic systems (Table 2). This is particularly true of organic nitrogen (1 mg/l) and phosphorus (0.2 mg/l) and orthophosphate (0.2 mg/l). Nitrates, however, are quite low (0.05 mg/l) as would be expected in a reducing environment. Ammonia concentrations (avg 0.1 mg/l) are highly variable and appear related to the degree of stagnation; high in areas of low flushing and lower elsewhere.

A nutrient budget computed for a section of swamp receiving agricultural drainage indicates that this system is effective in removing nitrate nitrogen but that orthophosphate, organic nitrogen and organic phosphorus are, on the average, added to the water. However, during the winter, when oxygen levels rise, phosphate is removed by the sediments, thus indicating the redox-related reversibility of uptake-release phenomena for this nutrient form. Kitchens *et al.* (1975) studied nutrient dynamics in the Santee Swamp in South Carolina. As river water flowed through the swamp, they measured decreases in turbidity and nutrient levels (particularly PO_4), but there was little or no oxygen depletion. This indicates how water flow can affect chemical dynamics.

In summary, chemical dynamics of swamps are very complex and strongly affected by local physical, hydrological and geological conditions. Higher water flow generally leads to more aerobic conditions, but this is affected by sediment type (sand, peat or clay). The development of an oxygenated water column and sediment surface promotes the uptake of most inorganic forms. Anaerobic conditions promote leakage of most forms.

Table 2. Comparison of nitrogen and phosphorus values in Barataria Bay estuary and other eutrophic areas (annual mean in mg·l^{-1})(Butler 1975).

Station	Total-N	Organic-N	$(NO_3^- + NO_2^-)$-N	NH_4^+-N	Total-P	PO_4^{-3}-P
Bayou Chevreuil (C)	2.13	1.63	0.28	0.25	0.34	0.15
Bayou Boeuf (E)	1.79	1.36	0.14	0.19	0.20	0.12
Lac des Allemands (A)	1.60	1.35	0.24	0.16	0.27	0.08
Lower Estuary						
Brackish Bay		1.27	0.08	0.25	0.10	0.05
Saline Bay		1.05	0.04	0.066	0.08	0.02
(Ho, unpublished)						
Lake Mendota	6.7 to 1.29					
(Domogalla et al., 1925)						
Central Florida Lake						
eutrophic		1.98				
meso-eutrophic		1.25				
(Shannon and Brezonik, 1972)						

HYDROLOGY

As is evident from the foregoing discussion, much of the ecology and chemistry of swamps and bottomlands is determined by hydrological conditions. Obviously, the presence of water is part of the definition of swamps. However, such factors as the rate of flow, seasonality, and amount are crucial in determining community structure, composition, and chemical cycling.

On the other hand swamps and bottomlands have a marked effect on hydrological patterns. The vegetation, soils, and topography of swamps result in the internal stabilization of often erratic water regimes (Littlejohn 1977); water stored during wet periods is released slowly during dry periods.

An excellent example of these processes, and one we believe is generally applicable to many coastal areas, is a study of the Gordon River Basin near Naples, Florida (Littlejohn 1977). Before human settlement, the area consisted of upland communities, swamp wetland, mangroves, and estuarine waters. Much of the area is now urbanized with most water needs supplied from well-fields in sandy aquifers. Littlejohn conducted a model study of the effects of drainage of much of the swamp area for development.

The area is characterized by seasonal rainfall (Figure 3). Even with strong seasonal precipitation, aquifer storage and discharge into Naples Bay were relatively constant (Figure 3). These results exemplify the buffer effect of wetlands on water flow. Similar findings have been reported for Louisiana (Hopkinson 1979).

SWAMP ESTUARY COUPLINGS

Swamps can affect estuarine productivity by serving as nursery habitat, by contributing nutrients, and by stabilizing hydrological conditions. Obviously, these couplings are more pronounced the closer a swamp system is to the coast. Since most swamps are found in the coastal plain, many swamp systems have significant effects.

HABITAT

Where swamp systems border the coastal zone, estuarine-dependent species can use them as nursery habitat. Hinchee (1977) reported that swamps bordering Lake Pontchartrain served as important habitat for a number of estuarine species, including shrimp, blue crab, menhaden, and seatrout. Similar findings were reported for fresh areas in the Barataria Basin, Louisiana (James Stone, pers. comm., Center for Wetland Resources, Louisiana State University). McIntire *et al.* (1976) listed a number of marine and estuarine species which penetrated into fresh water along the Louisiana coast. These included *Rangia* clams, blue crabs, as well as numerous fishes (Table 3).

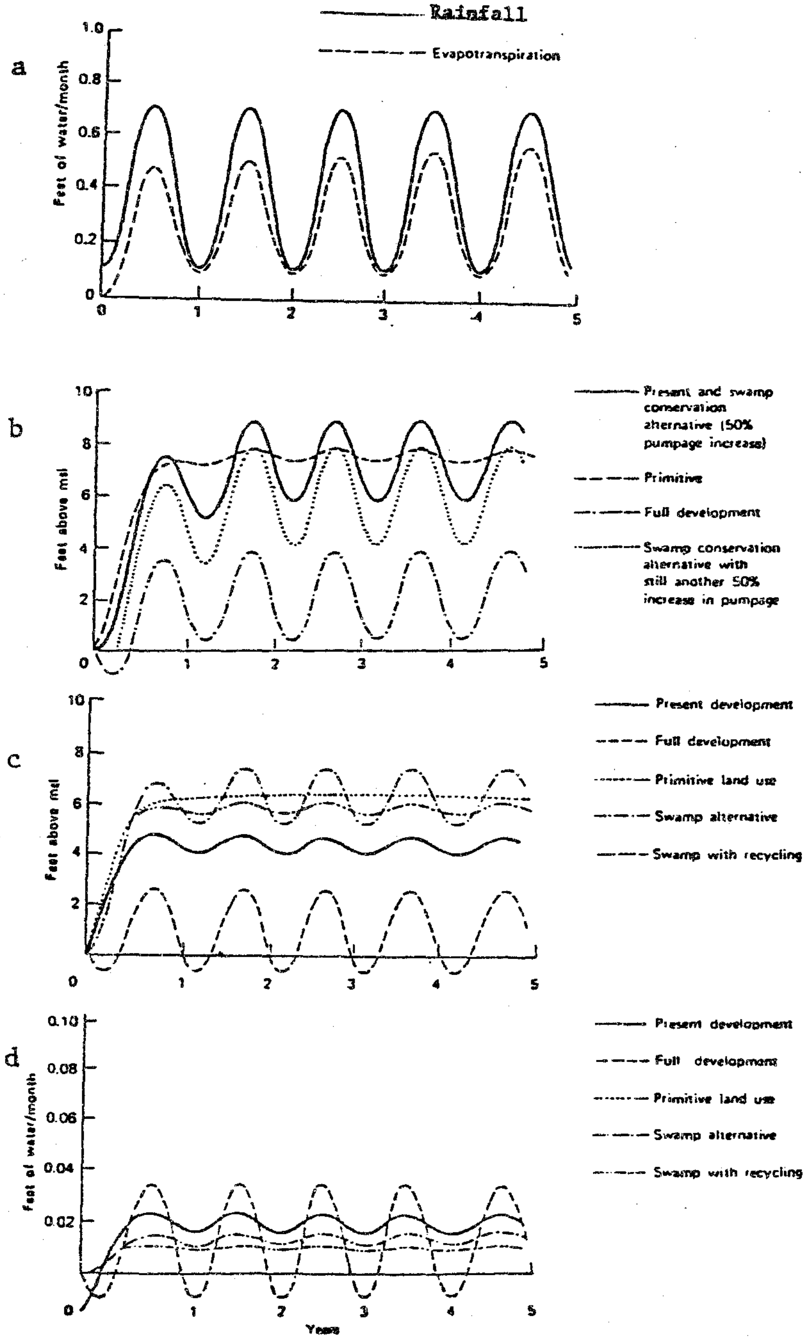

Figure 3. Hydrology of Gordon River Basin near Naples, Florida (Littlejohn 1977).

a. Coastal-ridge flows simulating primitive conditions.
b. Coastal-ridge aquifer storage for comparison. The swamp-conservation alternative results in aquifer behavior almost identical to that presently observed, although municipal pumpage is increased to 50%.
c. Basin aquifer storage.
d. Variations in surface discharge for each alternative of land use.

Table 3. Marine fishes known to occur in inland fresh waters of Louisiana, exclusive of anadromous forms (McIntire *et al.* 1975).

Family, scientific and common names

FAMILY CARCHARHINIDAE - requiem sharks
Carcharhinus leucas (Valenciennes)
bull shark

FAMILY DASYATIDAE - stingrays
Dasyatis sabina (Lesueur)
Atlantic stingray

FAMILY ELOPIDAE - tarpons
Elops saurus Linnaeus
ladyfish

FAMILY CLUPEIDAE - herrings
Brevoortia patronus Goode
Gulf menhaden

FAMILY ENGRAULIDAE - anchovies
Anchoa mitchilli (Valenciennes)
bay anchovy

FAMILY ARIIDAE - sea catfish
Arius felis (Linnaeus)
sea catfish
Bagre marinus (Mitchill)
gafftopsail catfish

FAMILY BELONIDAE - needlefishes
Strongylura marina (Walbaum)
Atlantic needlefish

FAMILY ATHERINIDAE - silversides
Membras martinica (Valenciennes)
rough silverside
Menidia beryllina (Cope)
tidewater silverside[a]

FAMILY SYNGNATHIDAE - pipefishes, seahorses
Syngnathus scovelli (Evermann&Kendall)
Gulf pipefish[a]

FAMILY CARANGIDAE - jacks and pompanos
Caranx hippos (Linnaeus)
crevalle jack
C. latus Agassiz
horse-eye jack

FAMILY SCIAENIDAE - drums
Cynoscion arenarius Ginsburg
sand seatrout
C. nebulosus (Cuvier)
spotted seatrout
Leiostomus xanthurus Lacepede
spot
Micropogon undulatus (Linnaeus)
Atlantic croaker

FAMILY MUGILIDAE - mullets
Mugil cephalus Linnaeus
striped mullet
M. curema Valenciennes
white mullet

FAMILY BOTHIDAE - lefteye flounders
Paralichthys lethostigma Jordan & Gilbert

FAMILY SOLEIDAE - soles
Trinectes maculatus (Block & Schneider)
hogchoker

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[a] not truly diadromous

NUTRIENT INPUTS

Swamps can be important sources of nutrients of estuarine systems. Day *et al.* (1977) reported that large quantities of nitrogen, phosphorus, and carbon were exported from the upper Barataria Basin into the lower estuarine zone (Figure 4). A large part of this was introduced during the highly productive spring period. Cramer (1978) measured high levels of nitrogen and phosphorus in swamp water flowing into Lake Pontchartrain, Louisiana.

Rivers introduce large quantities of nutrients into coastal systems. Important chemical changes take place if these waters flow through swamps (Kitchens *et al.* 1975; Kuenzler *et al.* 1977; Seaton 1979; and Kemp 1978).

HYDROLOGICAL EFFECTS

Brackish water is one of the main characteristics of estuaries. A brackish gradient is maintained by upland freshwater input. Swamps can help stabilize erratic freshwater pulses. Littlejohn (1977) showed that swamps stabilized aquifer storage and discharge into Naples Bay, Florida, even in the face of a short seasonal pulse in precipitation (Figure 3).

In Louisiana, Day *et al.* (1977) measured water flow from swamp forests into the lower Barataria Basin (Figure 4). Fresh water was discharged into the lower Bay from September through May, but there was little net flow in the summer because of high evapotranspiration and southerly winds.

HUMAN IMPACTS

Since the arrival of the first settlers, forested wetlands have been viewed as land that needed to be reclaimed. Towards this goal, provisions were made through the Land Acts of 1849 and 1850 to transfer all "swamp and overflowed lands" to individual states under the condition that they sell the land and use the money to build levees and drains necessary to reclaim the land (Harrison 1951). Thousands of acres of wetland forests have been cleared. In Louisiana alone, only 5.6 million acres remain of the original 9.4 million acres of forested wetlands (R. Eugene Turner, pers. comm., Center for Wetland Resources, Louisiana State University).

Those forests not cleared for agricultural use have also been affected by man's activities. Nearly every virgin stand of bottomland hardwood and cypress forest has been cut at least once. Canals and pipelines crisscross swamp lands. Existing streams have been dredged and/or shortened for navigation, flood control, and drainage. All of these activities in one way or another affect the hydrologic regime of the wetland areas.

Most food chains in floodplain environments are detritus-based. The clearing or clearcutting of wetland forests, whose trees are the source of detritus, deprives organisms of a major food source. Day *et al.* (1977),

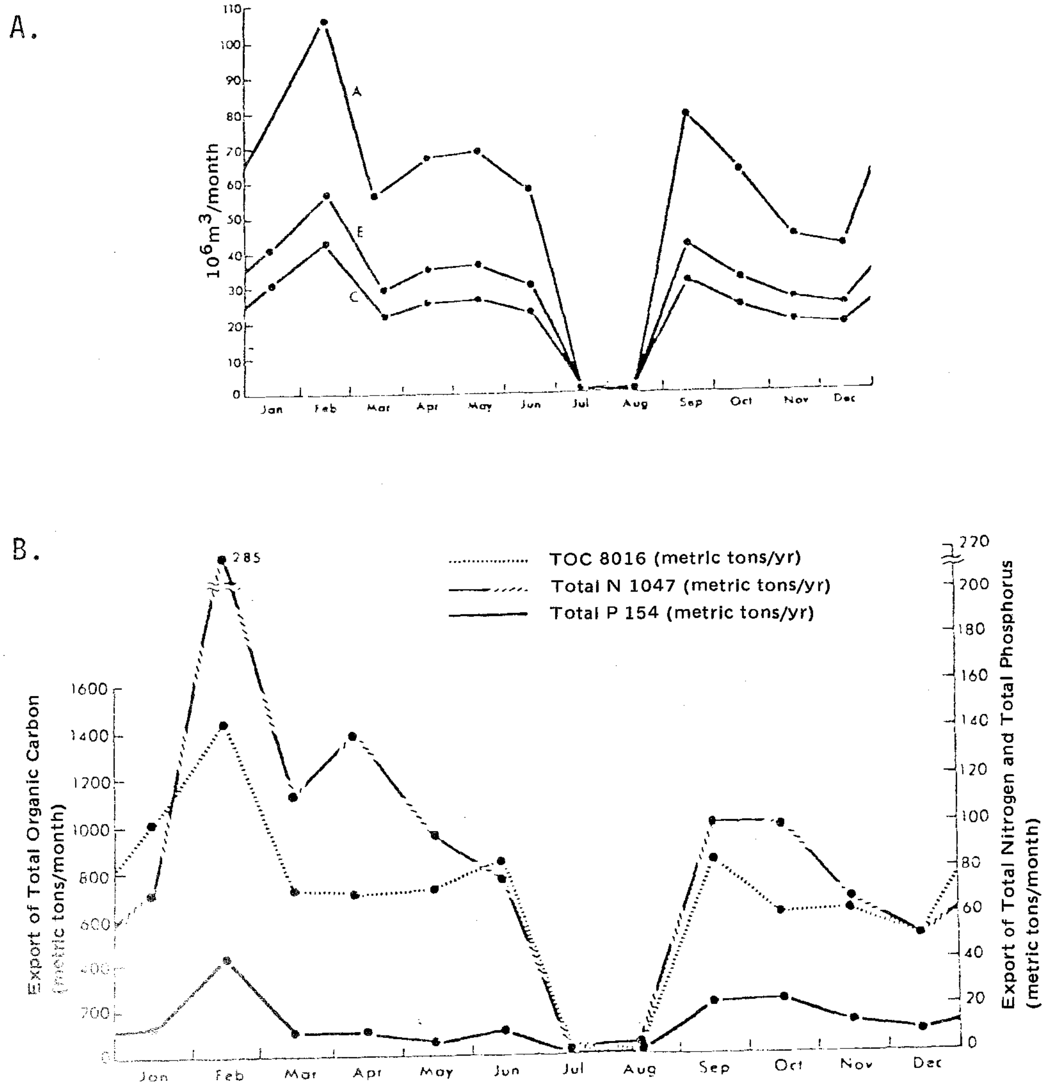

Figure 4. Monthly mean water discharge (A) and materials export (B) from the des Allemands swamp to the lower estuary measured during 1974 (from Day *et al.* 1977). Curves C and E are tributaries to Lac des Allemands.

Kemp (1978), and Seaton (1979) found that pulses of carbon, nitrogen, and phosphorus are released to the adjacent estuary during periods of runoff.

Productivity of Apalachicola Bay, Florida, is regulated by annual pulses of organic matter and silt from upstream and by major high water flows every 6 to 8 yr (Livingston 1978). Clearcutting and ditching in the Apalachicola delta and adjacent Tate's Hell area have severely damaged marine productivity in East Bay (Livingston 1978).

In the swamp forests, canals with their associated spoil banks alter or interrupt water flow. In many cases, areas of forests have become impounded. With the constantly standing water, there is no recruitment of new trees to replace those that die or are blown over. Productivity of these areas decline yearly. Conner (pers. comm., Center for Wetland Resources, Louisiana State University) reported the productivity of an impounded swamp forest (impounded for 25 yr) as 822 $g/m^2/yr$ as compared to 989 to 1755 $g/m^2/yr$ for natural swamp forests. In addition to the lowered productivity, there is very little export of nutrients or organics. This affects life in the streams and marshes below the forest.

Upland runoff combined with hydrological changes can lead to altered nutrient dynamics. Channelization and canals can speed nutrient laden waters past swamps to receiving water bodies. This leads to lower productivity in the swamps and potentially to eutrophication of water bodies (Day *et al.* 1977; Kemp 1978). For example, Kemp found that N/P ratios in Bayou Chevreuil in the upper Barataria Basin, Louisiana, were closely related to runoff patterns (Figure 5). Between rainfall periods, N/P ratios in the Bayou were low (2:1) and closely approximated values in the swamp. If sampling occurred during or immediately following (within 5 days) a significant rainstorm, N/P ratios in the Bayou were elevated, in one case as high as 20:1. There were two types of water flowing into Bayou Chevreuil: natural levee upland runoff and swamp drainage. If the swamps are adjacent to the coastal zone, eutrophication of estuarine waters can result (Hopkinson and Day 1979; Seaton 1979; Cramer 1978).

It is obvious that hydrology as well as human impact, is a key to understanding swamp dynamics and swamp-estuary couplings. In Littlejohn's work in Florida, loss of swamp wetlands was related to altered hydrologic patterns and saltwater intrusion (Figure 3). In Louisiana wetlands, canal density has been related to land loss (Craig *et al.* 1979) and water quality (Gael and Hopkinson 1979). Hopkinson (1979) constructed a model of the swamp forest surrounding Lake des Allemands, Louisiana. Simulation of the removal of all canals and levees to create a more "natural" condition, resulted in smoother hydrographs, higher swamp productivity, and lower trophic status of the lake.

MANAGEMENT

In terms of management, the foregoing information suggests a central theme. Hydrology is a key consideration in both the management of swamps and

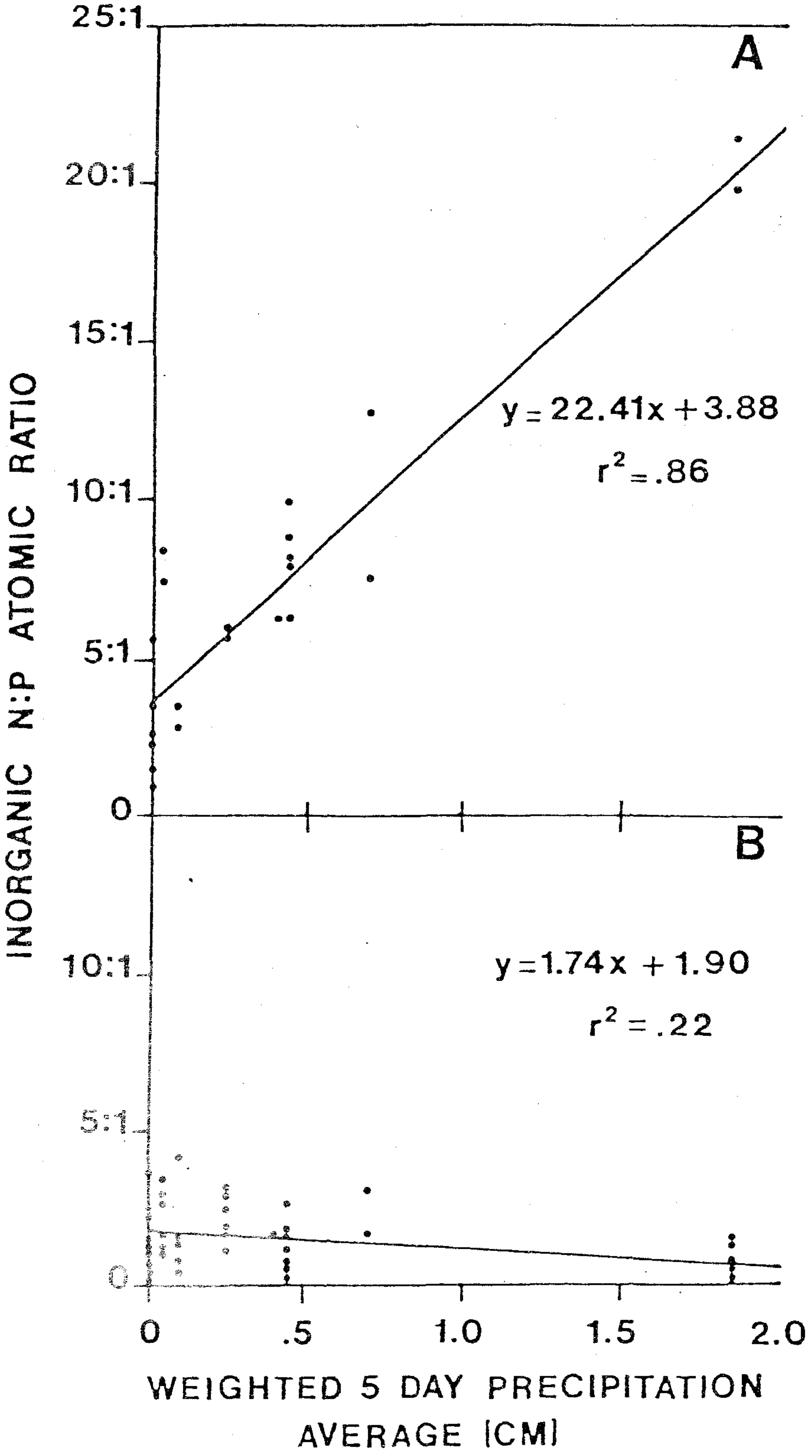

Figure 5. Relationship between recent precipitation and inorganic N:P atomic ratio. (A) Bayou Chevreuil (B) Swamp floodwater (Kemp 1978).

swamp-estuary couplings. This includes land management as it affects water movement. Important topics for management include channelization, canal construction, spoil placement, and water quality.

A second consideration is the level of management. Bahr *et al.* (1977) constructed a conceptual model of the Chenier plain of Texas and Louisiana. They concluded from the standpoint of time scale and areal extent of important events and structure that the drainage basin was the most appropriate level for management (Figure 6).

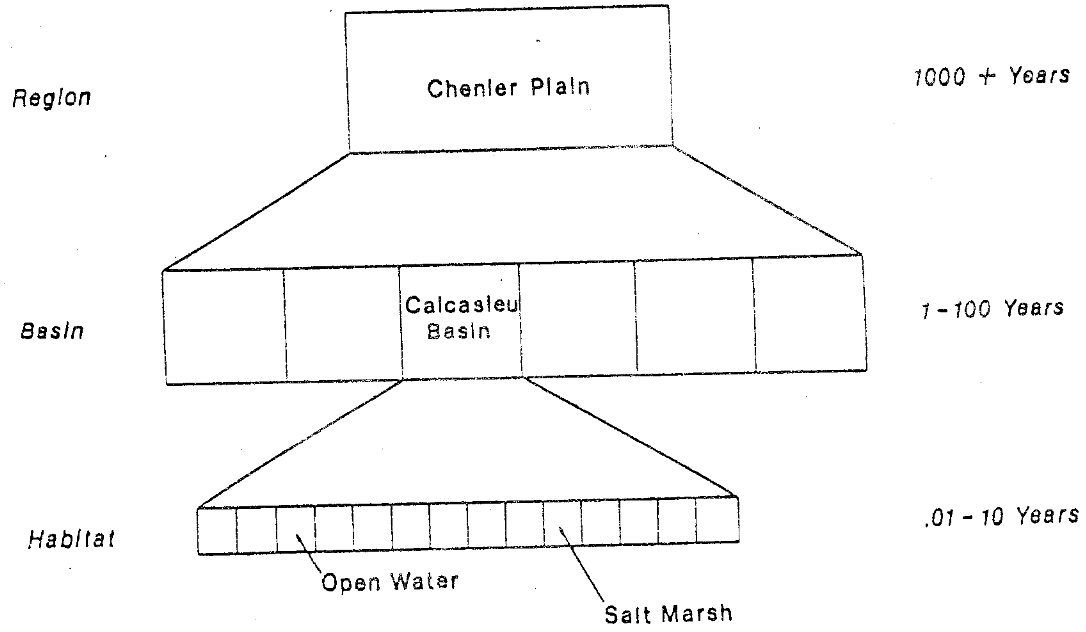

Figure 6. Hierarchical conceptual model of the Chenier Plain in Louisiana and Texas (Bahr *et al.* 1977).

For large river systems, it is impractical to include the whole river basin. An important question: What is the most reasonable cutoff point in terms of coastal management? In determining Louisiana's Coastal Zone, McIntire *et al.* (1975) used factors such as geology (contact point of Recent and Pleistocene terraces), elevation, soils, vegetation, flood and tide information, salinity, and occurrence of marine, freshwater, and terrestrial organisms.

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RECENT ADVANCES IN OUR UNDERSTANDING OF SALT MARSH ECOLOGY

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ABSTRACT

Our understanding of the ecology of coastal marshes has revolved about the role of this ecosystem as a source and reservoir of energy and nutrients, and as a vital habitat for certain life stages of a number of marine organisms. While recent advances in salt marsh ecology have emphasized the metabolic processes and material fluxes that permeate the marsh-estuary, current research developments are geared towards a better understanding of the marsh as a carbon sink. Thus, investigations of 1) marsh surface productivity, 2) below-ground dynamics, and 3) decomposition processes, may dominate future research developments in salt marsh ecology.

INTRODUCTION

That the marsh is among the most productive natural ecosystems in the world and a vital habitat necessary for the completion of the life cycle of certain organisms have long been recognized as basic principles of marsh ecology. It is understandable therefore, that the emphasis of ecological research on the salt marsh has revolved about its role as a producer of organic matter, which forms the basis of the food web in the estuarine and marine environments, and as a nursery ground for certain stages in the life cycle of many marine animals. The various processes concerning the basic function of the marsh as an energy source are illustrated in Figure 1 and can be summarized as follows:

1) The net primary productivity (NPP) of the vascular plants in the marsh is among the highest in the world;

2) Only a small percentage of the organic material produced by the marsh plants enters the grazing food chain (GFC);

3) The bulk of the plant materials dies (annually for most of the species) and falls to the marsh floor where it may decompose to particulate detritus or be transported to the estuarine waters and neighboring marine environment, or both, and serves as the basis of the detritus food chain (DFC);

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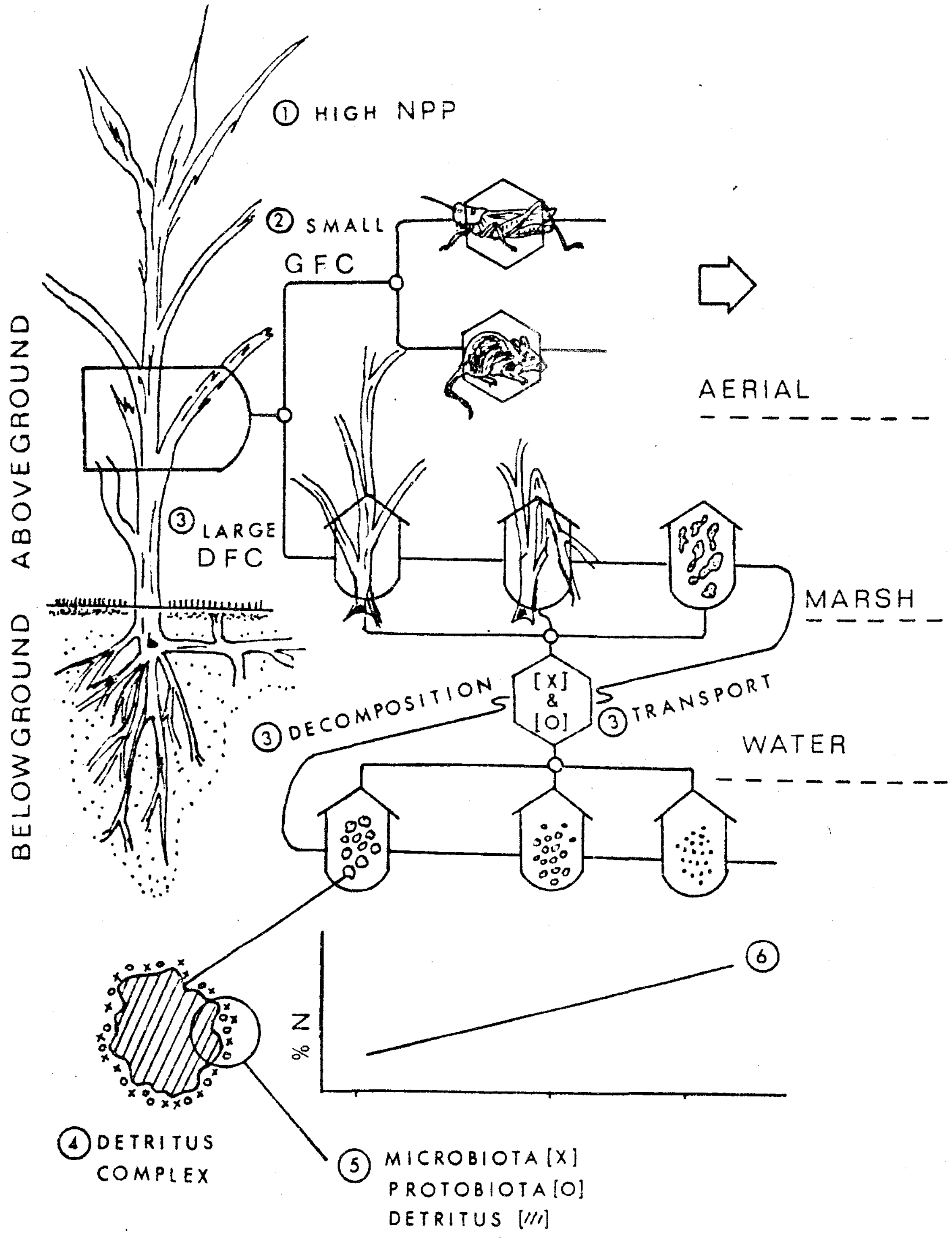

Figure 1. Composite diagram of Y-shaped energy flow, metabolic processes, and fluxes of materials in the salt marsh. NPP=net primary productivity, GFC=grazing food chain, DFC=detritus food chain.

4) The detritus is attacked by microbes and both detritus and microbiota are consumed by detritovores, mostly filter feeders and benthic scavengers, which form the base of the food chain for secondary and higher consumers;

5) The detritus complex consisting of plant residue and attendant bacteria, fungi, and protozoa is food of high nutritional value;

6) The attendant microbes increase the protein (N x 6.25) content and either maintain or increase the caloric value of the detritus.

As an obligatory habitat for larval stages of shellfish and juveniles of fish, the marsh-estuary provides: 1) a brackish environment to which they have adapted evolutionarily; 2) a habitat protected from strong current and intense radiation; 3) a place with abundant food supply and mineral nutrients; and 4) a shelter devoid of large populations of predators.

Recent developments in salt marsh research have essentially addressed themselves to the same basic concepts summarized above. In general, the impact of these investigations on our present store of knowledge has been: 1) the acquisition of more accurate data as a result of better conceived experimentation and employment of more refined methodologies; 2) the obtainment of new evidence that challenges the initial concepts of marsh ecology; 3) the addition of new dimensions to our understanding of marsh ecology as a result of new discoveries. The aim of the present paper is to illustrate some of the recent advances and current developments in marsh ecology that deal mainly with the functions of the marsh as a producer and reservoir of energy and nutrients, and as a vital habitat for fish and wildlife.

RECENT ADVANCES

BIOENERGETIC FUNCTIONS

Primary Productivity

One of the primary factors contributing to the biological fertility of the marsh-estuary is the presence of three producer taxa which are programmed for year-round production. These are: 1) emergent vascular vegetation (marsh grass); 2) benthic algae (filamentous, diatoms, blue-green); and 3) phytoplankton (in the estuarine waters inundating the marsh). While all these producer organisms are important and contribute to the primary energetics of the marsh ecosystem, only the vascular angiosperms or marsh grass will be discussed in this paper.

The main issue in angiosperm productivity studies, as addressed by recent investigations, dealt with methodology. Over the years, measurements of annual net primary productivity of above-ground materials (*i.e.* aerial shoots) have utilized novel techniques from the application of linear mathematical models (Williams and Murdoch 1972) to remote sensing procedures (Gallagher *et al.* 1972). The traditional Harvest Method, however, is still the most used procedure but not without modifications. This method basically measures the increase in plant biomass during the growing season, that is, maximum biomass at the end of the growing season in early fall minus minimum biomass at the beginning of the growing season in early spring. Most of the recent studies of marsh grass productivity were designed either to test and compare the accuracy of the various modifications of the harvest method (Linthurst and Reimold 1978a); to compare the primary productivity of different marsh plant species in the same marsh locality (*e.g.* de la Cruz 1974b, White *et al.* 1978, Hopkinson and Gosselink 1978); to compare the same marsh plant from different geographic regions (Linthurst and Reimold 1978b, Turner 1976); or to compare the different ecophenes of a species, for example, *Spartina alterniflora* (Kirby and Gosselink 1976) and *Juncus roemerianus* (Kruczynski *et al.* 1978).

The modifications of the Harvest Method had included: 1) the Peak Standing Crop (*e.g.* as used by Nixon and Oviatt 1973); 2) Smalley (1958) method; 3) Wiegert and Evans (1964) method; 4) Milner and Hughes (1968) method; and 5) the Method of Valiela, Teal and Sass (1975). Linthurst and Reimold (1978a) observed that differences as great as ten-fold were found between these methods. The Wiegert and Evans Method tends to overestimate net primary productivity (NPP), while the other four methods underestimate NPP. Most recently, Hackney and Hackney (1978) devised a NPP estimate based on a predictive periodic model where the monthly data of live and dead plant materials are fitted into a periodic regression model. Since the fitted curve in the periodic model included samples collected over the entire marsh, the resulting maximum biomass minus minimum biomass (max-min) value will reflect the variation in plant density within the marsh, as well as the inherent error between samples. This statistical technique further allows: 1) the use of stratified sampling collection procedures which are less destructure to the marsh; 2) determination of NPP of associated minor species in mixed communities; 3) correction for die-back during the growing season; and 4) statistical comparisons between any two studies regardless of when or where they are made.

Ideally, a primary productivity method must account for: 1) the variation between sampling times; 2) the variation in plant density within the study area; 3) the death of some plants during the growing period; 4) the loss of plant biomass through mechanical factors; and 5) the biomass loss through herbivory. Any of the modifications of the harvest method mentioned can accommodate one or more, but not all of the ideal considerations listed above. Unfortunately, NPP studies are greatly determined by the amount of effort available, and effort availability is drastically influenced by the community to be studied. The tidal marshland is definitely not the most feasible habitat to sample, and the extra effort expended is oftentimes offset by inherent variability in the specific procedures employed.

The specific harvesting procedure has also concerned investigators in recent years. The method of harvest, the size and shape of plots to be harvested, the number of replicates per sampling time, and the time interval between harvests have varied greatly in past studies. These factors are primarily determined by the type of community or growth form of plants to be studied. Recommended sampling procedures for aboveground production of freshwater and brackish water marsh plants have already been summarized by de la Cruz (1978a). The variability in sampling procedures and the differences in the methods and formulae employed in calculating production values are primary reasons that have prevented reliable comparisons of existing marsh productivity data.

The amount of information on the primary productivity of tidal salt marsh vascular plants has increased steadily during the last decade. Data summarized by investigators show production values ranging from several hundreds to several thousands g/m^2/yr (Keefe 1973, Turner 1976). It is apparent that the primary production of marsh angiosperms varies widely. This variability is believed to be due to the types of plant species involved, salinity and hydrology of the habitat, geographic latitude and temperature, and sampling methodology (de la Cruz 1978a).

Until very recently, most of the studies concerning the primary production of coastal marshes were concerned only with aboveground materials (*i.e.* aerial shoots), presumably because of the difficulty in sampling subterranean materials (*i.e.* roots and rhizomes). The few studies available on belowground productivity and summarized by de la Cruz (1979) show annual production values ranging from 450 g dry wt/m^2 to over 2000 g dry wt/m^2 for the short form of *S. alterniflora*; 500 to 3500 g dry wt/m^2 for the tall form of *S. alterniflora*; and about 1400 g dry wt/m^2 for *J. roemerianus* (de la Cruz and Hackney 1977). From these belowground productivity values, it is apparent that the total production of marsh vascular plants is approximately double of that previously reported.

The major difficulty in studying belowground productivity also concerns the sampling methodology, particularly in separating the live from dead roots. Estimates of belowground productivity have generally been determined from periodic increases in standing crop or the max-min biomass method. There are basically two ways for obtaining the change in underground biomass: 1) from the amount of root materials per individual plant collected; or 2) from the root biomass recovered from cores taken throughout a quadrat. In sampling belowground biomass, root morphology, rooting depth, wetland type and pattern of vegetations must be considered since these factors will determine the size and shape of sampling device, number of samples, location of samples with respect to major plant clumps, and the time interval of sampling (de la Cruz 1978a).

Energy Pathways

The energy flow in the salt marsh follows a Y-shaped pathway, the grazing food chain (GFC) and the detritus food chain (DFC) pathways (Figure 1). The primary consumers of the GFC are herbivores (mainly insects and rodents) which feed on the living marsh plants. There are few consumer species in this food chain and they transform energy seasonally. These animals are not active during the summer and must reduce their activity during winter when their food is unavailable. The primary consumers of the DFC feed on the marsh plant detritus derived from decomposing dead plant tissues, in the water and on the marsh floor. The energy flow of these populations is more constant throughout the year since detritus is produced continually, allowing development of an extensive food web with many types of primary and secondary consumers (Keefe 1972: 171). More dead grass is present in the colder months but this is counterbalanced by the more rapid decomposition during the warmer months, so there is a continuous supply of food for consumers in the detritus food chain.

Since the early works of Smalley (1960) and Marples (1966) on insect herbivory on the marsh, and of Sharp (1967) on the selective feeding of the rice rat *Oryzomys palustris* and *S. alterniflora* in Georgia, only one study recently conducted by Parsons and de la Cruz (unpublished, Mississippi State Univ.) on the energy flow of Conocephaline grasshoppers has dealt with the GFC pathway in the marsh. It has long been known, however, that fur-bearing mammals like muskrat and nutria, grazed substantially on a number of brackish water marsh vegetations (O'Neil 1949).

Most of the energy flow studies in the salt marsh were concerned with DFC, and dealt mainly on the consumption of detritus by detritivores (*e.g.* Odum 1970), and the nutritional value of marsh plant detritus at various stages of decay (*e.g.* de la Cruz 1975).

Particulate detritus, suspended in the water and deposited on the sediment surface, is a high-quality food source readily available to consumers anywhere in the estuary and adjoining marine areas. Studies involving stomach analyses, experimental feeding using radioactive tracers, and tissue analysis using $^{13}C/^{12}C$ ratios have shown that many species of fishes and invertebrates feed wholly or partially on particulate detritus. The availability of detritus particles of different sizes and at different stages of decomposition (Figure 1) is also significant because it allows the detritus to provide energy to various feeding niches. Most filter feeders are size-selective with regard to their food and are unable to differentiate between detritus particles and plankton of similar size. Detritus-eaters, or detritivores, form the base of the food web in the estuarine-marine environment and are the critical link between detritus production and the production of higher consumers.

The nutritional value of marsh plant detritus has been examined by investigators in conjunction with decomposition studies which are discussed below.

Decomposition of Detritus

The relationship between the marsh and the secondary productivity of adjacent estuarine waters depends on three basic processes: 1) the production of abundant detritus from marsh plant material; 2) the flux of the formed plant detritus into the water that inundates the marsh; and 3) the assimilation of detritus particles and dissolved detritus by-products into the food web that supports secondary production. Central to the processes which link the high primary productivity of wetlands to the biological fertility of neighboring bodies of water is the process of decomposition. The overall scheme of degradation and decay involves three fundamental processes which take place simultaneously: 1) leaching of soluble substances, a process which is quite rapid and accounts for the majority of weight reduction during the early stages of decomposition; 2) weathering or mechanical fragmentation due to abrasion by wind and ice, wave and tidal action, or animal trampling and incomplete grazing by herbivores; and 3) biological decay arising from the oxidation of detritus by attendant bacteria and fungi. Animals ingest and eat the detritus, fragmenting it into smaller particles, or graze on the attendant bacteria and fungi. The resulting feces are rapidly recolonized by microorganisms. There is a gradual decrease in particle size and detritus biomass, with simplification of chemical structure.

Most of the *in situ* litter bag decomposition studies on marsh plants were done on smooth cordgrass, *S. alterniflora*, and black needlerush, *J. roemerianus*, (de la Cruz 1979). A few data exist for other estuarine plants and for the leaves of red mangrove, *Rhizophora mangle*. The later stages of decomposition have also been investigated on *J. roemerianus* and *S. alterniflora* detritus of different particle sizes, in conjunction with nutrient analysis.

Caloric and nutrient analysis data obtained from decomposing detritus of *S. alterniflora, J. roemerianus* and other estuarine marsh species indicated that energy and protein values remain high, and in most cases increase, during decomposition to particulate detritus. The higher levels of amino and fatty acids in marsh grass particulate detritus over those found in intact dead tissues are indicative of microbial activity in detritus production. Microbial activity is also reflected in increased oxygen uptake by highly decomposed detritus particles. The high caloric value, high protein content, and microbial loads of marsh plant detritus exported by tides from coastal marshes indeed make this detritus a food source of high nutritional value to aquatic consumers. Nutrient enrichment has been ascribed to the buildup of microbial populations on the detritus particles of bacteria, fungi, diatoms, and protozoa.

But, recent work by de la Cruz and Poe (1975) suggested other sources of nitrogen other than marsh macrophyte decomposition; and investigations by Odum *et al.* (1979) challenged the concept of protein buildup in decomposing detritus. Because protein values reported by investigators were based on protein as (N x 6.25), Odum *et al.* (in press) contend that non-protein nitrogen has exaggerated the values previously reported. Indeed, as much as 30% of the nitrogen content of aged detritus exists in the form of non-protein, particularly amino sugars such as chitin.

Studies on litter bag decomposition of belowground materials (*i.e.* roots and rhizomes) are just beginning. A study recently concluded by Hackney and de la Cruz (in press b) showed that the decay of rhizospheric material is slow. This is expected because physical conditions belowground are often not those considered ideal for decay (Gallagher 1978). Hackney and de la Cruz (in press b) found *J. roemerianus* rhizomes decomposed faster (27%) than root materials (16%), and that virtually no decomposition occurred below the 20 cm (8 in) depth during the one-year study. In addition, there were slight increases in nitrogen and caloric values in decomposing root materials. Decay rates a few centimeters below the water-logged soil proved to be slow (Chamie and Richardson 1978) because of the anaerobic conditions existing below a thin layer of soil.

Detritus Transport

Organic matter produced on the marsh reaches the neighboring waters in various forms. In salt marsh-estuaries, dead but intact shoots of plants are carried from the marshes by spring tides and wind-driven tides such as the seasonal storm tides. Along the south Atlantic coast, it is not uncommon to see rafts and shoals of *Spartina* drifting out to sea with the tides. Depending on the height of the prevailing tide, 2 to 16 kg of floating debris can be exported during one tidal cycle from a small tidal creek draining 10 to 25 ha of a *Spartina* marsh watershed (de la Cruz 1965). Massive accumulations of dead *Juncus* leaf fragments are often seen piled along beaches and shores of the Gulf coast. One study has shown that roughly 3 kg of floating debris are exported from a tidal creek draining a 6-ha marsh watershed dominated by *Juncus* (Hackney 1977). The back-and-forth movement of the tide breaks these materials into bits and pieces that are eventually washed out to sea.

Energy is also exported from the marsh in the form of traction materials (*i.e.* via bed-load transport), which are rolled along the banks and bottoms of creeks, rivers, bayous, and tidal channels. It has been shown that dissolved organic substances are leached from decaying plant tissues, and that a great deal of nutrients (silica, phosphate, bicarbonate and ammonia) are leached from the sediment, presumably from plant materials buried in the mud and from the massive mats of rhizomes and roots (Gardner 1978).

For the most part, however, past investigations have focused on the transport of carbon from coastal marshes to estuarine waters in the form of suspended particulate detritus. The pronounced turbidity of water in lagoons, bays, and sounds is due primarily to the presence of detrital materials that are constantly being washed out of marshes and other wetlands and resuspended from the bottom by tides or current. The particulate detritus remains suspended in the water, and, in many instances, comprises the bulk of the particulate organic load (*i.e.* seston) of the water. Recent works pioneered by Haines (1977) on stable carbon isotope ratios in estuarine detritus in a Georgia estuary has shown that suspended particulate materials may be derived predominantly from phytoplankton and terrestrial plants indicating the contribution of these components to estuarine productivity.

Results of early studies on carbon transport (de la Cruz 1979) led to the hypothesis that coastal marshes function as net exporters of energy in the form of particulate detritus. Recent investigations, however, have challenged the universality of the export hypothesis by showing that particular marshes may actually import particulate organic carbon and (or) other nutrients. In general, studies reporting net import show rather low values for import (1 to 6% of the marsh net primary productivity), and both Nadeau (1972) and Hackney (1977) indicate that there was generally an export of floating debris.

It appears that marshes are both sinks and sources of organic material. Variations in transport direction and organic particle loading have been attributed to hydrologic characteristics such as tidal regime, to the proximity of any freshwater input, to the geomorphic orientation of the marsh drainage system (Hackney and de la Cruz, in press a) and to some meteorological phenomena.

Our current investigation in Mississippi indicates that exports of particulate detritus are irregular in some coastal areas (*e.g.* Mississippi Gulf Coast), and that the coastal marsh serves as a holding area for riverborne materials. Coastal marshes do not only export detritus to offshore waters but also regulate the overall release of organic detritus from estuaries.

HABITAT FUNCTIONS

For Wildlife

Because of the high energy output and heavy standing crops of marsh-producer organisms, marshes provide food and shelter for a rich diversity of fish and wildlife resources. Fur bearers (*e.g.* river otter, mink, raccoon, muskrat, and nutria) are important in coastal marshes. The coastal marshes are also the domicile for small rodents like the hispid cotton rat and marsh rice rat which are important links in food chains of birds of prey (hawks and owls) and secondary carnivores (foxes and coyote). Certain marshes provide either temporary or permanent homes to birds (*e.g.* rails and coot), amphibians (*e.g.* frogs and toads), and reptiles (*e.g.* American alligator and snapping turtles).

For Fish and Shellfish

Tidal creeks, bays, and estuaries serve as nursery areas for early life history stages of economically important crustaceans like shrimp and blue crabs, and finfishes like menhaden spp. and Atlantic croaker. In fresh to brackish marsh areas, largemouth bass, bluegill and freshwater catfish are abundant. Oysters and clams support a thriving shellfish industry.

Previous work by Herke (1971) on the use of tidal marshes as nurseries by fishes and crustaceans and recent work by Hackney (1977) on the movement of animals in the marsh creek habitat also reveal a number of marine species whose young and larval stages nurse in the tidal creeks and bayous of estuarine marshes. Therefore, there is essentially an export of "fattened" animal tissues from marshes to the sea, which is probably as important to marine productivity as the export of floating debris, suspended particulates (detritus) and dissolved organics (nutrients).

Most of the conservation and management studies discussed below are related to the habitat functions of marshes for wildlife and as sites for fish and shellfish aquacultural development.

CONSERVATION, MANAGEMENT AND VALUATION

It would be a serious omission if this review did not mention the research advances in the conservation, management and valuation of marshes. During the last decade, a great deal of work has been done in artificial marsh creation (*e.g.* Woodhouse *et al.* 1972), artificial enrichment of marshes (Sullivan and

Daiber 1974), nutrient assimilation capacities of marsh plants (Valiela *et al.* 1976), pesticide and oil pollution fate and effects (Baker 1973, de la Cruz unpublished, Mississippi State Univ.), and recovery of marsh communities following winter fire (de la Cruz and Hackney, unpublished, Mississippi State Univ.; Whipple and White, unpublished, Louisiana State Univ.). Data being generated from these studies will provide the much needed information in the multiple use of marshland areas and management for resource production. It is possible to conserve large tracts of marshlands and manage them for production of pelt mammals (Chabreck 1976), dissolving pulp (de la Cruz 1978b), chemical derivatives (Miles and de la Cruz 1976) and other cultural alteration through traditional farm-plantation operation without jeopardizing their bioenergetic and habitat functions.

On the other hand, small areas of marshlands should not be easily given up for commercial development because they are often of high ecological value (Gucinski 1978); neither should a marsh that is completely surrounded by areas of intense development be considered worthless as it has not necessarily lost its ecological value (Oviatt *et al.* 1977).

At the present state of knowledge, data supporting the various functions attributed to coastal marshes are far from definitive. It is for this same reason that alteration and developments of marsh areas should be approached with caution.

EMPHASIS IN FUTURE RESEARCH

Our understanding of salt marsh ecology will continue to be based on the bioenergetics and habitat functions of this ecosystem. Undoubtedly, studies of primary productivity, marsh fauna and flora, detritus formation, transportation and consumption, will proceed with the same intensity especially in places where there are abundant but yet unstudied marshes. Marsh ecologists will be persistently concerned with marsh conservation and management, especially if the marsh is put into widespread multiple use for resource production (de la Cruz 1976). Unfortunately, these continuing directions of research will not add any new concept that can expand or deepen our understanding of marsh ecology.

The key to deeper understanding of biological processes in the salt marsh, and to more comprehensive perception of the value of the marsh as an ecosystem, lies in its role as a carbon sink. Several investigators (*e.g.* de la Cruz 1974b; Gallagher 1974; Smith *et al.* in press) have shown the tremendous store of plant biomass below the marsh floor. Compounds derived from this material by aerobic and anaerobic processes constitute a large potentially available nutrient pool (Smith *et al.* in press). Thus, the fluxes of materials belowground also involve production and decomposition. Productivity studies of the marsh surface components such as epibenthic algae (Gallagher and Daiber 1974, Van Raalte *et al.* 1976) and the belowground roots and rhizomes are emerging (de la Cruz and Hackney 1977; Smith *et al.* in press). Studies of underground decomposition and mineralization are the focus of very recent and continuing research by marsh investigators (*e.g.* Hackney and de la Cruz, in press b; Kaplan *et al.* 1979; Teal *et al.* 1979).

As Gallagher (1978) has already pointed out, belowground dynamics probably follow pathways similar to those identified for aboveground. Most of the major differences between the aerial and subterranean systems can be traced directly or indirectly to the differences between the milieu (fluid or gas vs. solid) of the plant material. In the aboveground portion of the system, the milieu consists of gas and(or) water phases where exchange of material between the dead plants and their environment is by convection as well as diffusion. Conversely, conditions belowground make diffusion processes relatively more important.

Our present knowledge of belowground dynamics is rather primitive. As more descriptive and functional work becomes complete, a fuller understanding of the marsh ecosystem as a carbon sink will emerge which can lead to formulation of yet unconceived concepts about salt marsh ecology.

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ROLE OF SEAGRASSES IN ESTUARINE SYSTEMS

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INTRODUCTION

Seagrasses are found worldwide in shallow coastal waters. Owing to the protection they provide from erosion, their role in sediment accretion, and their high primary productivity, seagrasses are extremely important. This paper discusses the ecology of North American seagrasses, their functions in the coastal ecosystem, and their tolerances and responses to a variety of natural and human-initiated perturbations.

The approximately 45 species of seagrasses, all monocotyledonous plants, belong to two families and 12 genera. The family Potamogetonaceae contains nine genera and 34 species. The family Hydrocharitaceae contains three genera and 11 species. Most seagrasses have submerged flowers, with pollination occurring underwater. Seagrasses are found world-wide, but are conspicuously absent on the entire west coast of South America, much of the east coast of South America, the west coast of Africa, and the Arctic and Antarctic.

A realization that seagrass meadows constitute a coastal ecosystem developed gradually in the mid-1960's. In 1973 with the aid of the National Science Foundation (NSF) and the International Decade of Ocean Exploration (IDOE), C. P. McRoy (University of Alaska) formed a steering committee that convened an International Seagrass Workshop at Leiden, The Netherlands. Members of the Workshop assessed past studies and formulated future research needs. Following the workshop, the NSF/IDOE funded a Seagrass Ecosystem Study by U.S.A. investigators to conduct research on seagrasses from an ecosystem perspective. This study is providing data for explaining patterns of development and activity in seagrass ecosystem processes such as productivity, phenology, and nutrient cycling. It is becoming clear that seagrass meadows form highly productive ecosystems with a suite of both biological and physical functions which greatly transcend the boundaries of the actual seagrass community.

ECOLOGICAL CONCEPTS

Estuaries typically support large seagrass meadows. Bostwich Ketchum of the Woods Hole Oceanographic Institution has estimated that 80 to 90% of commercial and sport fishes depend on estuaries for part or all of their life cycle. The problem is that until recent years the presence and importance of

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these meadows went virtually unrecognized. Marine and fishery biologists who worked in or close to seagrasses have been interested only in the particular organism of their concern. Only since the mid-1960's have oceanographers included the shallow benthic coastal zone as a part of the ocean system, and only recently has it been recognized that seagrasses form an ecosystem which contributes significantly to the total ocean system.

The functions of eelgrass (*Zostera marina* L.) were summarized by Wood *et al.* (1969), and these can be expanded for all seagrasses:

1. The leaves retard currents and increase sedimentation and inorganic materials around the plants.

2. The roots bind sediments together and, with the protection afforded by the leaves, surface erosion is reduced, thereby preserving the microbial flora of the sediment and the sediment-water interface. Seagrass rhizomes form a dense interlacing mat; the leaves form a dense baffle. The plants are so effective in their hold on the bottom that they persist despite severe storms. In the tropics, seagrasses persist through 150-kn winds during hurricanes.

3. Eelgrass produces much detritus when leaves are released and then decompose (the organic matter of this detritus and that of other components of the ecosystem including decaying roots supports sulfate reduction: the seagrass ecosystem maintains an active sulfur cycle).

4. Although a few organisms feed directly on eelgrass and several graze on the epiphytes (grazing chains), the major food chains are based on eelgrass detritus and its resident microbes (detritus chains).

5. The leaves support large numbers of epiphytic organisms, with a total biomass approaching that of the plants themselves.

6. Eelgrass has a high growth rate, producing on the average about 300 to 600 g dry weight/m^2/yr, not including root production. Dry weight can be converted to carbon, following Westlake (1963) by a proportion of 38% (McRoy and McMillan 1977).

7. A fundamentally important nutrient cycle is performed by eelgrass (phosphorus is absorbed through the roots and leaves; both nitrogen and phosphorus are returned to the water column from sediments via eelgrass).

Seagrasses are positioned in the coastal zone between upland ecosystems and the offshore oceanic ecosystem. As a result of their sediment trapping and high productivity functions, seagrasses tend to link these otherwise dissimilar ecosystems. In this respect, they are similar to salt marsh ecosystems. They trap terrigenous materials and export quantities of plant and animal products to the open sea. These products range from whole leaves and stems, to detritus, to dissolved organic matter. Turtlegrass (*Thalassia testudinum* Konig, a tropical seagrass) has been reported floating on the ocean surface in large rafts off North Carolina and on the bottom at a depth of 3208 m (Menzies *et al.* 1967), and in deep trenches off Puerto Rico up to 8900 m (5.5 mi)(Wolff in press). Wolff (in press) found an abundance of animals, including isopods, amphipods, annelids, gastropods, and bivalves, eating the plant fragments.

By their presence on a landscape of relatively uniform relief, seagrasses create a diversity of structured habitats and substrates from a relatively structureless one. Stauffer (1937), working on eelgrass invertebrate communities, classified the structure formed as:

1. on the plants;
2. among the plants;
3. on the substrate surface; and
4. in the substrate.

Only the latter two categories would be available without the plants.

SEAGRASS ECOLOGY

Salinity

Seagrasses appear to be euryhaline, with various species growing in waters of 6 to 60‰ (parts per thousand) salinity. For eelgrass (a north temperate species), the optimum range appears to be 10 to 30‰. For turtlegrass, a tropical species, the optimum range is more restricted, *i.e.* 20 to 35‰. Shoalgrass, *Halodule wrightii* Aschers., also a tropical species, is a pioneering and more adaptable species, and its salinity range extends from 10 to 60‰.

Kikuchi and Peres (1973) stated that eelgrass in the Baltic Sea displayed a stunted condition and rarely formed dense stands when salinities were as low as 6‰. Biebl and McRoy (1971) found that eelgrass at Izembek Lagoon, Alaska, had a wide tolerance to salinity (less than 15, up to 31‰) but that photosynthesis declined sharply in fresh water and at twice normal seawater salinity. The osmotic resistance of the plant tissue varied directly with salinity from 0 to 93‰.

Osterhout (1917) proposed physiological types for eelgrass which adapted to alternating exposures of freshwater on Mount Desert Island, Maine. Protoplasts of leaf cells from eelgrass in Maine waters were harmed in fresh water, while those from stream mouths withstood fresh water for several hours. In the laboratory, root cells were killed by fresh water, but were not affected by fresh water in the field.

Salinity is the principal factor influencing seed germination in some seagrass species. For eelgrass, most germination occurred at dilute salinities:

60% in 4.5 to 9‰ (Arasaki 1950); up to 70% in 5 to 10‰ (Phillips 1972). Seed germinations in full strength seawater are depressed: Japan (Arasaki 1950); England (Tutin 1938); Alaska, Puget Sound, and San Diego (Phillips 1972 and unpublished data). However, eelgrass seeds from the Gulf of California, Mexico, displayed a 100% germination response in full strength seawater (Phillips unpublished data). Eelgrass at the latter location is an annual plant.

Temperature

McMillan (1978) subjected various seagrass species to varying conditions of temperature and suggested that widely distributed species may have geographic variants, *i.e.* genotypes of the species which have been selected for adaptation to a suite of local conditions. This phenomenon could explain the tolerance of certain seagrasses to wide salinity and temperature variations in a local area and could explain the narrow or widespread geographic distributions of seagrasses.

Seagrasses tolerate a wide range of water temperatures from 0 to 40°C. The optimum temperature for growth and development of a species seems to be dependent on a local area. In Puget Sound (Phillips 1972) and in St. Margaret's Bay, Nova Scotia (Harrison and Mann 1975a), eelgrass vegetative growth and flowering stalk formation occurs below 10°C, while in Beaufort, North Carolina, these events occur over a range of 0 to 33°C.

Biebl and McRoy (1971) found that eelgrass was tolerant to temperatures ranging from 0 to 35°C for short periods of time, but that variants which possess similar temperature tolerances may exist only in geographic areas subjected to those temperatures. Tidepool eelgrass in Alaska showed increased photosynthesis to 35°C, while subtidal eelgrass showed a decline above 30°C. The tidepool plants also seemed to be more cold-resistant.

In the northern Gulf of Mexico, turtlegrass and shoalgrass tolerate water temperatures from 7 to 32°C. In southern Florida the range is 17 to 32°C, while in the eastern Caribbean (St. Croix, U. S. Virgin Islands) the range is 23 to 30°C. McMillan (unpublished data, University of Texas at Austin) has found that turtlegrass from each area forms a gradient of adaptive response to chill tolerance, that from the northern Gulf of Mexico having the broadest tolerance, while that from St. Croix has the narrowest range of adaptation.

Studies done at Turkey Point, Biscayne Bay, Florida, documented changes in algal and seagrass communities when heated discharges were made from a power plant (Roessler and Zieman 1969; Zieman 1970; Roessler 1971). Where waters were heated 5°C above ambient, *Thalassia, Halodule, Syringodium*, and all algae died. Sublethal effects were noted on these plants in temperatures only 2°C above ambient.

Light and Depth

The depth distribution of seagrasses depends on a number of interrelated factors: depth, waves, currents, substrate, turbidity, and light penetration.

In the temperate zone, eelgrass occurs from low tide down to about 10 m (32.8 ft). In some parts of the Pacific Northwest, a small *Zostera* species, *Z. noltii*, grows from low tide upward to 1.5 m (4.9 ft). In the tropics, only shoalgrass grows in the intertidal zone. Turtlegrass grows down to 12 m (40 ft) in most areas, but has been observed to 30 m (98 ft) in the Bahamas (Phillips 1960). In waters which are very turbid, seagrasses are restricted to less than 1-m deep.

Backman and Barilotti (1976) demonstrated that eelgrass flowering and density in a southern California lagoon were directly related to light intensity. Using canopies in shallow depths, they reduced downwelling illuminance by 63%, to simulate light conditions that exist at the lower limit for eelgrass growth. By Day 18, mean shoot densities under the canopies decreased relative to that of adjacent unshaded areas. Over 9 mo of the study, shoot densities declined to 5% of the controls in adjacent unshaded areas. Flowering was also reduced.

Any activity which increases turbidity or reduces light penetration in water over seagrasses limits the growth and survival of the plants. Among human-related factors which have such impacts are dredging and sewage release.

Substrate

In Denmark, eelgrass grows on firm sand to soft mud (Ostenfeld 1908). In England, Tutin (1938) found eelgrass in substrates varying from soft mud to gravel mixed with coarse sand. In Puget Sound, eelgrass grows on mud and sand mixtures, to liquid mud (Phillips 1974). Virtually the same range holds for the tropical species, *i.e.* turtlegrass and shoalgrass.

ECOLOGICAL FUNCTIONS

PRODUCTIVITY

Mann (1972) concluded that benthic nearshore ecosystems, *i.e.* seaweeds and marine macrophytes, were more productive than phytoplankton. These systems include benthic microalgae, macroalgae, epiphytes, marshes, mangroves, and seagrasses. Seagrass productivity outputs range from whole fresh leaves to detrital material to dissolved organic material.

Representative values of annual production of seagrasses range from 125 to 4000 g C/m^2/yr for turtlegrass, and 50 to 960 g C/m^2/yr for eelgrass (Table 1). Overall, turtlegrass shows approximately twice the productivity as eelgrass (McRoy and McMillan 1977). Average total productivity for subtropical zones is 1000 g C/m^2/yr; that for temperate zones is about 480 g C/m^2/yr. This could be a function of the length of the growing season. McRoy and McMillan (1977) assigned a growing season of 250 days to areas which support turtlegrass, but only 120 days to eelgrass. Thus, seagrasses yield more than cultivated corn (412 g C/m^2/yr), rice (497 g C/m^2/yr), hayfields, or tall grass prairies (Odum 1959).

Table 1. Net production of sea grasses in North America.

Ecosystem	Detritus ($gC/m^2/yr$)	Live tissue ($gC/m^2/yr$)	Dissolved organic matter ($gC/m^2/yr$)
I. Seagrass and source			
a. *Zostera marina*			
1. Puget Sound (Phillips 1972)		84 to 480	1.26 to 7.2[a]
2. Alaska (McRoy 1970a and b)		369 to 456	
3. Alaska (McRoy 1966)		960	
4. North Carolina (Penhale and Smith 1977)	330		5.0
5. North Carolina (Thayer *et al.* 1975)		120	
6. New York (Burkholder and Doheny 1968)		580	
7. Rhode Island (Conover 1958)		48 to 348	
b. *Thalassia testudinum*			
1. Florida (Iverson *et al.* 1979)		500	
2. Florida (Jones 1968)		900	
3. Florida (Zieman 1968)		425 to 575	
4. Florida (Odum 1963)		1425 to 4000(O_2 method)	
5. Texas (Brylinsky 1971)		580	
6. Texas (Odum and Hoskin 1958)		225 to 2250(O_2 method)	
7. Bahamas (Patriquin 1972)		125 to 750	
II. Epiphytes and source			
a. On *Zostera marina*			
1. Massachusetts (Marshall 1970)		20	
2. North Carolina (Penhale and Smith 1977)	73		1.5
b. On *Thalassia testudinum*			
1. Florida (Jones 1968)		200	

[a] After Penhale and Smith 1977

The epiphytic component of the seagrass ecosystem has been found to contribute much carbon. Den Hartog (1970) compiled a list of about 200 algal species epiphytic on eelgrass alone. Humm (1964) listed 113 species of algae epiphytic on turtlegrass. Epiphyte productivity was measured at 20% of the mean annual net production of turtlegrass in Florida (200 g C/m^2/yr)(Jones 1968), and about 25% of the annual production of eelgrass in North Carolina (Dillon 1971). Penhale and Smith (1977) found that eelgrass and its epiphytes contributed almost 15% of the total dissolved organic carbon in the estuarine system near Beaufort, North Carolina.

Three different techniques are used to measure productivity of seagrasses. The older method of measuring O_2 evolution, used for example by Odum (1957, 1963), results in very high numbers and is now discounted. Hartman and Brown (1967) showed that leaves of aquatic macrophytes store and internally recycle oxygen. Zieman (1974) developed a leaf marking method using staples (Appendix A) to determine leaf production, leaf turnover rate, and standing crop. This method neglects root and rhizome biomass and production. Patriquin (1973) devised a method for assessing production in leaves, roots and rhizomes (Appendix A).

Recently, Bittaker and Iverson (1976) used the ^{14}C uptake method with *Thalassia*. When corrections were made for inorganic losses, differences between the Zieman stapling technique and the ^{14}C method were insignificant.

FOOD CHAINS

Some of the earliest studies conducted on food chains in seagrass ecosystems were done in Denmark. Petersen (1891) stated his belief that fish abundance in Denmark was due to eelgrass. Other studies done by people from the Biological Station in Copenhagen (Petersen and Boysen-Jensen 1911; Blegvad 1914, 1916; Petersen 1915, 1918) concluded that eelgrass was the main source of organic matter on the sea bottom in Denmark, that organic detritus from eelgrass decay was the basic source of animal nutrition in Danish marine waters, that eelgrass detritus was the principal food of nearly all invertebrates in the Danish waters, and that the eelgrass belt in Denmark was the richest faunistic area. A consensus of all this work was that detritus from the eelgrass system was the basis for the invertebrate communities which supported several species of food fish important to the Danish economy.

This consensus was threatened in 1931 when a massive die-off of eelgrass throughout the North Atlantic resulted in a reduction of 90 to 99% of the eelgrass. In North America most of the animal community associated with the eelgrass ecosystem disappeared (Dexter 1944). In Denmark, fish populations declined, but not as sharply as Petersen might have predicted (Rasmussen 1977). It is now believed that the rich organic sediment built up by the eelgrass system over the years, now devoid of the plant cover, began to release nutrients into the water mass, thus cushioning an immediate effect on the fisheries (Harrison and Mann 1975b).

Many animals occupy seagrass meadows only temporarily as planktonic larvae (crabs, scallops, fishes) or while migrating (fishes, turtles). Others live in the beds throughout all or most of their lives (clams, shrimp, crabs, fishes). Seagrasses are of importance by their direct food value to animals. They also provide a valuable nursery function to many commercial and noncommercial fishes and invertebrates.

The tendency of marine macrophytes to generate detritus rather than enter grazing food chains has been noted (Mann 1972). Milne and Milne (1951) stated that only 20% of the eelgrass biomass could be directly consumed by fishes and waterfowl and that nutrient material entered food chains primarily from decomposition of detritus. In North Carolina, Thayer *et al.* (1975) reported that eelgrass meadows supported larger populations of invertebrates and fishes than adjacent estuaries. They also found that eelgrass occupied only 17% of the estuarine area, but supplied 64% of the combined total production of phytoplankton, *Spartina*, and eelgrass.

Until now most authors stated that few consumers graze on living seagrass tissue (Thayer and Phillips 1977), but a recent compilation reveals a large list of grazers (McRoy and Helfferich, in press). The list of grazers is greater in the tropics where dugongs, manatees, turtles, fishes, waterfowl, and sea urchins eat living seagrasses. In Izembek Lagoon, Alaska, McRoy (1966) estimated that black brant, *Branta bernicla*, and Canadian geese, *B. canadensis*, consume about 17% of the eelgrass standing crop. Boone and Hoeppel (1976) noted that less than 5% of the eelgrass biomass is lost by invertebrate grazing. Marshall (1970) showed that in southern New England 2/3 to 3/4 of the eelgrass annually decays into the sediment, and that eelgrass, epiphytes, and macroscopic algae contribute 125 g C/m^2/yr as detritus. Mann (1972), quoting from the work of Krey (1967), noted that detritus in suspension, derived from coastal macrophytes, makes a substantial contribution to planktonic food chains.

The evidence suggests that microorganisms are the most important consumers of marine macrophytes, and that detritus-feeding invertebrates derive their nourishment primarily by stripping the microorganisms from the plant material as it passes through their guts (Mann 1972; Fenchel 1970, 1972). The fecal pellets may be recolonized by microorganisms and the process repeated until all plant material has been utilized (Harrison 1977). The work of Zobell and Feltham (1938) demonstrated that many invertebrates can live almost indefinitely on an exclusive diet of bacteria.

The studies of Thayer and Phillips (1977), Kozloff (1973), Ricketts and Calvin (1968), Marsh (1973), Orth (1973, 1977), Kikuchi and Peres (1973, 1977), Davis (1911), Allee (1923a, 1923b), and Nagle (1968) on the eelgrass system and the papers by O'Gower and Wacasey (1967), Voss and Voss (1955, 1960), Tabb and Manning (1961), and Tabb *et al.* (1962) on the *Thalassia-Halodule* system established that the seagrass ecosystem is very complex. It is composed of a diverse and interrelated group of benthic and epiphytic micro- and macroalgae, sessile and motile epifauna, benthic infauna, and transient motile fauna. Variability exists in the biota with geographical location and season, but the general types of organisms are very similar in at least eelgrass beds throughout the northern hemisphere (Boone and Hoeppel 1976).

NUTRIENT CYCLING

Seagrass meadows are extremely important in the cycling of nutrients. Nitrogen (Patriquin and Knowles 1972; McRoy *et al.* 1972), phosphorus (McRoy and Barsdate 1970), carbon (McRoy 1976), sulfur (Wood *et al.* 1969), and other nutrients are converted into forms more readily usable by other organisms. These nutrients are taken up by the plants through the roots and pumped into the water mass.

Izembek Lagoon, Alaska, has a surface area of 218 km^2 with eelgrass covering 116 km^2. Eelgrass there annually produces 116,000 mt (metric ton) of particulate carbon which contains 7,400 mt of nitrogen, 1,660 mt of phosphorus, 3.45 mt of copper, and 386 mt of silica (Barsdate *et al.* 1974). Only a small fraction of this was recycled within the lagoon. Patriquin and Knowles (1972) found that nitrogen was fixed in the rhizosphere of eelgrass. McRoy and Barsdate (1970) reported that eelgrass leaves and roots absorb phosphorus, the major pathway being from the roots to the leaves to the water; but they found that eelgrass could serve as a phosphorus sink in phosphate-rich waters.

Eelgrass appears to maintain an active sulfur cycle (Wood *et al.* 1969). The predominantly reduced environment around the plants allows for anaerobic microbial decomposition of detritus; the sulfides formed create a sink for many toxic metals in the marine environment. The thin oxidized surface layer allows for sulfate accumulation, which is available to the microorganisms involved in the decomposition processes (Wood *et al.* 1969; Fenchel 1973).

There is an important relationship between seagrass detritus formation and nutrient cycling, both within and across ecosystem boundaries. Nutrients enter seagrass food chains primarily through the transport and decomposition of detritus, despite the direct consumption of about 20% of the biomass by fishes and waterfowl (Milne and Milne 1951).

Microbial decomposition of detritus is of prime importance in nutrient release and cycling. Many nutrients are released as plant exudates during the growth of the plant. Mann (1972) reported that fresh and senescent leaves of eelgrass contain about 20 and 12%, respectively, water-soluble organics. Particulate detritus is poor in essential nutrients, while bacteria contain very high amounts of phosphorus and nitrogen (Fenchel 1977). Bacteria are located as a film around detritus particles. These bacteria absorb nutrients from the water and, while acting on the detritus, enrich it with N and P. Mineral nutrients cycle between bacteria and animals, the latter remineralizing the nutrients by digesting the bacteria. For example, bacteria store phosphorus, while animals excrete it. Concurrently, eelgrass plants in the system excrete dissolved organic carbon (Penhale and Smith 1977) into the water column which is available to epiphytes on the seagrass blades and to benthic macroalgae and microalgae in the meadows.

Particulate detritus from seagrass blade decomposition may remain in the water column or may settle to the bottom where it may enter an initial phase of oxidation (eelgrass sediments are oxidized in a small surface layer), but soon it enters an anaerobic layer below the surface (Fenchel 1969). Because of this and an abundance of sulfur bacteria, sediments tend to be dominated by the sulfur cycle. Although anaerobic decomposition is slow, it favors the release of mineral nitrogen, phosphorus, and readily assimilable organic constituents. There is additional evidence that anaerobic decomposition, in the presence of sulfate, produces six times more organic material than that occurring by aerobic decomposition (Fenchel 1972). This appears to be related to a rich microflora and micro- and macrofauna (Fenchel 1969, 1977; Fenchel and Riedl 1971; Orth 1973, 1977).

SEDIMENT STABILIZATION

Owing to the density and length of leaves, seagrass meadows form a baffle which increases the rate of particle sedimentation, preferentially concentrating finer particle sizes (Schubel 1973). They do this by the entrapment of water-borne particles by the leaf blades, by the formation and retention of particles produced within the meadows, and by the binding and stabilization of the substrate by the rhizome and root systems. These effects can be local or widespread. Long-term widespread influences of seagrasses on sedimentation include: 1) the carbonate bank along the eastern margin of Shark Bay in western Australia (Davies 1970); 2) the grass-bound "mattes" on the Mediterranean coast of France (Molinier and Picard 1952); and 3) the Tavernier and Rodrigues Banks off Florida (Baars 1963). Cottam and Munro (1954) noted that when eelgrass declined along the North Atlantic coast in the 1950's, the sediments progressed from organic fine silts to unstable sands. Fenchel (1973) and Barsdate *et al.* (1974) noted that the fine-textured sediment added stability to the substrate and greater nutrition for eelgrass.

The effect of seagrass meadows on sediment stabilization is well-documented. Sand banks, formerly covered by eelgrass, were lowered by 30 cm (12 in) or more almost overnight in Salcombe Harbor, Great Britain, after the plants disappeared in 1931 (Wilson 1949). Many species of filter feeding invertebrates, molluscs, and several flatfishes also disappeared. Up to 20 cm (8 in) of sediment eroded from unvegetated sand banks following a single storm in Chesapeake Bay, while little, if any, sediment disappeared from within an eelgrass meadow (Orth 1977). Thomas *et al.* (1961) recorded the effects of winds from Hurricane Donna in 1960 on *Thalassia* in Biscayne Bay. Winds gusted to 80 mph (70 kn) in the northernmost portion of the bay and exceeded 100 mph (87 kn) in the southern end of the bay for 24 h before and after the passage of the eye of the storm. Although windrows of leaves were cast up on shore, only light damage was done to the turtlegrass. Only a slight thinning of plants was noted in shallow water. They concluded that the high growth rate of *Thalassia* leaves (up to 25 mm increment per week) would lead to early recovery. They also stated that fresh water from rains during the storm probably contributed the little damage suffered by the plants.

Sediment stability is a function of density and the seagrass species (Schubel 1973). *Thalassia* (wide, flat blade) is more effective at binding sediment than is *Syringodium* (narrow, terete blade). Observations indicate that near the edge of an eelgrass meadow, there is an increasing density of plants and an increasing amount of sediment removed by turbulent water. Finally, Orth (1977) found a positive correlation between sediment stability and invertebrate infaunal diversity.

NATURAL AND HUMAN ACTIVITIES

Despite the adaptive responses of seagrasses to a fluctuating environment, several human-related activities have taxed the ability of plants to persist.

DREDGING

Dredging poses the greatest threat to the seagrass ecosystem (Zieman 1975a; Thayer *et al.* 1975; Phillips 1978). Not only are the plants themselves removed, but the entire physical, biological, and chemical structure of the ecosystem is changed. The extent of the area affected by actual dredging depends on the tidal range, current strength, and sediment texture in the area.

Sediments raised by dredging can bury plants away from the site; but more importantly, they may also drastically reduce plant density as a result of their effect on water clarity. Backman and Barilotti (1976) documented the reduction in eelgrass density, biomass, and flowering indicence (reduced to 5% of former levels) when canopies causing shading were placed in shallow areas of a southern California lagoon. This phenomenon might also occur with increased water turbidity caused by an increased silt load. The reduction in seagrass density caused by suspended silt may open an area to increased erosion of the bottom sediments which will further impact additional areas. Where turbid water prevails, eelgrass populations are limited to less than 1 to 3 m (Thayer *et al.* 1975; Burkholder and Doheny 1968); while growth has been observed down to 30 m (98 ft) where the water is clear (Cottam and Munro, 1954). In the Caribbean region, large areas of the highly productive turtlegrass have not recovered following dredging operations (Zieman 1968; Van Eepoel *et al.* 1971; Grigg *et al.* 1971). Taylor and Saloman (1968) reported that between 1950 and 1968, dredging and filling operations in Boca Ciega Bay (near St. Petersburg), Florida, reduced turtlegrass area by 20%. They found that the dredged portions of the bay contained less than 20% of the plant and animal species formerly recorded from the undisturbed bay (Phillips 1960, Springer and Woodburn 1960; Taylor and Saloman 1968). Using conservative and incomplete figures, Taylor and Saloman (1968) estimated an annual loss in fisheries and water sports of about $1.4 million per year from the bayfill operations (1,400 a filled).

In a natural experiment performed in the North Atlantic in 1931 when 90 to 99% of the eelgrass disappeared, loss of animal life was extensive. Black brant, particularly, declined sharply. There was a 2/3 reduction in the

Netherlands (Bruijns and Tanis 1955), a reduction from 250,000 to 22,000 at Scott Head Island in England (Ranwell and Downing 1959), and an 80% reduction by 1934 in the eastern U.S. (Moffitt and Cottam 1941). Soft-shelled and razor clams, lobsters, and mud crabs declined severely when eelgrass disappeared (Dexter 1944); cod, flounders, scallops, crabs, and other food animals were reduced (Milne and Milne 1951). In Denmark, fish populations fell off but not as sharply as Petersen (1918) had predicted (Rasmussen 1977). It is now believed that the rich organic sediment built up over the years, now devoid of the plant cover, began to release nutrients into the water mass, cushioning an immediate adverse impact on the fisheries (Harrison and Mann 1975b). In the Niantic River, Connecticut, scallop populations soared in the absence of eelgrass (Marshall 1947). In other areas scallops are dependent on eelgrass for spawning (Thayer and Stuart 1974). Recently, Dr. Michael Ludwig related that the National Marine Fisheries Service dynamited 15 a of prime eelgrass meadows in the Niantic River, Connecticut, to aid in scallop spawning (Address to the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi; 22 May 1979). Flemer *et al.* (1967) noted a 71% reduction in average numbers of organisms in a Chesapeake Bay spoil area after dredging. Briggs and O'Connor (1971) noted that diversity and density of fish species decreased when vegetated areas were covered by dredged materials in Great South Bay, New York.

Dredging upsets the redox potential of the sediments of a seagrass system, which reverses the entire nutrient flow mechanics of the ecosystem (*cf.* section on Nutrient Cycling).

In many areas agricultural clearing of uplands, real estate development, logging, and channelizing streams may increase the rate of erosion of sediments, detritus, and mineral nutrients, and may cause high inputs of sediments into estuaries and coastal areas (Thayer *et al.* 1975). Stream diversion would decrease input of fresh water and suspended sediments. This might enhance the spread of seagrasses over a wider area, but might also decrease the distribution of other species (Thayer *et al.* 1975). The potential deleterious effect of freshwater diversion lies not only in increased salinities, but also in the accompanying diversion of mineral nutrients usually introduced into estuaries in freshwater runoff.

The use of the hydraulic clam dredge is increasing. The dredge blasts sediments to a depth of 45 cm (18 in) and 1 m (39 in) wide. Since eelgrass rhizome mats are located at a maximum depth of 15 cm (5.9 in), this activity removes the entire ecosystem, both plant and soil structure. Godcharles (1971) reported on the use of the hydraulic clam dredge in turtlegrass beds in Tampa Bay and near Tarpon Springs, Florida. Seagrasses were blasted out. At one station some *Halodule* recovered, but no *Thalassia* or *Syringodium* ever recolonized.

Commercial fishermen use hand rakes and bar dredges to gather scallops in North Carolina (Thayer *et al.* 1975). While the hand rakes do minimum damage, the bar dredges denude the bottom of eelgrass over large areas. When this occurs bottom sediments are stirred up, promoting oxidation of the sediments so that recolonization of eelgrass and bay scallops is impeded (Thayer and Stuart 1974).

Probably the most preventable form of disturbance is that caused by boat propellors cutting through a meadow. Various investigators have documented the long term impacts on *Thalassia* when rhizomes were cut (Phillips 1960; Jones 1968; Scoffin 1970; Zieman 1975a).

Perhaps the greatest impacts on the seagrass ecosystem are yet to be applied. With the present world-wide energy crunch, there is a serious economic-political crisis with respect to the supply and transport of fossil fuels. Thus, we may presume not only an escalation of maintenance dredging in present waterways, but additional dredging projects culminating in channels and ports to receive supertankers. Channels which are normally 35 ft (10 m) deep for most shipping must be lowered to 70 ft (21 m) with accompanying increases in maintenance dredging. There is evidence that even small-scale dredging projects in some areas may constitute a severe perturbation on seagrass ecosystems (Port Aransas, Texas, area; Phillips, ms. in prep).

EUTROPHICATION

The impact of effluent discharges on seagrass beds is well-documented. Zieman (1975a) reported one of the most luxuriant growths of turtlegrass and epiphytic algae just inshore of a Miami sewage plant on Virginia Key, Florida. Taylor *et al.* (1973) found that significant portions of Hillsborough Bay, Florida, were damaged by dredging and domestic and industrial effluents, particularly phosphorus and nitrogen compounds and suspended solids. Effects noted were heavy growths of phytoplankton and filamentous algae, marked fluctuations in oxygen, and high turbidity. The latter resulted in reduced density and coverage of *Thalassia*. Fish and crustacean catches were low as compared to other areas where seagrasses were extensive. Dong *et al.* (1972) noted that extensive *Thalassia* was replaced by *Enteromorpha* when sewage inputs and dredging increased in Christiansted Harbor, St. Croix, Virgin Islands. Nichols *et al.* (1972) documented a 66% reduction of grass beds in the harbor at St. Croix over a 17 yr period (as reported by Zieman 1975a). McNulty (1970) reported a lack of seagrasses in an area polluted by sewage effluents in Biscayne Bay, Florida. Only *Halophila decipiens* and *Halodule wrightii* and no *Thalassia* persisted within 1 km (0.6 mi) of the outfall. Beyond 1 km, *Thalassia* occurred sparsely.

TEMPERATURE AND SALINITY

All seagrasses appear to have upper and lower temperature tolerance levels (Phillips unpublished data; McMillan 1978) beyond which they may be destroyed (Thayer *et al.* 1975). These levels vary with the local area. Eelgrass in northern and southern areas may tolerate a much broader temperature range than that in the intermediate range. At Mt. Desert Island, Maine, and Puget Sound, Washington, normal temperature range is 5 to 17°C; above 20°C, eelgrass undergoes heat rigor. Near the southern boundary at Beaufort, North Carolina, and in Izembek Lagoon, Alaska, eelgrass tolerates an annual range of 0 to 35°C (Dillon 1971; Biebl and McRoy 1971; Phillips unpublished data). Phillips (1974) wanted that heated water discharges released into eelgrass habitats could disrupt phenological patterns. Thorhaug and Stearns (1972) reported that *Thalassia* growing at artificially elevated temperatures produced flowers but no fruits.

In Alaska, Biebl and McRoy (1971) found that tidepool eelgrass showed increased photosynthesis up to 35°C, above which it declined; while subtidal eelgrass photosynthesis declined above 30°C. Zieman (1975b) reported that photosynthesis in *Thalassia* sharply declined above and below the temperature range of 28 to 30°C.

Zieman (1970) found that seagrasses tend to be more resistant to thermal pollution stress than do algae. This may be related to the location of the rhizomes several cm below the substrate level. Glynn (1968) observed that *Thalassia* leaves were killed by temperatures of 35 to 40°C in Puerto Rico, but that the rhizomes were not affected. Arasaki (1950) reported that eelgrass survived a temperature extreme of 40.5°C at a depth of 3 to 5 cm (1 to 2 in) in Japan.

The overall conclusion is that seagrasses form photosynthetic and phenological biotypes which are adapted to local temperature ranges and this in turn controls the entire ecosystem. No one can generalize for seagrasses over a broad area with respect to their response to temperature changes. Raising the temperature regime of tropical seagrasses can have far greater effects than a similar modification in a temperate environment, since organisms in tropical waters live much closer to thermal death point (Biebl 1962, Zieman and Wood 1975).

The best documented study of the impact of thermal effluents is that from two fossil fuel power plants erected in April 1967 and 1968 at Turkey Point, Biscayne Bay, Florida (Roessler and Zieman 1969). Water near the two power plants was raised as much as 5°C above ambient. All seagrasses in an area of about 9.1 ha (22.5 a) off the mouth of the discharge canal disappeared, while those in an area 30 ha (74.1 a) further out declined. The animal communities associated with these meadows also disappeared. Sediments around the fossil fuel plants also contained higher levels of nickel, copper, vanadium, lead, cadmium, zinc, and iron than those not affected by the thermal plumes. Thorhaug (1979) reported that by January 1976 the inner totally denuded area contained 0 to 10 blades of *Thalassia* per m^2.

Salinity changes appear not to have the extreme effects on seagrasses as do temperature changes, although species seem to have a range of tolerance to salinity. Zieman (1975a) observed that the salinity ranges of the Caribbean seagrasses showed considerable variation. *Halodule*, a pioneering species, is very euryhaline (range 3.5 to 60.0‰) (McMahan 1968). Phillips (1960) found *Halodule* existing in fresh water for short periods of time. It was the most euryhaline species, but was out-competed by *Thalassia* and *Syringodium* when they were present. McMillan and Moseley (1967) found that *Halodule* showed the greatest resistance to high salinity, *Thalassia* was intermediate, and *Syringodium* was the least resistant.

Hammer (1968) found that photosynthesis of seagrasses reached a maximum in full strength seawater, and decreased as salinity decreased. Part of this decrease could have been a result of the dilution of the carbon supply as the salinity was diluted.

Zieman (1970, 1974) reported an interaction of salinity and temperature affecting the seasonality of *Thalassia*. The combination of high temperature and low salinity was found to cause the greatest decline in the plant populations.

WIND AND SEA STRESS

Thomas *et al.* (1961) reported on the negligible effects of Hurricane Donna in 1960 on *Thalassia* in Biscayne Bay, Florida. In Texas, Oppenheimer (1963) found that inshore *Thalassia* was undamaged following the passage of Hurricane Carla in 1961. Winds were estimated up to 175 mph (152 kn). In some parts of the general area, there was extensive sediment erosion.

In 1963, Hurricane Edith passed Puerto Rico (Glynn *et al.* 1964). Winds reached 75 mph (65 kn), but were 42 to 49 kn inshore and on the coral reefs. Water surge was only 0.5 m (19 cm) owing to protection from the fore reef. *Thalassia* beds were not noticeably damaged, although mangroves and *Syringodium* leaves suffered some effects.

Eelgrass is patchy on the south coast of England where wave exposure is severe (Tutin 1938), and is absent in Denmark where waves beat heavily (Ostenfeld 1908). Moderate currents seem to enhance eelgrass growth. In Puget Sound, Washington, the most luxuriant growths are located where tidal currents reach 3.5 kn, but are absent where wave shock is regular. In February 1964, the west side of Whidbey Island, Washington, was lashed by 1 to 2 m waves for 2 days, driven by 40 kn winds. Following the storm, we found that 7 to 10 cm of sediment had been removed, exposing the rhizome mat. The plants remained in place and recovery of the meadow occurred (Phillips 1972).

POPULATION EXPLOSIONS AND OVERGRAZING

Where seagrasses occur with coral reef patches, overgrazing by reef fishes such as surgeon and parrot fishes (Randall 1965) and urchins, *e.g.* *Diadema* (Ogden *et al.* 1973) often produces bare "halo zones" surrounding the reefs. The effect of this grazing is localized and poses no threat to the grass beds (Zieman 1975a).

Camp *et al.* (1973) observed dense concentrations of the urchin, *Lytechinu* *variegatus*, off the west coast of Florida which caused massive destruction of mixed *Thalassia-Syringodium-Halodule* beds over a 26 km distance (beds 5.5 to 9.25 km offshore). Outbreaks of this urchin damaged 20% of the grasses, often completely denuding areas hundreds of meters long and several meters across. Density of individuals at the leading edges of the fronts averaged 63.6/m^2, with individuals piling up two to eight deep. Several meters behind the front, urchin densities averaged 5.6/m^2. The aggregates moved through the grass an average rate of 1.6 m/wk; thus, an aggregate 9 m wide could have denuded an area of about 14 m^2 in one week.

OIL POLLUTION

Good documentation of the effect of oil on seagrasses is lacking. The few existing reports state that direct contact of the oil and the seagrass plants is needed to cause death of the plants. Diaz-Piferrer (1962) found that beds of *Thalassia* were badly affected by crude oil on the south shore of Puerto Rico. Plants deteriorated over a period of several months. The normal algal flora was denuded and replaced by blue-green algae.

Following the Santa Barbara, California, oil spill which commenced on 28 January 1969, heavily coated leaves of *Phyllospadix torreyi* were killed when they were in contact with the air (Foster *et al.* 1971). Those plants in 10 cm water were protected from any damaging effects of the oil. Neushul (1970) found that oil adhered to *Phyllospadix* leaves, which were subsequently lost. However, when the oil was removed, new leaves were produced by the rhizomes. Neushul (1970) added that oil entered the sediment and had a severe effect on benthic invertebrates. This oil could then move up the food chain and eventually be consumed by humans.

It is these latter aspects, that of the interaction of the oil with the sediment, that are of very serious concern. Seagrasses tend to stabilize fine-grained sediments, but as oil seeps into the sediment, it agglomerates into large lumps. This increases the buoyancy of the sediments, thus making the removal of the sediments easier (Zieman 1975a). Diaz-Piferrer (1962) recorded the loss of 3,000 m^3 of sand from Tamarindo Beach in less than a week due to this effect.

Largely unknown is the effect of the oil on the anaerobic microbial decomposition of seagrass detritus and subsequent effects on the food chains. Also, unknown are the effects of sediment-oil interaction on the nutrient relations of the seagrasses. Knowledge of these relations must be gained soon.

METALS AND OTHER MATERIALS

In recent years, humans have dumped increasing amounts of heavy metals, oil products, synthetic products, such as DDE, DDT and other chlorinated hydrocarbons, solid wastes, domestic pollution, pesticides, detergents, fertilizers, PCB's, and pharmaceuticals, into our shallow coastal zones. There has been little concern for the presence or absence of plant communities in these areas or for the impacts of these products on the plants present. All these products, commonly classified as pollutants, should be considered as to quantities produced, their toxicity, and their persistence. Additions of toxic materials have been shown to affect animal components of seagrass systems, but not the seagrass itself (Thayer *et al.* 1975). The direct effects of pesticides and chlorinated hydrocarbons, heavy metals, and petroleum products, while being documented for many types of marine organisms, are unknown on the seagrasses themselves.

There has been little work on the role of seagrasses and their detritus in accumulating these products and transferring them to other trophic levels (Thayer *et al.* 1975). Since most seagrasses require a reducing environment around the roots (Wood *et al.* 1960), but an oxidized environment around the leaves, they can pick up metals in a variety of forms (Zieman 1975a). Parker *et al.* (1963) found the highest concentrations of cobalt and manganese in Texas bays in seagrasses (one order of magnitude higher than in surrounding sediments). Iron was in the same concentration as in the sediments, but more concentrated than in any other plant or animal. Parker (1962) reported that zinc in *Thalassia* and *Halodule* was 5 to 10 times the concentration in the sediments. Thus, the possibility exists that excess metals in estuaries from sewage, nuclear plants, and desalination plants may be concentrated in seagrasses and passed up the food chain.

ECOLOGICAL GOALS

Following this discussion of the seagrass ecosystem, it is now clear what must be done in the future to insure the continued presence of this system in as undamaged a state as possible. If dredging and other impacts are judged absolutely necessary in or around seagrass meadows, then studies should precede such work to minimize damage. There are also some well-developed restorative techniques available (Phillips 1974, 1976; Thorhaug 1974, 1979; Thorhaug and Austin 1976).

Since seagrass ecosystems are dynamic entities, with a suite of adaptive properties in a changing environment, it is imperative that scientific studies continue on these plants and this ecosystem. These studies should be conducted not only in mildly- or heavily-impacted areas (these areas should give data on the ability of the plants to adapt), but it is absolutely imperative that studies be continued in "sanctuaries", or some such areas totally devoid of impacts to yield baseline data which can be used as "control" information on the inherent genetic, morphological, and physiological capabilities of the plants and their systems. If these fundamental baseline studies cannot be conducted in areas unavailable to the hordes of tour-hungry humans or to industrial development, it is altogether possible that management of our natural world will be done from obsolete file cabinets by the year 2000.

A second goal of future studies is to establish improved means of assessing the consequences of environmental change. It is hoped that fundamental research and this assessment of the consequences of change can allow us a predictive capability for more intelligent management of our coastal resources.

A third major goal is to assess the role of seagrasses in the overall ocean system of the world. At the present we are only beginning to learn the basics of the size of particular meadows, their distribution, and seasonal productivity. An overall assessment is needed to fit these data into the total system.

It is hoped that we can assess the role seagrasses have in local areas, in particular oceans, and *in toto*, before they are so diminished that we do not even know what we have lost.

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APPENDIX A

TECHNIQUES FOR MEASURING THE PRODUCTIVITY OF SEAGRASSES

A. Zieman (1974) technique for estimation of seagrass production.

1. A "Tot 50" stapler is used, modified by wrapping the lower arm of the stapler with a strip of aluminum foil to reduce the pressure needed to discharge the staple.

2. Push a 10 cm^2 or 20 cm^2 wire frame into the substrate. Leave a one or two cm space between the sediment and frame. Mark all leaves within the frame with a staple (staple placed vertically with lower end level with wire frame). Record number of leaves initially marked and the distance from the base of the staple to the leaf tip in each leaf.

3. After two to four weeks, collect all leaves in the frame, cutting them at the level of the frame.

4. Divide leaves into two groups: new leaves (no staples) and old leaves (with a staple). For new leaves: a. Count them; b. Measure length and width; c. Record presence or absence of original tip; d. Record amount of epiphytism (distance along leaf in cm); e. Record degree to which the leaves have been chewed by urchins and small fish. For old leaves: a. Measure distance from base of leaf to bottom of staple, and add to this the former distance from base of staple to leaf tip.

5. Production: cut all old leaves below the staple. Place this basal growth in a sieve, wash it, and dip it in a bath of 50% phosphoric acid to remove carbonates adhering to leaves. Then thoroughly wash all leaf material under a stream of running water, oven-dry material at 105°C for 24 hours and weigh it. Repeat procedure with new leaves (use entire length of leaves), and finally with excised tips of old leaves.

6. Data: a. Standing crop of leaves (g/m^2)-add weight of new and old leaves. Express on m^2 basis.

   b. Leaf production ($g/m^2/day$)-weight of new leaves plus weight of old leaves below the staple (new growth) divided by the number of days between marking and collection. Express on a m^2 basis.

   c. Community replacement rate (turnover): divide standing crop by productivity value.

7. Constraints of Method:

   a. Gives data on leaf growth rates only.

   b. Neglects root and rhizome production which constitute 75 to 85% of the biomass and an unknown proportion of the productivity of a seagrass.

   c. Does give an accurate estimate of leaf production which is the energy applicable to most community energy flow studies (energy passes on to higher trophic levels).

   d. Technique limited to wide-blade seagrasses, such as *Zostera* or *Thalassia*. For fine-blade seagrasses (*Halodule, Syringodium*), use ^{14}C method (Bittaker and Iverson 1976).

B. Patriquin technique for estimation of seagrass production (mimeo, 1974; David Patriquin, Biology Department, Dalhousie University, Halifax, Nova Scotia, Canada).

1. Clip the youngest exposed leaf on 30 shoots with a diagonal cut across the apex.

2. After n days (about 20) remove plants, including the underground parts.

3. Count the number of new leaves produced and determine the plastochrone index (P.I.):

$$\text{P.I.} = \frac{\text{number of plants x observation period in days}}{\text{number of new leaves produced}}$$

4. Calculation of production:

   a. $\text{Leaf production per shoot} = \frac{\text{average biomass of fully formed leaf}}{\text{P.I.}}$

   b. $\text{Rhizome production per axis} = \frac{\text{avg. rhizome biomass on 4th or 5th youngest node}}{\text{P.I.}}$

   c. $\text{Root production per axis} = \frac{\text{avg. root biomass on 4th or 5th youngest node}}{\text{P.I.}}$

5. Constraints of Method:

   a. To get leaf production per m^2, must conduct separate leaf density measurements in field and determine average biomass of fully formed leaf.

6. Further data that can be obtained (Patriquin 1973)(true for *Thalassia* in Barbados and Bermuda; could be tested for its applicability to *Thalassia* in the Gulf of Mexico and *Zostera* in temperate regions):

   a. After finding the periodicity of new leaf appearance, the age of a specific leafy shoot may be determined by counting the leaf scars and leaves on an erect branch, and multiplying this number by the periodicity in days.

   b. An estimate of the rhizome growth rate can be obtained by dividing the length of the rhizome between two erect shoots by the difference in ages of the two erect shoots.

   c. Net production of *Thalassia* in Bermuda and Barbados was equal to 0.0037 x standing crop (wet weight). This could easily be tested for applicability to turtlegrass and eelgrass elsewhere.

STUDIES OF FRESHWATER NEEDS OF FISH AND WILDLIFE RESOURCES IN NUECES-CORPUS CHRISTI BAYS, TEXAS

Nicholas A. Funicelli[1]

INTRODUCTION

Estuaries are mixing zones of fresh and salt water with combinations of temperature, salinities, foods, substrata, and biota which do not exist in marine or inland environments. Freshwater inflows create needed salinity gradients in the estuary and also supply nutrients to the marshes and other shallow water habitats of the estuary. Periodic flooding and overbanking of rivers flowing into estuaries result in the inundation of delta marshes and contiguous tidal pools, and this maintains vital nutrient levels and sustains habitat integrity. Reduced freshwater inflow into estuaries can have the following significant effects: nearshore waters may become more saline; estuarine habitats may decrease in quantity and quality; estuaries may become deficient in essential nutrients derived from inland areas; bottom sediments may become anaerobic and less productive; land area will be lost because beach and marsh erosion can exceed replenishment of sand and fine sediments carried in from inland areas; and saltwater encroachment may alter the natural coastal environments and underground water supplies.

This paper addresses the specific freshwater inflow needs of estuarine biota inhabiting Nueces-Corpus Christi Bays. This bay system is a large, shallow, well-mixed body of water, in the vicinity of Corpus Christi, Texas separated from the Gulf of Mexico by Mustang Island which limits the exchange of Gulf waters with this system. These bays provide nursery habitat for several species of commercial and recreational fishes and shellfishes, including red drum (*Sciaenops ocellata*), black drum (*Pogonias cromis*), Atlantic croaker (*Micropogon undulatus*), spot (*Leiostomus xanthurus*), spotted seatrout (*Cynoscion nebulosus*), sand seatrout (*C. arenarius*), southern flounder (*Paralichthys lethostigma*), striped mullet (*Mugil cephalus*), gulf menhaden (*Brevoortia patronus*), brown shrimp (*Penaeus aztecus*), white shrimp (*P. setiferus*), blue crab (*Callinectes sapidus*), and American oyster (*Crassostrea virginica*). In addition, a fertile brackish delta marsh is sustained by discharge of the Nueces River into upper Nueces Bay.

The U.S. Fish and Wildlife Service (FWS) is currently in the 23rd month of a 27-mo study to determine the freshwater needs of fish and wildlife resources in Nueces-Corpus Christi Bays. This study was in response to the proposed construction of the Choke Canyon Reservoir (an upriver impoundment on

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the Nueces River near Three Rivers, Texas). This dam, when completed, could adversely affect the productivity of the Corpus Christi-Nueces estuarine system by reducing the inflows of fresh water, nutrients, and sediments. The Bureau of Reclamation has estimated that the Choke Canyon Reservoir would reduce the average annual freshwater flow from the Nueces River into the Corpus Christi-Nueces estuary system by 43.5%, an annual average loss of 163,000 ac ft (acre-feet) by the year 2000. Average annual return flows to the estuary system would increase from 70,000 ac ft without the project to 153,000 ac ft with the project, an average annual increase of 83,000 ac ft. Thus, the total annual freshwater flow into the estuary system would be reduced, according to the Bureau of Reclamation, by 80,000 ac ft by the year 2010.

The FWS study has been divided into five study phases. Phase I consisted of an information synthesis (detailed results of Phase I are contained in Henley and Rauschuber 1978a). Phase II was a proposal for additional field studies, which were deemed necessary to overcome data gaps identified in Phase I. Phase III is the performance of these field studies and the study is presently nearing the conclusion of this phase. Phase IV will be development of water management recommendations and Phase V will be distribution of public information materials.

FIELD STUDIES DURING PHASE III

Upon completion of Phase I, it was deemed necessary to document: 1) the comparative primary production rates of the various biotypes existing in Nueces-Corpus Christi Bays; 2) the temporal occurrence and quantification of nutrient flows into and out of the biotypes; and 3) the temporal and spatial utilization of the biotypes by study species. The study biotypes and species present in the bay system area are listed in Table 1.

TABLE 1. Biotypes and Component Species Present in Nueces-Corpus Christi Bay System.

A. Salt marsh biotype

1. *Spartina alterniflora* (saltmarsh cordgrass)
2. *Spartina spartinae* (high marsh cordgrass)
3. *Batis maritima*
4. *Borrichia frutescens* (sea oxeye)
5. *Baccharis halimifolia* (groundsel bush)
6. *Avicennia germinans* (black mangrove)
7. *Distichlis spicata* (saltmarsh grass)
8. *Salicornia bigelovii* (Salicornia)
9. *Salicornia virginica* (Salicornia)
10. *Monanthocloe littoralis*

Table 1 (Cont'd)

B. Seagrasses or grassflats biotype

1. *Halodule wrightii* (shoalgrass)
2. *Thalassia testudinum* (turtlegrass)
3. *Ruppia maritima* (widgeongrass)

C. Fishes and shellfishes

1. *Penaeus setiferus* (white shrimp)
2. *Penaeus aztecus* (brown shrimp)
3. *Callinectes sapidus* (blue crab)
4. *Crassostrea virginica* (American oyster)
5. *Brevoortia patronus* (Gulf menhaden)
6. *Cynoscion nebulosus* (spotted seatrout)
7. *Leiostomus xanthurus* (spot)
8. *Micropogon undulatus* (Atlantic croaker)
9. *Mugil cephalus* (striped mullet)

Primary production estimates for each plant zone were determined using biomass techniques developed by Wiegert and Evans (1964) and subsequently employed by Kirby and Gosselink (1976). Plants were collected and production measured from September 1978 to June 1979 from 10 transects representative of the Nueces delta, Harbor Island and Mustang Barrier Island study areas. These transects were established based on the information synthesis work of Henley and Rauschuber (1978b). Dissolved nutrient parameters were monitored during diurnal samplings and included carbon (total organic, particulate organic and inorganic carbon), nitrogen (organic nitrogen, ammonia, nitrate, and nitrite), and phosphorus (total and orthophosphate).

Sampling for finfishes and shellfishes by plankton tows and seine hauls was designed to determine utilization of marsh and seagrass habitats and movements into and out of these areas. Methods were utilized which sampled larval, post-larval, juvenile, and adult finfishes and shellfishes occurring at various stations in Nueces Marsh, Redfish Bay, and Mustang Island seagrass beds (Henley and Rauschuber, 1978b). Physiochemical data were collected at all stations and included salinity, temperature, conductivity, dissolved oxygen, pH, redox potential, depth and wind velocity and direction.

PRODUCTIVITY AND NUTRIENT EXCHANGE RATES

Total macrophytic primary production data suggested that the Nueces marsh was approximately five times more productive than the Harbor-Barrier Island study area. This figure should be viewed with suspicion because it does not include data for the summer and early fall growing seasons in which the seagrass production component would be expected to be higher. Temporal trends in vegetative growth patterns occurred as expected in both the Nueces salt marsh and the Harbor-Barrier Island study areas. Live standing crop was highest during late spring, summer, and early fall, and lowest during the winter months. Maxima for dead standing crops occurred during February in the Nueces delta and March in the Harbor-Barrier Islands.

The highest detrital processing rates were found in the seagrass beds, with lower rates occurring in the high marshes of Harbor Island. Litter dispersal trends were significantly amplified during the months of April and May 1979. These trends were probably influenced by heavy rains totaling more than 19 cm (7.5 in) that occurred during this period in the Nueces River watershed.

Inorganic nutrient concentrations (carbon, nitrogen, and phosphorus) were typically higher in the Nueces marsh than in the seagrass beds of the Harbor-Barrier Island areas. This was expected because the Nueces marsh area receives greater amounts of direct runoff than the seagrass areas. In addition, metabolic processes occurring in the seagrass beds appear to be greater than those in the marsh. Thus, nutrient stocks tend to be depleted and incorporated into live biomass more readily in the seagrass beds than in the Nueces delta marsh. This was illustrated by the extremely fast detrital processing components of the seagrass beds during decomposition studies.

Analysis of nutrient exchange data into and out of the Nueces marsh during the period October 1978 to June 1979 indicated that the net annual flow of all nutrients (carbon, nitrogen, and phosphorus) was into the marsh. On a seasonal basis, however, net flows of nutrients were somewhat different. During the fall months of October and November, all nutrients were flowing from the marsh to the bay. During winter they were mixed, that is, carbon forms flowed from the marsh into the bay, while nitrogen and phosphorus forms flowed from the bay into the marsh. February was similar to October and November; all nutrient net flows were into the bay. Spring and early summer months exhibited the largest fluxes, with net flows entering the marsh.

Analysis of fish data indicated decreased utilization of marsh habitat during the winter months, with the lowest biomasses recorded from November 1978 to February 1979. Seagrass bed habitats did not reveal this trend. It should be noted that these results pertain to gross biomass utilization and that individual utilization by species was temporally variable (*i.e.* believed to be temperature-dependent).

APPLICATION OF DATA TO MANAGEMENT DECISIONS

Although the results presented here are preliminary, certain freshwater inflow management decisions can be presented. The Phase III sampling program was designed to not only answer the question of quantity of freshwater inflows needed for fish and wildlife resources, but also, perhaps more importantly, the timing of these freshwater releases. That is, as the quantity of fresh water is diminished (due to drought or industrial, agricultural and municipal development), the timing of these releases will become very critical. In support of this methodology for freshwater inflow management, preliminary modeling results reveal that delivery of all the available fresh water at any given time would have a very small effect on salinity. Furthermore, observations reveal that the study species are not salinity-limited in these habitats. The motile study species are distributed by food and habitat availability. If the study species of the Nueces-Corpus Christi estuary are food or habitat-limited, it becomes a question of inflow management to optimize primary production and nutrient, detrital and sediment flows.

Study results may indicate that primary production of Nueces marsh is greater than the seagrass beds. Flood flows (over-bank flooding) of the Nueces River may be more beneficial to the Nueces delta and its marshes than flows modified and reduced to within-channel capacity.

Nutrient inflow and outflow study results raise several interesting questions. Releases could be timed to provide additional nutrient inflows when the system approaches sink conditions. Preliminary speculation of the author would be to key these releases to phosphorus depletion. These releases should be timed on a seasonal basis to coincide with larval fauna needs.

Preliminary study results indicate that freshwater inflow management can not be tied to salinity management in Nueces-Corpus Christi Bays. We must consider freshwater inflow as a transport system for estuarine nutrients and a mechanism for flooding which allows optimum habitat utilization.

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ECOLOGY OF A HYPERSALINE LAGOON:

THE LAGUNA MADRE

Warren Pulich, Jr.[1]

INTRODUCTION

A coastal Gulf of Mexico ecosystem, the Texas Laguna Madre has long been a fascinating place to scientists because it represents one of only three oceanic hypersaline lagoons in the world (Gunter 1967). The extensive reviews of Hedgpeth (1947), Simmons (1957), Breuer (1962), and Gunter (1967) provide excellent historical accounts of the physical characteristics and ecology of the Laguna up to the late 1960's. The purpose of this paper will be to 1) describe the present habitat of the Laguna, pointing out major changes that have occurred in the last decade; 2) present evidence for the probable causes of the evolutionary developments; and 3) outline some critical ecological questions which require future study if the dynamic Laguna ecosystem is to be preserved.

GEOGRAPHIC DESCRIPTION

The Laguna is essentially composed of two separate geographic sections: the Upper and Lower portions which are divided by the Middle Ground or "Land Cut" area (Figure 1). Simmons (1957) postulated that the Land Cut was formed by sand washed over from Padre Island during a hurricane in 1919, and that the Upper and Lower portions became separate only then. Because of differences in water circulation and points of access to the Gulf, these areas have developed into two distinct lagoonal subenvironments. The Lower Laguna possesses a flow-through circulation pattern due to openings to the Gulf 48 km (30 mi) apart: one at the south end, Brazos Santiago Pass, a natural pass, and the other at the north end, Mansfield Pass, an artificial channel and pass dredged in the late 1950's. The Arroyo Colorado, a dredged freshwater floodway, drains much of the Rio Grande Valley, and flows into the Lower Laguna about 16 km (10 mi) south of Port Mansfield.

The Upper Laguna, in contrast, communicates to the Gulf only indirectly and has a much more limited water exchange pattern. At the north end, it connects with generally hyposaline Corpus Christi Bay. The GIWW (Gulf Intracoastal Waterway), which runs the entire length of the Laguna (ca 180 km or 110 mi) from Corpus Christi to Brownsville, provides for water exchange to the south

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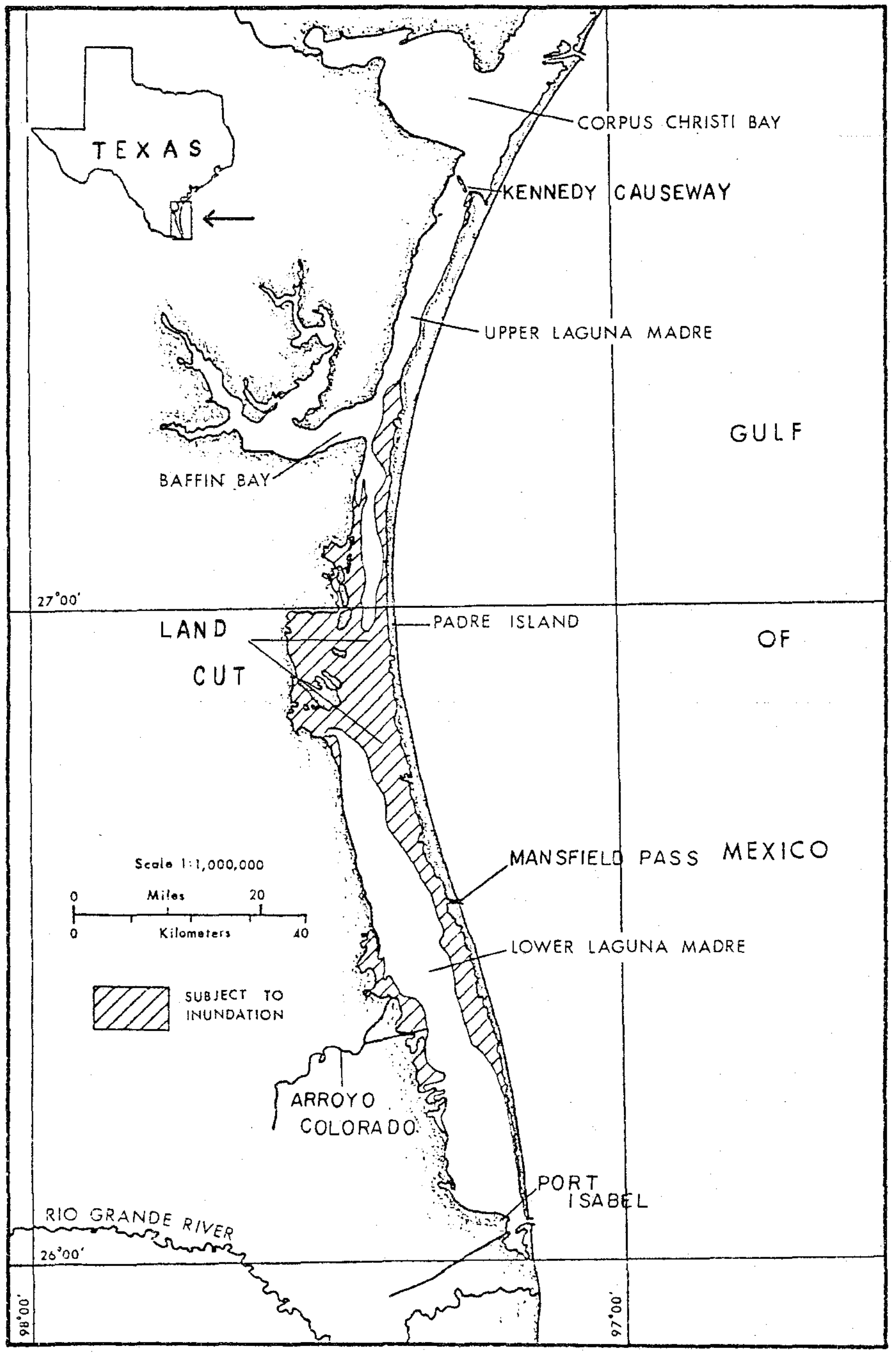

Figure 1. Map of south Texas coast, showing Upper and Lower Laguna Madre and relationship to barrier island, Padre Island. Map courtesy of Glen Merkord.

(to the Lower Laguna). The GIWW extends 32 km (20 mi) through the Land Cut, and, the Land Cut acts as a bottleneck to restrict rapid water flow between the two sections. Freshwater inflow from Baffin Bay (a hypersaline area itself) into the Upper Laguna is usually minimal. The main effect of the GIWW since its completion in 1948 has been to ameliorate long-term, lethal salinity conditions (*i.e.* greater than 80‰) and to provide an avenue of escape for fishes (Simmons 1957). The distinction between the two portions must be kept in mind, and most reference to hypersaline conditions applies chiefly to the Upper Laguna at the present time.

GENERAL ENVIRONMENTAL CONDITIONS

A hypersaline environment is defined by Kinne (1964) as a body of water having salinity between 40 and 80‰, as opposed to a brine which exists above 80‰. Before 1948, when dredging of the GIWW was completed, the Laguna waters often fit the definition of a brine, with salinities over 100‰ not infrequent (Simmons 1957). Since 1948, the salinity has rarely surpassed 80‰, and indeed, in the last 15 yr, the highest value recorded has been around 60‰ in the Upper Laguna (Warshaw 1974). However, the average salinity during this same time has also not dropped below 30‰ except after hurricanes or other occasional storm events (Figure 2), and this is a temporary situation.

While salinity fluctuation between 30 and 60‰ now constitutes a major feature of the Laguna Madre, various climatic and geographic factors help to maintain this hypersalinity and are perhaps more significant for the organisms there. High temperature and high evaporation combined with a low annual rainfall at this southern latitude favor the production of hypersaline waters. There is an almost total lack of freshwater inflow except for the Arroyo Colorado and occasionally from Baffin Bay. A study of the tidal circulation by Smith (1978) showed that very little water is exchanged in the Upper Laguna on a diurnal basis with at most a 3.5 cm (1.4 in) daily tidal change. The average depth (1.5 m or 5 ft) of the Laguna typifies the shallowness of a hypersaline lagoon. This produces a high surface to volume ratio of the water mass, which promotes a high evaporation rate. The shallow depth in turn provides a competitive advantage to rooted marine plants, which require a relatively high light intensity for good growth.

PHYSIOLOGICAL CHARACTERISTICS OF LAGUNA BIOTA

The harsh, stressed environment afforded by the Laguna Madre raises questions about the adaptations of the biota which enable them to compete for available niche space. The overriding influence of salinity makes the Upper Laguna too unstable for biological succession to occur, and consequently, colonizing species persist. This type of ecosystem can be accurately described as a "pioneer climax" system. The plants and animals there represent species competing, not so much with each other, but rather with the physical environment for their survival. The Lower Laguna, in contrast, has shown gradual

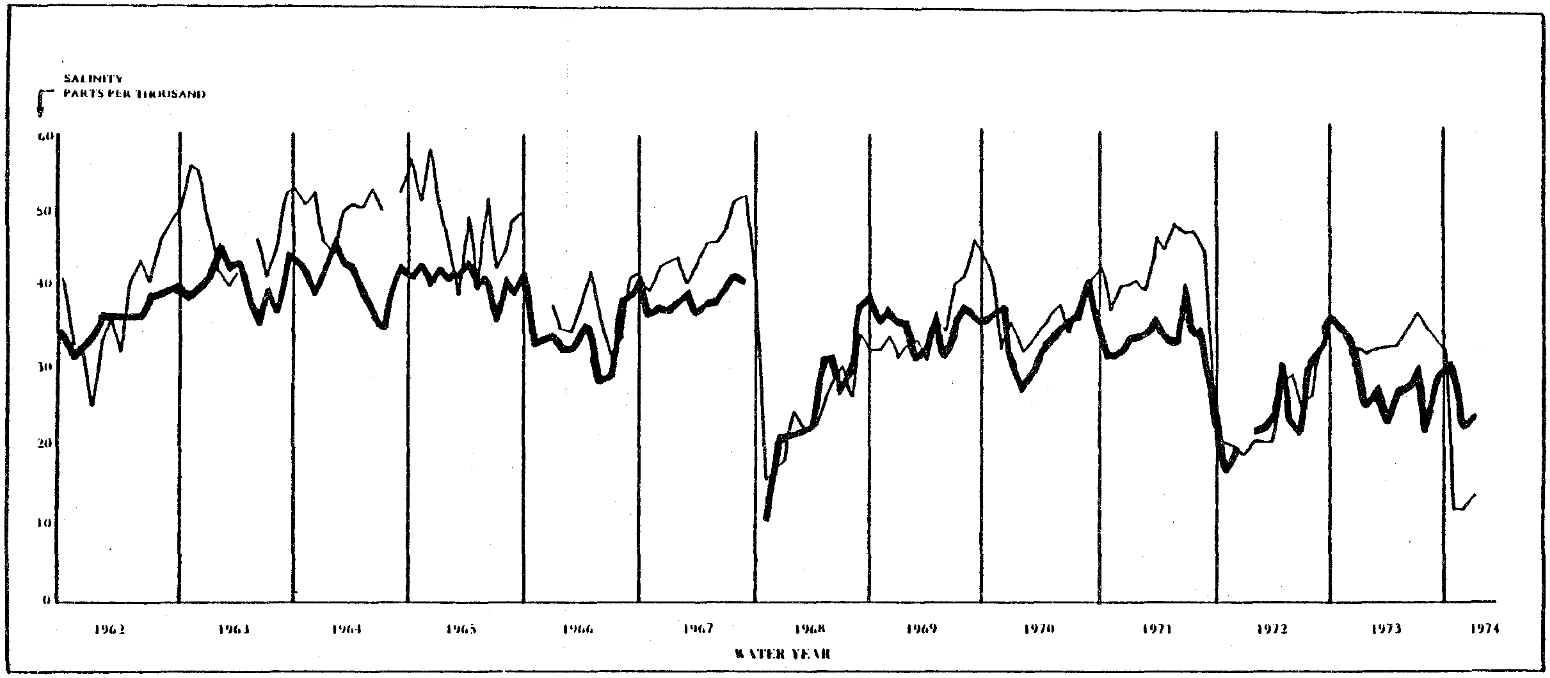

Figure 2. Twelve year salinity records for Upper (light line) and Lower (heavy line) Laguna Madre. Data from Warshaw (1974).

shifts in species abundance in recent years, and can rightly be considered as undergoing succession. However, these changes probably have resulted from human impact rather than natural successional processes.

In general, the organisms found in the Upper Laguna Madre are typical pioneer or colonizing species, capable of living in an unstable, stressed environment (Carpelan 1967). None of the flora and fauna are endemic to this area; they are merely tolerant to an environment characterized by fluctuating salinity (from 30 to 70‰). Just as they can tolerate increases in salinity to 70‰, they also tolerate salinities lower than 35‰, and are appropriately called euryhaline species. In physiological terms, these organisms have solved the problem of osmoregulation, *i.e.* maintaining their body fluids (blood or cytoplasm) at a constant solute concentration. A corollary to this is that by regulating solute concentrations, organisms maintain water balance, and therefore do not dehydrate in hypersaline waters or swell and burst in fresh water. The capacity to osmoregulate may seem to be a specialized trait, but in terms of evolution, cellular osmotic regulation is apparently an early, primitive feature (Carpelan 1967). Therefore, these euryhaline species are not specialized, but rather they have retained the trait of osmoregulation during evolution, in contrast to their phyletic counterparts.

LAGUNA FOOD CHAIN RELATIONSHIPS

A curious ecological principle is illustrated by the Laguna biota: while the number of species found in a hypersaline lagoon is known to be much lower than in marine waters, the number of individuals of those species is very high (Carpelan 1967). Historically, the very high productivity of the Laguna is reflected by high finfish production data. Hedgpeth (1947), Simmons (1957), and Warshaw (1974) have noted that the Laguna supplies about 60% of the total State catch of bay fishes even though it comprises only 20% of the total bay area. Hellier (1962), during a study of Laguna productivity, calculated the efficiency of conversion of plant production into fish production at 0.074% or a dry weight basis which is considerably higher than that calculated for offshore fishing banks or for coral reefs.

In an ecosystem with large populations of a few species, food chains tend to become simplified (Carpelan 1967). Simmons (1957) stated that many animals lived primarily among seagrasses, including polychaetes, amphipods, grass shrimps (*Palaemonetes* sp.), young penaeid shrimp, pistol shrimp, crabs, bivalves, molluscs, and many forage fishes, *e.g.* killifishes, pipefishes, and pinfish (*Lagodon rhomboides*). Most of these (except penaeid shrimp and red drum, *Sciaenops ocellata*) spawned only in the grass. Commercially-important finfishes (*e.g.* red drum and spotted seatrout, *Cynoscion nebulosus*) regularly fed in grassbeds.

Fry and Parker (1979) have recently postulated that the food chain in the Upper Laguna is predominantly based on benthic plants rather than phytoplankton, as a result of carbon isotope ratio ($\Delta^{13}C$) analyses. Most of the animals probably obtain seagrass carbon via an abbreviated detrital food chain as a result of decomposition of dead seagrass. In this way, top trophic level carnivores, such as red drum and spotted seatrout, depend on seagrass even though they actually eat shrimp and forage fishes. This abbreviated detrital food chain also makes the transfer of carbon from benthic plants to higher trophic levels more efficient than for a phytoplankton-based food chain and gives detritus-feeding organisms a competitive advantage in the Laguna.

Several species of waterfowl (including pintail, *Anas acuta*; American widgeon, *A. americana*; and redhead, *Aythya americana*) are known to feed heavily on live seagrass, specifically shoalgrass (*Halodule*) and widgeon grass (*Ruppia*) (Martin and Uhler 1951). The dependence of these ducks on Laguna Madre seagrasses is impressive; it has been estimated that 50 to 75% of the entire North American population of redhead regularly winters in the Laguna Madre (Cornelius 1975). From a study of the food resources of wintering redhead, Cornelius (1975) concluded that between 4 to 5% of the fall standing crop of *Halodule* in the Lower Laguna was consumed by these birds alone. *Halodule* comprised 70% of the birds' diet, and rhizomes were preferred over other seagrass parts.

DOMINANT PLANT HABITATS

The previously-discussed environmental constraints have led to the dominance of three monotypic plant habitats. These are: 1) seagrass beds, which are meadows of submergent marine flowering plants; 2) algal mat communities; and 3) benthic or drifting seaweeds (macroalgae). Planktonic microalgae (*i.e.* phytoplankton) while sometimes present as "blooms" of mostly naviculoid diatoms, green flagellates, and some dinoflagellates, are usually temporary in nature and not a permanent feature of Laguna waters. Emergent salt marsh of *Spartina alterniflora* does not develop because of the arid climate and hypersaline water (Hoese 1967).

ALGAL MAT COMMUNITIES

Much of the Laguna is extremely shallow, less than 15 cm (6 in) deep at normal tide, and consists of extensive flats of bare sand covered with algal mats (Sorensen and Conover 1962). Seasonal tides and the arid climate cause these areas to alternate between inundation and dessication. This also effectively prevents the permanent establishment of seagrass beds, although occasionally patches of *Ruppia* are found growing in high tide pools (salinity 30 to 40‰) during late summer and autumn. As it evaporates, the water over these flats can reach the saturation limit for some salts; and often crystals of $CaCO_3$ and $CaSO_4$ can be seen precipitated out on the surface of the sediment, when salinities rise above 80‰. Such salt flats and algal mat areas are especially common on the back side of Padre Island in the "Land Cut" region where blowing sand from Padre Island has filled in much of the Laguna proper.

The algal mats are composed of microalgae in an ordered arrangement, which has been described by Sorensen and Conover (1962). A surface layer of filamentous blue-green algae, mostly *Lyngbya confervoides*, comprises 80% of the mat, and this layer extends down to a depth of 3 to 8 mm. Four to 10 mm below the surface, the bottom zone of the mat merges with the underlying sediments. This layer is reddish-yellow due to the presence of purple bacteria, protozoans, diatoms, and other bacteria (presumably heterotrophically-growing organisms). The oxygen concentration in this layer is low and no light penetrates.

The productivity achieved by such algal mats is appreciable. Pomeroy (1959) estimated the production of similar algal films in Georgia salt marshes at 200 g C/m^2·yr. The heterotrophic layers would be expected to be important in the decomposition of detrital material washed up and stranded on these flats by winds and occasional high tides. Most importantly, these mats contribute a significant amount of reduced (*i.e.* fixed) nitrogen to the lagoon system. Recent studies have demonstrated that many strains of blue-green algae isolated from such algal mats are rapidly growing, nitrogen-fixers (Gotto *et al.* 1979). Actual measurements of N_2 fixation by algal mat communities from the south Texas coast reveal average summertime rates of around 2 mg N/m^2·h, which extrapolate to approximately 50 kg N fixed/ha·yr (John Gotto, pers. comm., University of Texas, Port Aransas Marine Laboratory). This average value for algal mats compares with N fixation input for tropical grasslands of about 90 kg/ha·yr, 40 to 400 kg N/ha·yr for pasture legumes, and 100 to 500 kg N/ha·yr for seagrass beds (Knowles 1977).

DRIFT ALGAE

Although not a stationary habitat, the floating seaweeds accumulate to such an extent in channels, depressions and bare parts of the Laguna, particularly during the warmer months of the year, that their production represents a major contribution to the energy budget of the ecosystem. Cowper (1978) stated that drift algae may represent the situation of an outside environment (the open Gulf system) importing to coastal Texas bays. Sorensen (1979) has listed the seaweeds found in the Laguna Madre, a total of about 30 species of various green, brown and predominantly red algae. The most noticeable and abundant during the warm months are the green algae, *Acetabularia crenulata*, and the red algae, *Jania capillacea, Gracilaria* sp. and *Laurencia poieti*. During the winter the red algae, *Chondria* sp., is frequently found.

These drift algae are much more sensitive to salinity than the seagrasses and the microalgae communities, and are not encountered above 50‰ salinity. However, at lower salt conditions, biomass values of up to 200+ g dry wt/m^2 have been measured (Cowper 1978; Pulich unpublished data). An interesting characteristic is that many of these macroalgae are calcareous species which store deposits of calcium carbonate within their tissue. This process is aided by the high salt, alkaline conditions (pH 8.0 to 8.9), which exist in the Laguna during the warm months.

SEAGRASS MEADOWS

All species of seagrass along the Texas coast are typical subtropical or tropical species which achieve maximum growth potential in the warm shallow waters of the Laguna. Major differences exist between the seagrass species found in the Upper and Lower Laguna Madre, however, and these differences in distribution appear to result from salinity and turbidity regimes. The Upper Laguna contains extensive beds of *Halodule wrightii* (shoalgrass) with variable amounts of *Halophila engelmannii* and *Ruppia maritima* (widgeongrass), dependent on local conditions. The Lower Laguna, while possessing sizable populations of *Halodule*, is also conspicuously vegetated with manateegrass (*Syringodium filiforme*), as far north as near Port Mansfield. At the southern end near Port Isabel, turtlegrass (*Thalassia testudinum*) has been and still is found in abundance, associated with manateegrass.

Standing crop values for Laguna Madre seagrasses are comparable to the most productive terrestrial crop plants. Representative mid-summer biomass measurements (in g dry wt/m^2) are: 300 to 600 for *Halodule* in the Upper Laguna (Merkord 1978; Circe 1979; Pulich unpublished); 400 to 700 for *Syringodium* in the Lower Laguna (Merkord 1978); and 400 to 800 for *Thalassia* in the Lower Laguna (Merkord 1978; Pulich unpublished). Underground tissues comprise the major portion of this biomass. During early summer of 1977, an average of 62% of the *Halodule* biomass at study sites in the Upper Laguna was represented by roots and rhizomes, and leaves composed only 38% of the total biomass (Pulich unpublished). Circe (1979) found a ratio of 70% underground biomass and 30% leaves during the summer of 1978 . During the winter months, this ratio increases to 80% for roots and rhizomes, since leaves are shed while underground tissues apparently overwinter (Circe 1979). *Thalassia* biomass is similarly divided between leaves and underground tissues, with average values of 66% roots plus rhizomes and 34% leaves obtained during early summer 1977 (Pulich unpublished).

The high leaf densities of seagrasses provide enormous surface area for productivity, both primary and secondary, as well as protective habitat for many juvenile animals. Leaf area index values (m^2 leaf surface/m^2 ground covered) of 6 to 10 have been measured for Upper Laguna *Halodule* (Pulich unpublished). Net leaf production rates for *Halodule* of 3.0 g dry wt/m^2•day (1.0 gC/m^2•day) have also been measured during late June 1977 (Pulich unpublished), and this still does not include production which went into the aforementioned underground tissues.

McMillan and Mosely (1967) and McMahan (1968) have reported that *Halodule* (maximum salinity limit 60‰) is much more tolerant of hypersalinity than turtlegrass or manateegrass (maximum salinity limit 40‰). This factor would seem to explain the total absence of *Thalassia* and *Syringodium* in the Upper Laguna, given the high average salinity over the years. The dominance of these latter two grasses in the Lower Laguna may be attributed to their oft-quoted ability to out-compete *Halodule* (den Hartog 1977) at moderate salinities, the exact mechanism of which has not yet been clarified.

The comprehensive survey by Merkord (1978) provides evidence of the changes in seagrass populations, particularly in the Lower Laguna, since Simmons (1957) and McMahan (1968) did their studies. Merkord's work documents that seagrass abundance has increased in the Upper Laguna, with *Halodule* and *Halophila* both expanding their ranges since 1966. A dramatic shift in species distribution has occurred in the Lower Laguna as evidenced by the spread of manateegrass northward from the Arroyo Colorado and a decline in *Halodule* to the south of Port Mansfield along the eastern half of the Laguna. This range expansion by *Syringodium* may be a result of a general increase in turbidity noted in the Lower Laguna (Glenn Merkord, pers. comm., University of Texas, Port Aransas Marine Laboratory) although this has not been quantified. It is also possible that run-off from the Arroyo Colorado which includes nutrients, pesticides, herbicides, and silt (Warshaw 1974) has allowed *Syringodium* to grow relatively unchecked. Physiological data obtained by Buesa (1975) indicate that *Syringodium* is much more efficient at using blue light for photosynthesis than *Thalassia*. Since most other visible wave lengths of light are filtered out as sunlight passes through water, blue light would predominate in turbid water (Jerlov 1966). If *Halodule* was also inefficient at using blue light like *Thalassia*, then growth of *Syringodium* could be favored by such turbid waters.

CONDITIONS PROMOTING GROWTH OF SEAGRASSES IN THE UPPER LAGUNA MADRE

While the species distribution of benthic plants in the Laguna Madre is attributable to the general salinity conditions, the abundance (*i.e.* standing crops) of seagrasses in the Upper Laguna can be traced to a number of additional factors.

WATER CLARITY

The contrast in water clarity between the hypersaline Laguna and an adjacent hyposaline bay is readily apparent (Figure 3) when light transmittance of Upper Laguna water is compared with that of Redfish Bay water to the north near Port Aransas. In Figure 3, light conditions at study sites in typical seagrass (*Halodule*) meadows in each estuary are compared. Over the 1979 growing season, the transmittance of Upper Laguna water averaged 45% of surface light at 50 cm (20 in) depth, compared to 27% at the same depth in Redfish Bay. The Laguna water clarity is consistently higher and a feature of widespread public knowledge as evidenced by the numbers of people who visit the Laguna to go snorkeling in the seagrass beds.

The high water clarity of the Upper Laguna does not result from unusually calm conditions there, since southeasterly or southerly winds are regular along this part of the coast from March to November (and occasionally during the winter). Rather, the sediments, which are predominantly quartzose sand (Shepard and Rusnak 1957), are not readily suspended; and this tends to keep turbidity normally low. In a truly estuarine bay such as Redfish Bay, higher turbidity results from heavy riverine input of silt and clay. At times when the Upper Laguna does appear turbid or murky, it is generally the result of

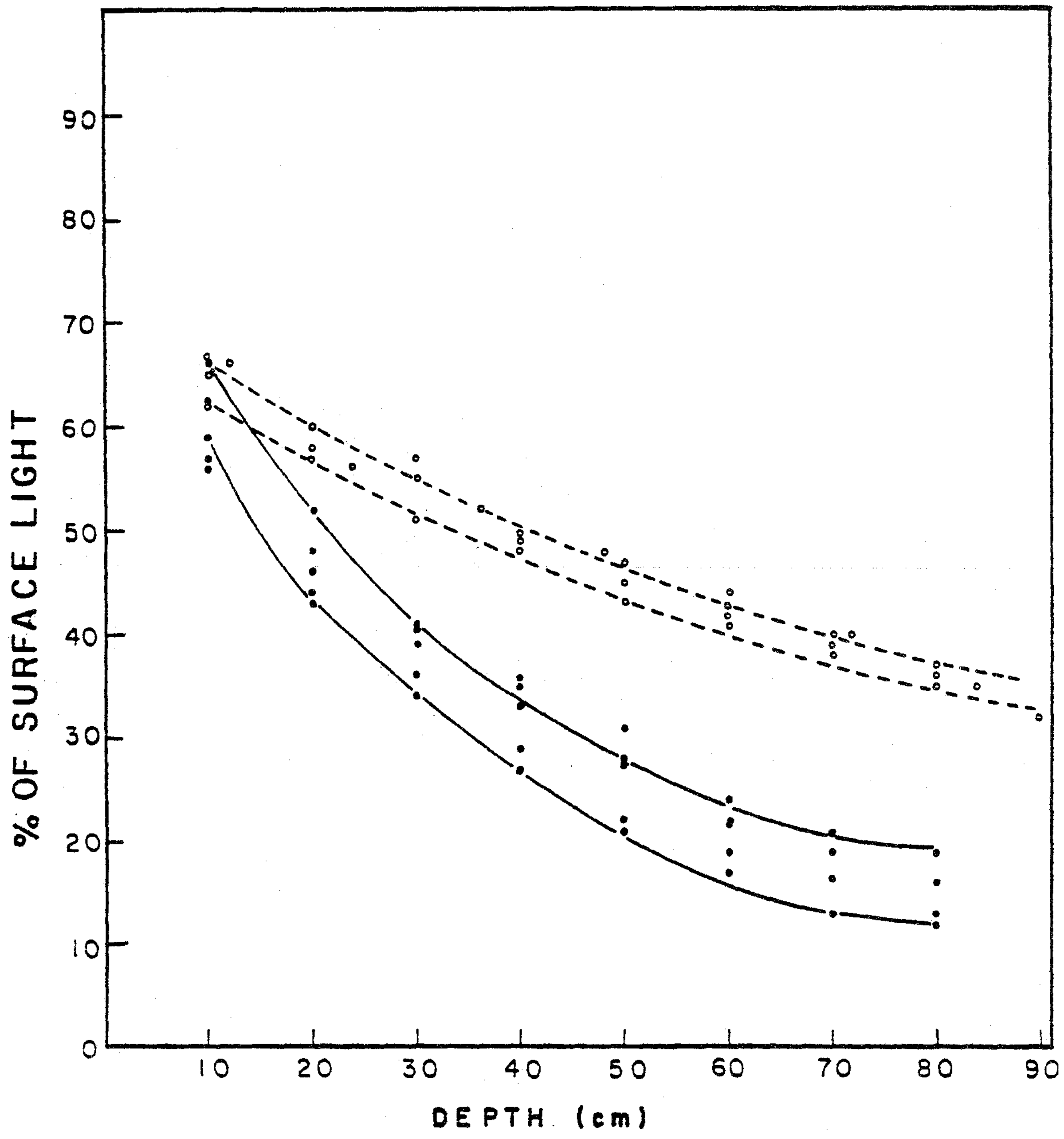

Figure 3. Light transmittance data for water column at two stations near Pita Island in Upper Laguna Madre (open circles) and two stations near Ransom Island in Redfish Bay near Port Aransas, Texas (closed circles). Measurements were made five times between 1 May 1979 and 1 August 1979 at these stations. Lines represent range of light transmittance values for Laguna Madre (dashed line) and Redfish Bay (solid line) over this time period.

phytoplankton blooms (as evidenced by high particulate chlorophyll values, *e.g.* 25 to 50 μg/ℓ during summer of 1978) or the so-called "bad water" described by Simmons (1957). This latter term describes the highly discolored, but not muddy water, which is probably caused by decaying vegetation (detritus) trapped in the Laguna.

Water clarity and the shallow depth of the Upper Laguna combine to provide favorable light conditions for enhanced growth of the seagrasses. Figure 4 illustrates the rate of photosynthesis of *Halodule* in the Upper Laguna, as a function of light transmitted through seawater. From this curve, it is evident that *Halodule* photosynthesis does not become light-saturated until 60% of full sunlight, a rather high light intensity. From consideration of Figure 3, one can deduce that this amount of light penetrates to only about 20 cm (8 in) depth even in the Laguna water. Hence, shoalgrass below that depth in the Laguna still does not photosynthesize at its maximum capacity, and the amount of available light is a major factor in regulating its abundance.

NUTRIENT LOADING EFFECTS

In order to grow at maximum rate under optimal light conditions, primary producers must also have available sufficient nutrients. This principle leads to a paradox when it is applied to the Upper Laguna. The Upper Laguna historically can be described as an oligotrophic system according to Hutchinson (1975), characterized by low nutrient loading, high water clarity, and hypersaline conditions preventing species succession of primary producers. Simmons (1957) was the first to point out that dissolved nutrient concentrations in the Laguna Madre are usually low and he attributed this to the lack of an adequate watershed for the area. Water quality data obtained from the Texas Department of Water Resources (1978) verify that concentrations of nitrate, ammonia and phosphate are usually higher at the mouth of Arroyo Colorado in the Lower Laguna and at the north end of the Upper Laguna at the Kennedy Causeway near Corpus Christi, points of inflow to the system, than they are in the central parts of the Laguna (Table 1).

Table 1. Nutrient Concentrations at Texas Department of Water Resources Monitoring Stations in Laguna Madre during 1978. Average of Three Measurements for Each Site (March, June, September). Values in mg/l. Data from Texas Department of Water Resources (1978).

Site	NO_3	NH_4	PO_4
Kennedy Causeway	0.09	ND[a]	0.320
Marker 59	0.05	ND	0.160
Mouth of Baffin Bay	0.03	ND	0.122
Marker 225A	0.02	ND	0.140
Port Mansfield	0.02	ND	0.150
Arroyo Colorado Mouth	0.30	0.10	0.550
Port Isabel	0.02	ND	0.120

[a] Not detectable; less than 0.5 mg/ℓ

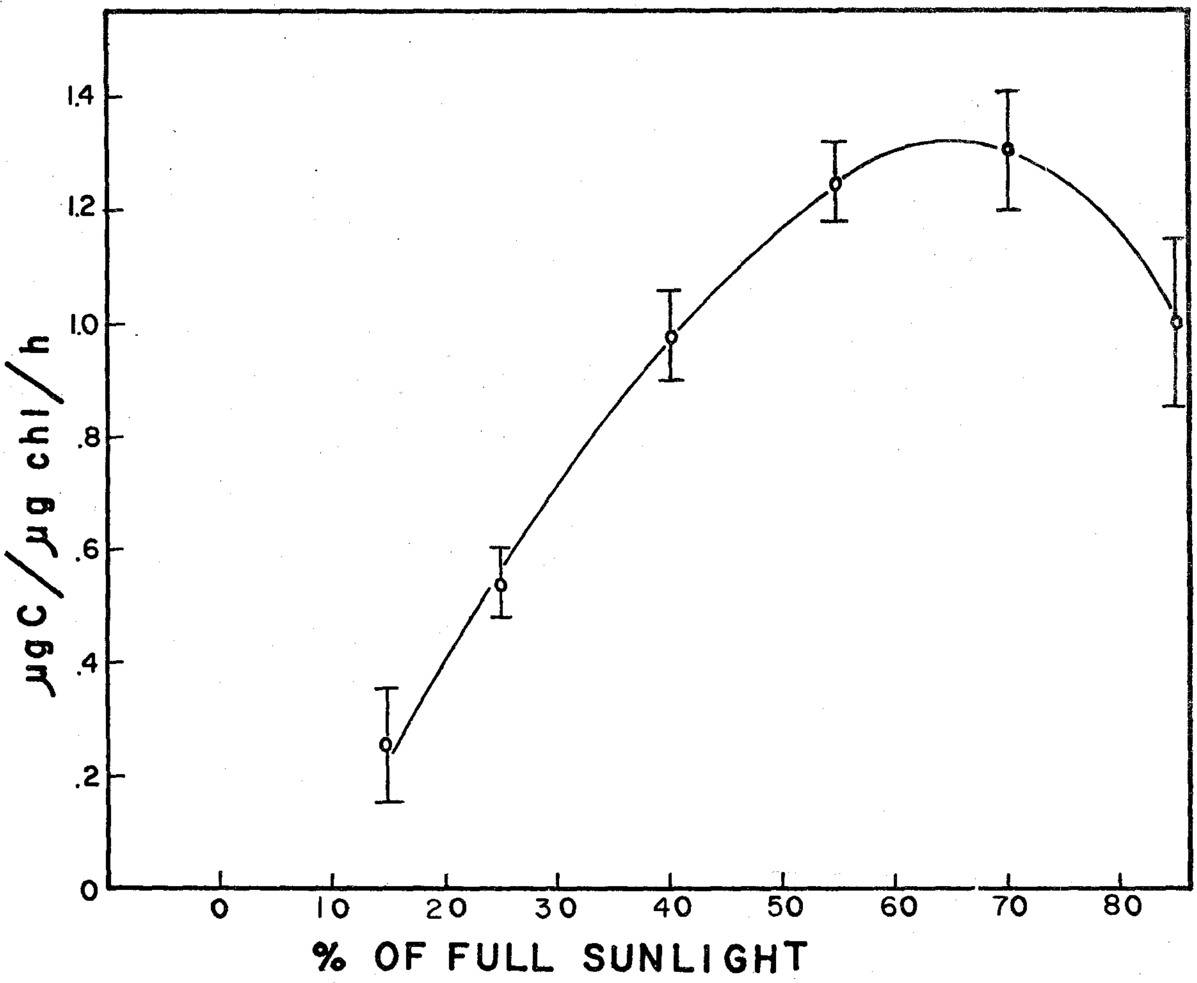

Figure 4. Photosynthetic rate of shoalgrass, *Halodule wrightii*, as a function of mid-summer surface sunlight (100% value = 2100 μEinsteins/m^2·sec). Rates determined *in situ* under Upper Laguna Madre water conditions, August 1978 (Pulich unpublished data).

The high values for nutrients observable at the Arroyo Colorado mouth illustrate the major impact of the Laguna on this floodway. Pollutants such as pesticides, herbicides, and metals, drained from Rio Grande Valley agricultural and residential areas, most certainly are changing the Lower Laguna today. The extent of its impact should be documented and measures taken to correct this impact.

The effect of low nutrient loading on the Upper Laguna is beneficial to seagrass productivity because it decreases the standing crops of epiphytes and periphyton (fouling organisms). Conover (1964) previously noted that epiphytism was most pronounced in plant communities thriving in normal seawater or hyposaline environments. In lagoons where salinities were above 40‰, very little epiphytism occurred, which he suggested resulted from inability to tolerate high salinities, with the exception of blue-green algae. However, recent quantitative measurements of fouling community production suggest that other explanations besides salinity might hold true (*e.g.* nutrient load, grazing pressure, and antibiotic or growth-suppressant chemicals elaborated by seagrass).

Production rates of fouling organisms were measured in 1976 and 1979 at the previously-mentioned sites in Upper Laguna Madre and in Redfish Bay near Port Aransas, the latter location with reduced water clarity and lower salinity regime compared to the former. Table 2 (a and b) shows that Laguna Madre locations generally produced less periphyton biomass than the hyposaline Redfish Bay areas. Moreover, this relationship was much more pronounced when seagrass vegetated and unvegetated sites were considered separately. For example, in both years, Laguna Madre periphyton production at 20 to 40 cm (8 to 16 in) depth was about one half that of the vegetated Redfish Bay sites, but much less (1/6 to 1/7) that of the unvegetated Redfish Bay sites. This inverse relationship between periphyton and seagrass abundance implies a biotic effect of seagrass or seagrass bed areas on periphyton production.

The epiphyte loads on seagrass leaves (*Halodule*) in both estuaries have also been measured and compared (Pulich unpublished). During June and July 1976, Upper Laguna Madre *Halodule* plants averaged 80% less epiphyte biomass on their leaves (2.0 g ash-free epiphytes per m^2 leaf surface) compared to Redfish Bay plants. Near the GIWW, Laguna Madre *Halodule* leaves showed increased amounts of epiphytes (6.0 g/m^2 leaves), but this was still 40% less than Redfish Bay plants.

These results parallel those of Fitzgerald (1969), who studied the conditions under which lake macrophytes became covered with epiphytes. He concluded that in general epiphyte growth was negligible if the macrophytes were nitrogen-limited. When combined nitrogen (either nitrate or ammonium) was present in the water in excess of the requirements of the macrophytes, epiphyte growth was enhanced.

A mechanism proposed recently (Phillips *et al.* 1978) to account for macrophyte decline in eutrophying fresh waters seems relevant to the Laguna Madre system as well. These workers postulated that eutrophication of a water system leads to reduction in submerged macrophyte productivity due to increased growth of, and shading by, epiphytes and filamentous algae which physically cover macrophyte leaves. Eutrophication is defined as an increase in nutrient loading, often with a decrease in water clarity due to turbidity from suspended sediments and pigmented compounds (tannins, humic acids, etc.). High densities of phytoplankton, though they may subsequently develop, are not considered causative of macrophyte decline.

Table 2. Biomass of Fouling Organisms Produced on Plexiglass Strips. Average for Three Stations in Upper Laguna Madre (South of Pita Island) and Redfish Bay (Near Ransom Island), Texas. Values in g(ash-free) dry wt/m^2.

Depth (cm)	Laguna Madre	Redfish Bay	
		Vegetated	Unvegetated
a. Production over 26 days during June 1976.			
0 to 20	10.7	11.3	28.9
20 to 40	5.6	12.6	36.0
40 to 60	3.5	12.3	20.0
b. Production over 36 days during June-July 1979.			
0 to 20	20.6	27.0	85.0
20 to 40	18.5	30.1	97.6
40 to 60	14.2	17.5	57.2

That macrophyte standing crops could increase unchecked in the absence of epiphytes finds considerable support from the physiological properties of macrophytes. Sand-Jensen (1977) showed that epiphytes caused a decrease in photosynthesis of the seagrass, *Zostera marina*, up to 58% by a combination of light shading and limitation of bicarbonate absorption. Most importantly, rooted macrophytes are capable of obtaining nutrients from the sediments through their roots (Bristow and Whitcombe 1971), and thus would not depend on supplies of nutrients dissolved in the water as do epiphytes.

IMPORTANCE OF NUTRIENT CYCLING

The combination of low nutrient input, but consistently high primary and secondary production of the Upper Laguna, testifies to the efficiency of the nutrient cycling processes there. As with other mature (climax) ecosystems, nutrient cycling in the Laguna involves a series of coordinated processes which replenish elements such as nitrogen, phosphorus, and trace metals, necessary to growth of healthy organisms. In a detritus-rich system without freshwater runoff or coastal upwelling, these nutrients are regenerated *in situ* in the top layers of the bottom sediments from decomposition of detritus (Fenchel 1977).

The land-locked nature of the Laguna, and consequent low amount of tidal flushing, is certainly one of the key features of efficient recycling of detrital constituents. In a previous study of trace metal cycling, Pulich *et al.* (1976) postulated that retention of detritus allowed trace metals to be recycled without major net losses or gains from the Laguna system. Release of trace metals into the water column or top few centimeters of surface sediments made the trace metals available for absorption by seagrasses or other organisms. Thus, retention of detritus within the Laguna is required for a gradual supply of nutrients. Any activity which opens the system to flushing (whether by dredging more channels or passes to the Gulf, creating more input canals *e.g.* Arroyo Colorado, etc.), would cause significant impact on cycling of nutrients from detritus. As unaesthetic as detrital decomposition may be at certain times of the year, it is the mainstay of the Laguna Madre System!

FUTURE RESEARCH ON LAGUNA MADRE

A delicate balance between nutrient cycling processes keeps the system in a steady-state of high production. However, certain processes are key ones, the so-called driving functions of the system. These processes remain largely undefined for the Laguna Madre System. It is important to delineate these critical processes in case one should be unusually sensitive to environmental perturbations.

Detritus furnishes organic material which is the substrate for numerous microbial metabolic reactions. If nitrogen is considered as the limiting element (as has most often been suggested for coastal ecosystems), then the model for N cycling worked out by Fenchel (1974) shown in Figure 5 demonstrates the great potential of one such anaerobic reaction, N_2 fixation, in furnishing combined (*i.e.* reduced) N to the Laguna system. N_2 fixation by algal mats has already been mentioned. In addition, N_2 fixation in the rhizosphere of seagrass beds has been implicated in other areas, *e.g. Thalassia* and *Halodule* beds in the Caribbean (Patriquin 1972). However, the contribution of N_2 fixation to the total N budget of a *Halodule*-dominated system such as the Upper Laguna is unknown, as is the influence of environmental

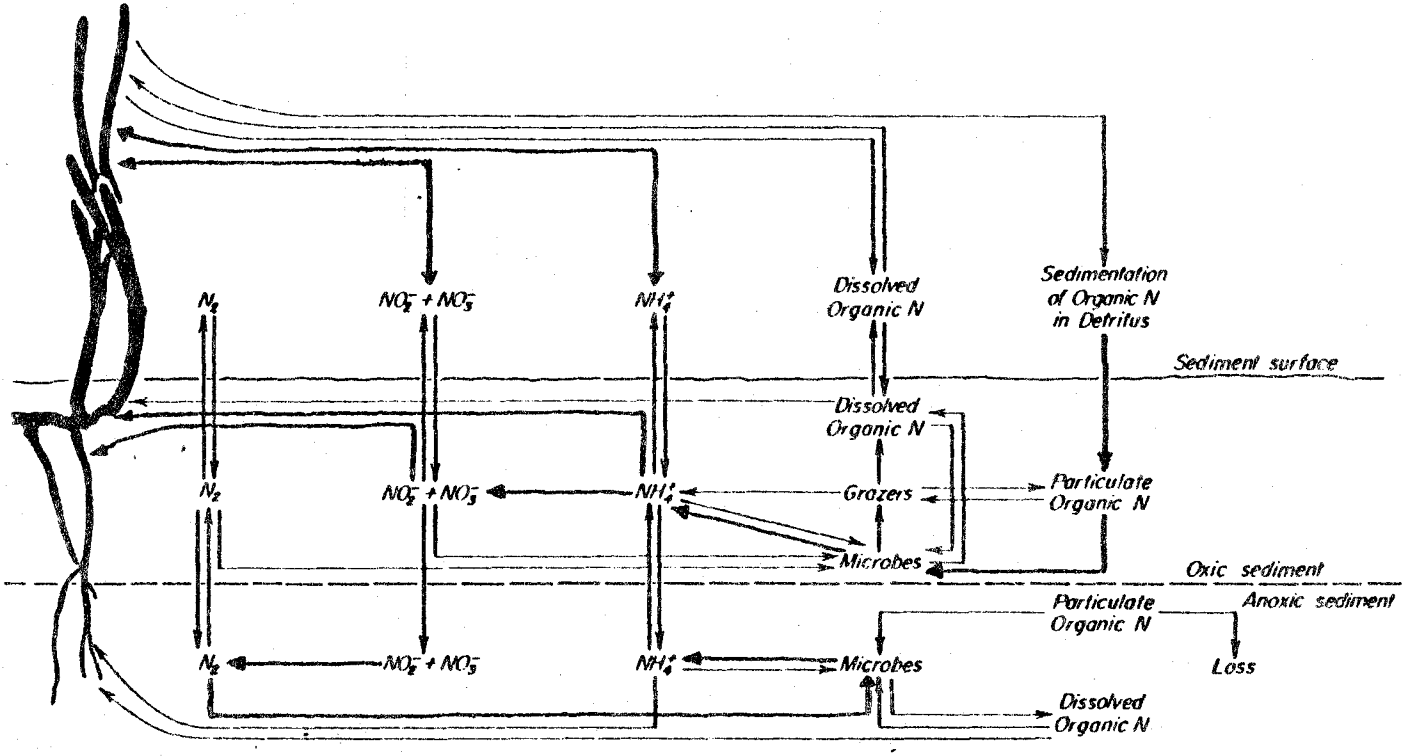

Figure 5. Schematic diagram of nitrogen cycling processes in a seagrass ecosystem. Various microbial processes are shown in relationship to (1) aerobic and anaerobic sediment layers and (2) the above sediment (leaves) vs. below-sediment (roots and rhizome) parts of a seagrass plant (Fenchel 1974).

conditions (*e.g.* hypersaline alkaline waters or pollutants) on various N cycling processes in the seagrass rhizosphere or algal mats.

To understand trophic relationships in the Laguna Madre, decomposer physiology should be investigated. The dominant agents of detritus degradation should be identified and their role in cycling quantified. Although microbes are the ultimate decomposers of detritus, such animals as polychaetes, amphipods, gastropods, and various crustaceans (*e.g.* grass and pistol shrimp) play an essential role in the food chain as direct detritivores. These fauna are known to participate in the degradation of detritus mainly by mechanically breaking down detritus into small pieces. However, some of these organisms appear to contain cellulase and "macerase" enzyme activity, and thus can directly degrade detritus biochemically (Foulds and Mann 1978). These biochemical properties could form the basis of abbreviated but highly efficient food chains, possibly typified by higher trophic organisms occurring in the Laguna.

Several questions arise concerning competitive interactions between organisms. Two interesting questions about *Halodule* can be formulated: 1) Does *Halodule* exert an allelopathic effect on *Ruppia* distribution? and 2) Does *Halodule* have a growth suppressant effect on epiphyte and periphyton production? Both of these questions imply that *Halodule* has a competitive advantage over other plants in the Laguna Madre as a result of secondary metabolite production. However, natural product physiology of seagrasses, particularly *Halodule*, has not been studied.

The accumulation of pollutants in the Laguna represents a particularly real threat to sustained productivity there. Toxic materials can easily enter the food chain, because the system is basically land-locked. High DDT concentrations already found in some spotted seatrout in the Lower Laguna may indicate the existence of such bioaccumulation problems (Warshaw 1974) resulting from Arroyo Colorado drainage. As the amounts of pollutants and toxicants increase, quality and productivity of higher trophic level organisms will decrease. If a critical ecosystem process such as detrital cycling or N_2 fixation is perturbed, then the very existence of the ecosystem itself would be in jeopardy. Thus, it is important to monitor the levels of suspected contaminants in specific biota at certain Laguna locations.

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ECOLOGY OF THE TEXAS GULF OF MEXICO SHELF

R. Warren Flint[1]

ABSTRACT

In 1974, the Bureau of Land Management instituted an environmental studies program on the south Texas outer continental shelf. These multidisciplinary studies focused on establishing a basis of environmental information against which to check future shelf perturbations from energy exploitation activities. The Texas shelf was found to be influenced by a host of complex hydrographic features which were driven by seasonal climatological variability. Several distinct water masses on the shelf were hypothesized from the patterns observed between primary producer biomasses (chlorophyll) and salinity.

The inner-shelf habitats appeared to be more dynamic in biological properties than habitats further out on the shelf. These differences may be related to local estuarine influences as suggested by the water mass characterizations. In these shallow, more productive waters, trophic coupling between the pelagic and benthic components of the ecosystem were examined, focusing on an economically important commercial fishery, shrimp. Using data from several sources, including the studies mentioned above, a food web was constructed for inner-shelf waters. It was concluded from this exercise that the majority of water column primary production is diverted to the benthic component of the ecosystem (detrital pool). This detrital pool provides much of the nutrition required by the demersal fisheries. The role of benthic infauna, both as a food source in this hypothesized web and as a factor influencing the general dynamics of the benthic detrital pool, are discussed.

INTRODUCTION

The chemical, physical, and biological interactions both internal and external to the world's oceans are among the most complex within the natural sciences. If, in fact the aspects and processes of these various interactions were understood, their scope and magnitude could be predicted for a given time and place. There are, however, many unknowns that must still be quantified.

In 1974, the Bureau of Land Management (BLM), as the administrative agency responsible for leasing of submerged federal lands, was authorized to initiate a National Outer Continental Shelf (OCS) Environmental Studies Program. As part of this national program, the BLM developed the Marine

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Environmental Study Plan for the south Texas Outer Continental Shelf (STOCS). This plan was developed to meet the following four specific study objectives:

1) provide information for predicting the effects of OCS oil and gas development activities upon the components of the ecosystem;

2) provide a description of the physical, chemical, geological, and biological components and their interactions, against which subsequent changes or impacts could be compared;

3) identify critical parameters that should be incorporated into a monitoring program; and,

4) identify and conduct experimental and problem-oriented studies as required to meet the basic objectives.

BLM contracted the University of Texas at Austin to act for and on behalf of a consortium program of research conducted by Rice University, Texas A&M University, and the University of Texas, to implement the Environmental Study Plan. This plan called for an intensive multidisciplinary 3-yr study (1975-1977) to characterize the temporal and spatial variation of the shelf marine ecosystem beyond 10-m water depth.

An ecosystem is defined as "any area of nature that includes living organisms and non-living substances interacting to produce an exchange of material between the parts" (Odum 1959). The central theme of the STOCS study was to provide an understanding of the living and non-living resources of the shelf. In order to approach the objectives outlined above a broad program was designed which included:

a) water mass characterization;

b) pelagic primary, and secondary productivity as described by floral and faunal abundances, standing crop, and nutrient levels;

c) benthic productivity as described by infaunal and epifaunal densities;

d) natural petroleum hydrocarbon levels in biota, water and sediment; and,

e) natural trace metal levels in biota and particulate matter.

The specific study areas and variables considered in this program are listed in Table 1. The design of the study provided knowledge of the various living and non-living components in sufficient detail to begin to understand their relationships and enhance our ability to anticipate changes resulting from pollution of the OCS ecosystem.

TABLE 1. LIST OF STUDY AREAS AND ENVIRONMENTAL VARIABLES MEASURED DURING THE SOUTH TEXAS OUTER CONTINENTAL SHELF PROGRAM.

	Study Area	Variables
Pelagic Non-living Characteristics	Hydrography	Temperature Salinity Depth Currents
	Nutrients	Silicate Phosphate Nitrate Dissolved oxygen
	Hydrocarbons	
	Low-molecular-weight (LMW)	Methane Ethane Ethene Propane Propene
	High-molecular-weight (HMW)	Hexane or benzene fractions Retention index w/concentrations
Pelagic Living Characteristics	Phytoplankton	Species densities Chlorophyll (biomass) C^{14} productivity
	Microbiology	
	Bacteriology & mycology	Species abundance Total counts and hydrocarbonoclastic counts
	Neuston	Species densities Tar ball concentrations
	Zooplankton	
	Micro & macro	Species densities Sample biomass Trace metal body burden HMW hydrocarbon body burden

TABLE 1 (Cont'd)

Benthic Non-living Characteristics	Sediment texture	Mean grain size Percent sand Percent silt Percent clay
	Sediment chemistry	Organic carbon Delta ^{13}C Ethene Ethane Propene Propane Methane HMW Hydrocarbons Hexane or benzene fractions Retention index w/concentrations
Benthic Living Characteristics	Microbiology Bacteriology & mycology	Species abundances Total counts and hydrocarbonoclastic counts
	Meiofauna	Species densities
	Macroinfauna	Species densities
	Macroepifauna	Species densities Trace metal body burden HMW Hydrocarbon body burden Tissue histopathology
	Demersal fishes	Species densities Biomass Trace metal body burden HMW Hydrocarbon body burden Tissue histopathology

STUDY AREA

The general area of study corresponded to that portion of the Gulf of Mexico off the Texas coastline designated by the Department of the Interior for future oil and gas leasing (Figure 1, insert). The area covered approximately 19,250 km^2 (7,430.5 mi^2) and was bounded by 96°W longitude on the east, the Texas coastline on the west, and the Mexico-United States International Border on the south. The continental shelf off Texas has an average width of approximately 88.5 km (55.0 mi) and a relatively gentle seaward gradient that averages 2.3 m/km (7.5 ft/0.621 mi).

No ecosystem is a completely self-contained unit, and the STOCS system is no exception. It is influenced by adjoining regions such as the open Gulf of Mexico, the Mississippi River to the northeast, and the land masses to the west. These adjacent regions have a marked influence on the climate and are the sources of many inputs into the system. Although we can look at the region as a somewhat discrete unit, we must continually keep in mind the influence of these contiguous territories.

The Texas coastal area is biologically and chemically a two-part marine system, the coastal estuaries and the broad continental shelf (Figure 1). These two components are separated by barrier islands and connected by inlets or passes. The area is rich in finfishes and crustaceans, many of which are commercially and recreationally important. Many of the finfishes and decapod crustaceans of the STOCS area exhibit a marine-estuarine dependent life cycle, *i.e.* spawning offshore, migrating shoreward as larvae and postlarvae, and utilizing the estuaries as nursery grounds (Gunter, 1945; Galtsoff, 1954; Copeland, 1965). The broad continental shelf also supports a valuable shrimp fishery which, as a living resource, contributes significantly to the local economy. An excellent overview of the zoogeography of the northwestern Gulf of Mexico is provided by Hedgpeth (1953).

Within the STOCS ecosystem there are many interrelated physical, chemical, geological and biological processes. In the following sections an attempt will be made to describe some of these important factors and develop a conceptual model illustrating the manner in which some of these factors interact.

Acknowledgments are due all of the scientists involved in this multidisciplinary program and the contributions they provided in developing this manuscript. For further reference concerning their specific contributions, see Parker (1976), Groover (1977), Griffin (1979), and Flint and Griffin (1979).

GENERAL ECOSYSTEM CHARACTERISTICS

Hydrographic variables illustrate the annual progression that occurs over the shelf and help to suggest possible factors that influence the functioning

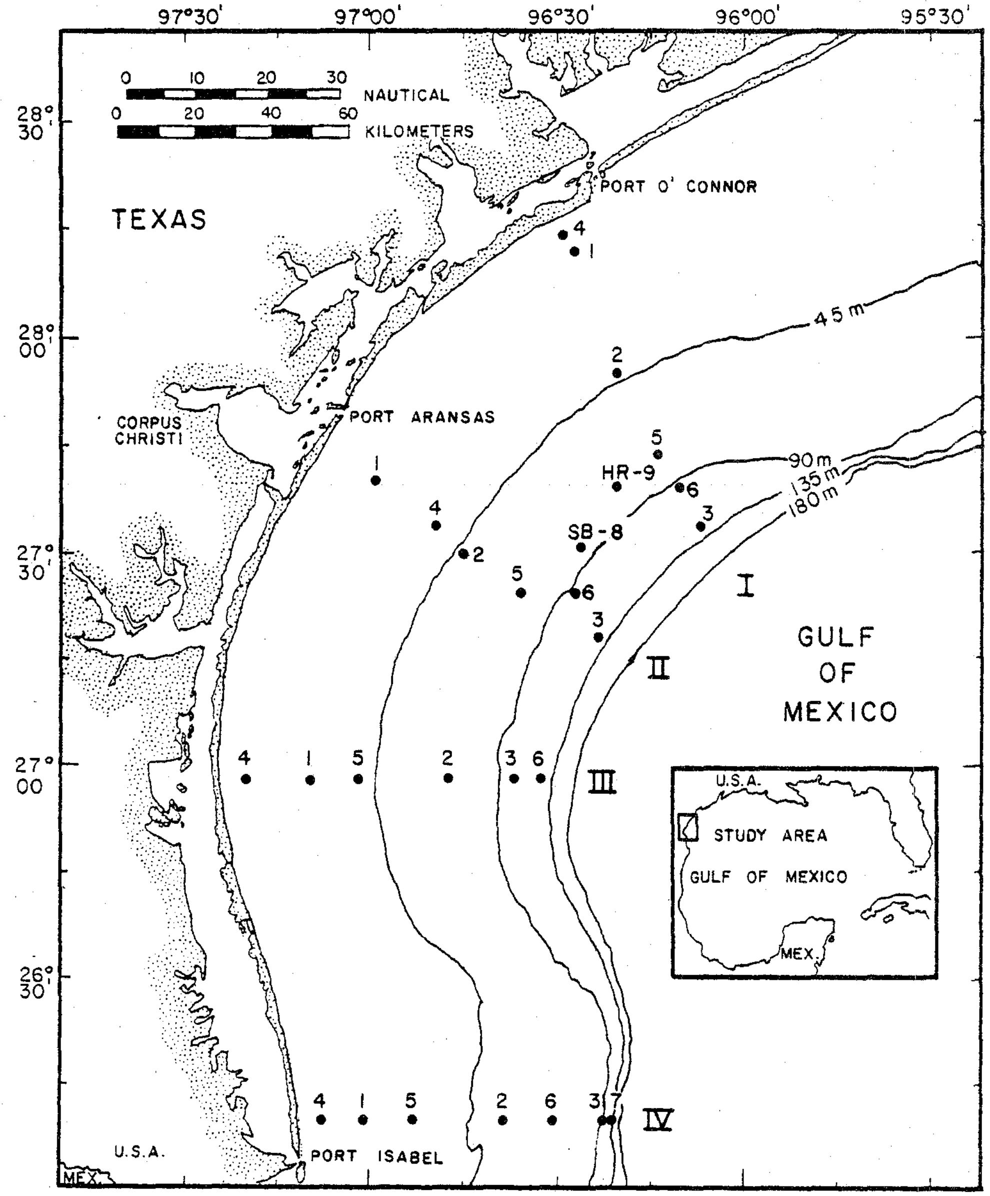

Figure 1. Map showing the south Texas continental shelf bathymetry and location of sampling sites.

of the ecosystem. A good overview can be obtained by examining time-depth plots of temperature and salinity for a shallow and deep station on the shelf. At deeper sites on the shelf, salinity shows very little variation with the exception of lower surface salinities in the spring of the year. Temperatures indicate a greater degree of variability, but there is no well-defined pattern at given depths with the exception of a prevalent stratification during the summer of each year. Surface temperatures suggest a sinusoidal variation with highest temperatures occurring in August.

Hydrographic data from surface and bottom layers at shallow shelf sites show a much greater vertical homogeneity with a more clearly defined seasonal variation at both depths (Smith 1980). The water column over the inner shelf is very nearly isothermal during the fall, winter and spring months. During mid-summer there is sometimes a slight stratification present. Salinities are almost totally influenced by local rainfall and riverine input at these sites.

A comparison of surface temperatures across the shelf provides a crude picture of the dynamics over the annual cycle (Smith 1980). During the summer months, temperatures of slightly over 29°C are observed at both stations suggesting minimal cross shelf gradients. In contrast, lowest values of approximately 14°C over the inner shelf are well below the minimum values of 19 to 20°C found over the outer shelf during the winter. This results in strong cross shelf gradients during these months.

Another characteristic of temperature and salinity that is important to biological communities is the significant negative correlation ($P < 0.05$) between their variation and water depth, indicating the extreme variability of shallow waters and contrasting stability of deeper waters. A deviation from this trend is noted for several of the collection sites deeper than 100 m (328 ft). Increases in the variance of salinity at these sites may suggest the occurrence of occasional upwelling of deep Gulf waters. This is further verified by the plot of temperature cross-section along a transect during the summer of 1977 (Figure 2). Warmest waters are found in surface layers at some distance from the coast. The onshore directed temperature gradient together with the layer of cool near-bottom water extending nearly to the coast indicates the existence of upwelling and a pattern of offshore Ekman transport of surface water with a near-bottom return flow. The summer horizontally isothermal conditions are ideal for this phenomenon to occur and are the only opportunity for cross-shelf currents perpendicular to the coast to occur with any regularity because of the predominant wind directions from the south-southeast.

Between approximately October and March, the currents along the shelf past Aransas Pass are toward the south-southwest and have a predominant longshore component. Between June and September, currents over the Texas shelf are substantially weaker. The longshore component reverses over very short time scales and there are often periods of water movement across the shelf, perpendicular to the coast as described above.

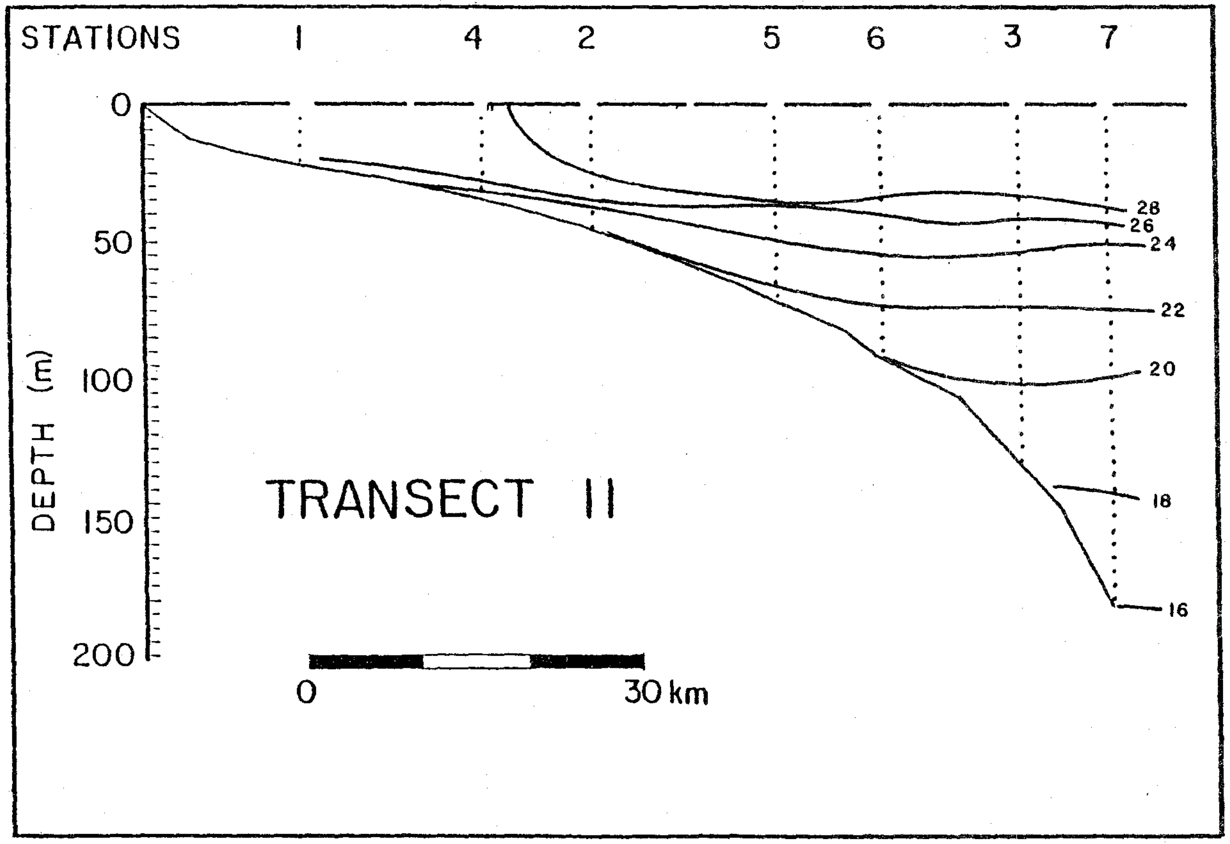

Figure 2. Temperature cross-section along Transect II, 4 August 1977 (from Smith 1977).

The seasonal variation in shelf circulation has a direct and obvious effect on the spatial distribution and temporal variability of hydrographic parameters and suggests possible influential factors forcing the ecosystem dynamics. The strong and quasi-steady flow to the south-southwest during the winter months, and especially into late spring, is responsible for the advective transport of Mississippi River water along the northwestern rim of the Gulf of Mexico at a time when discharge is at its maximum. During the summer months aperiodic near-bottom encroachment of water from depths over the outer shelf may play an important role in the ecosystem dynamics during times of relatively low riverine input. The importance of cross-shelf motion in transporting salts, heat, suspended solids and/or planktonic life becomes quite apparent.

Measures of chlorophyll a during the study period provided further evidence concerning the physical dynamics of this ecosystem. The highest monthly concentrations of chlorophyll a were usually associated with salinities less than 30‰. In contrast, variations in temperature did not appear to play an influential role in chlorophyll trends.

Of the various processes contributing to the variability of plant biomass across the shelf, freshwater discharge appeared to be most influential of those variables examined during the study. Figure 3 illustrates the relationship between salinity and particulate matter in the water column. This suggests that as salinity decreases from riverine input, the particulate matter increases (decreased Secchi depth) along with possible associated nutrients and increased primary productivity.

Through correlational research, Kamykowski and Milton (1980) demonstrated that the STOCS area is influenced by different freshwater sources depending upon distance from shore on the shelf. Figure 4 summarizes the relationships among chlorophyll a, salinity and freshwater inflow from five point sources hypothesized as influencing the STOCS area. The upper part of the figure is a plot of correlation coefficient vs. distance offshore (naut mi). The correlation coefficients interrelate 12 chlorophyll a and 12 salinity values available for successive 1 mi distances offshore. The zones (marked by vertical lines) within this plot are based on the results of similar correlation coefficients vs. distance offshore plots interrelating point source discharge with either salinity or chlorophyll a. The zones of maximum negative correlation with salinity (bars) or of maximum positive correlation with chlorophyll a (dots) are shown for each point source in the lower part of Figure 4.

An inshore zone between 0 to 14 mi (0 to 22.5 km) offshore is characterized by a high average correlation (-0.76) between chlorophyll a and salinity and by the highest correlations between Texas point source discharge and salinity. Chlorophyll a is not well correlated with any point source discharge within this zone.

The middle zone extends from 14 to 32 mi (22.5 to 51.3 km) offshore. The average chlorophyll a - salinity correlation (-0.41) decreases in this region. Neither the Texas source discharges nor the Mississippi River discharge is

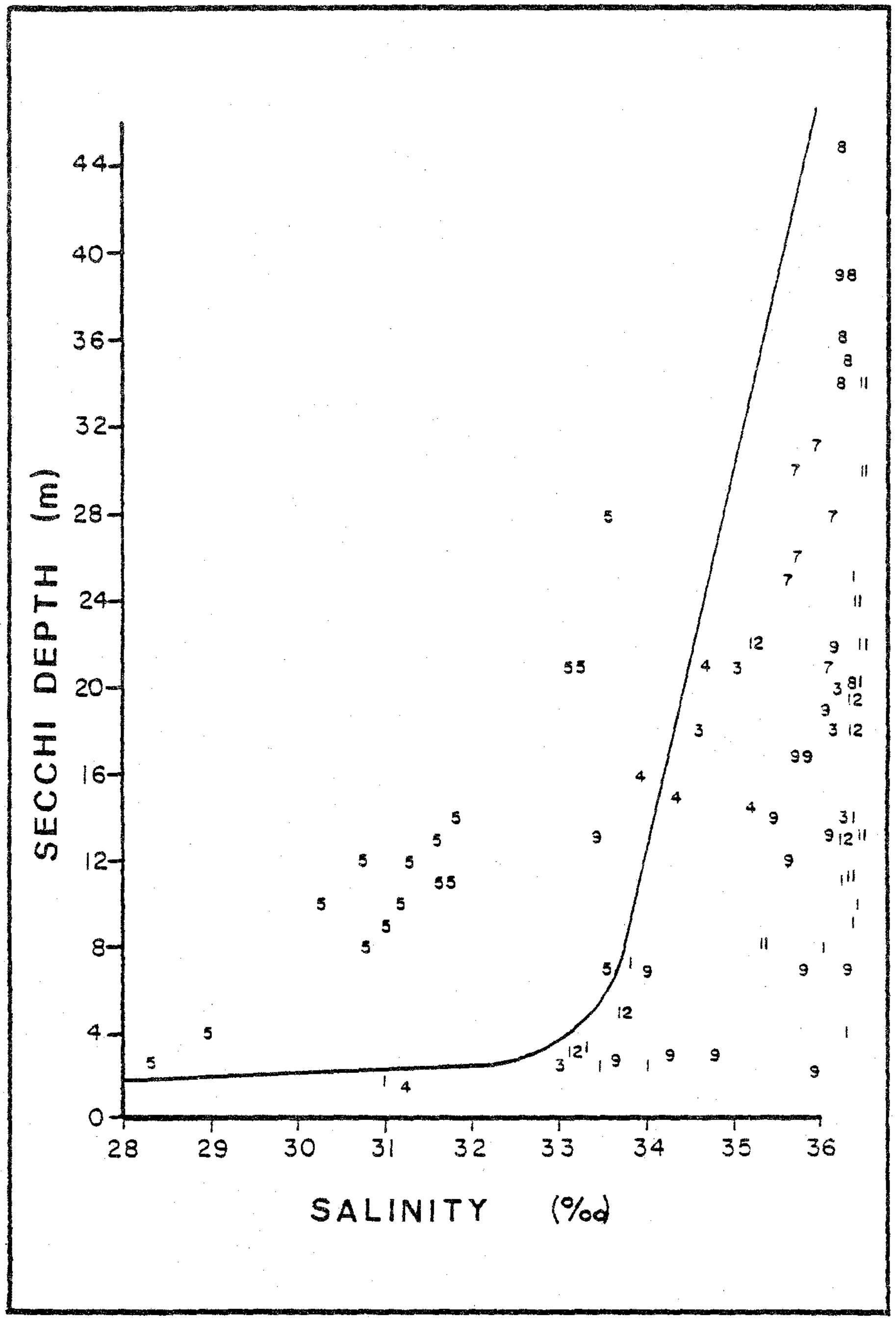

Figure 3. Relationship between salinity and Secchi depth for all stations. Solid line is arbitrary curve. Numbers refer to months of year (Kamykowski and Van Baalen 1979).

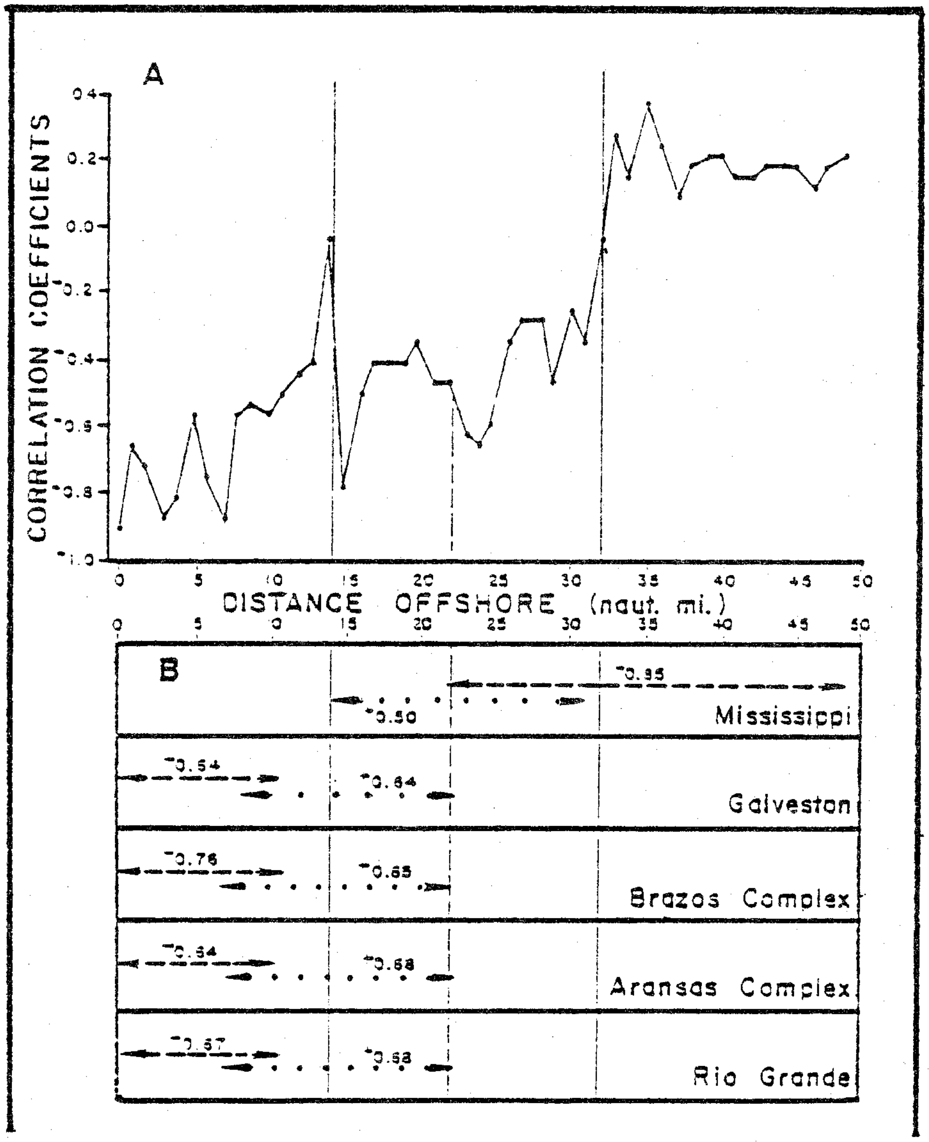

Figure 4.

A. Plot of distance offshore (naut mi) vs. the correlation coefficient of monthly chlorophyll a and salinity (12 points) for successive nautical mile distances offshore.

B. The zones of maximum correlation between monthly point source discharge and either monthly salinity (dashes) or monthly chlorophyll a (dots) for five significant freshwater sources in the northwest Gulf of Mexico. For example, monthly Mississippi River discharge in 1977 exhibits an average correlation of -0.85 with monthly salinity readings for every nautical mile between 21-48 naut mi offshore.

(Kamykowski and Milton 1980).

well-correlated with salinity throughout this zone. Texas river discharge, however, is related to salinity at the inshore side of the zone and Mississippi River discharge is highly related to salinity at the offshore side of this zone. The major correlations between point source discharge and chlorophyll a almost exclusively occur in this zone. The point sources north of the sampling transect yield an interesting pattern: the farther away the point source, the farther offshore occurs the band of highest correlation. The Rio Grande exhibits its highest correlation with chlorophyll a between 8 to 22 mi (12.9 to 35.4 km) offshore. The Texas point sources to the north of the cross-shelf transect, all abruptly end their high correlation with chlorophyll a at 22 mi (12.9 km) offshore. This feature divides the middle zone into two subzones: between 14 to 22 mi (22.5 to 35.4 km) offshore, chlorophyll a is best related to Texas freshwater sources; between 22 to 32 mi (35.4 to 51.3 km) offshore, chlorophyll a is best related to Mississippi River discharge.

The offshore zone extends from 32 mi (51.3 km) to the end of the transect (50 mi or 80.5 km). The average chlorophyll a - salinity correlation (+0.21) turns positive in this region, suggesting freshwater does not contribute to increased chlorophyll a. In fact, chlorophyll a shows a tendency to decrease with decreasing salinity. Mississippi river discharge is highly correlated with salinity in this zone.

This interpretation by Kamykowski and Milton (1980) further supports many of the physical dynamics observed from the hydrography patterns and more precisely defines the differences observed in the STOCS between inner and outer shelf waters. The preceding description of the hydrographic environment associated with the STOCS ecosystem indicates that many of the dynamics of this ecosystem can be explained by considering topography, local river inputs, Mississippi River discharge and climatic variables such as wind direction and velocity.

In terms of pollution indicators in the STOCS ecosystem, the results of 3 yr of evaluation for trace metals and hydrocarbons suggest that this area is relatively pristine. Low-molecular-weight hydrocarbons are shown to be derived from natural sources and in general related to peaks in primary producer concentrations (*e.g.* thermocline) and areas more directly affected by detrital input to the seafloor (*e.g.* shallow shelf areas). The only exceptions to the trend of low concentrations of high-molecular-weight hydrocarbons were observed for zooplankton samples. It was concluded that the higher concentrations of petroleum hydrocarbons in the zooplankton samples were the result of the presence of micro-tarballs. These were thought to be derived from tanker traffic rather than exploration or production in the area.

No significant trace metal pollution was observed in the study. Levels of cadmium, chromium, nickel and lead were all lower than most values reported in the literature.

Due to the low concentrations of hydrocarbons and trace metals, there were no real spatial patterns observed. This was not the case however, for the biota examined in this study. Figure 5 illustrates that the primary

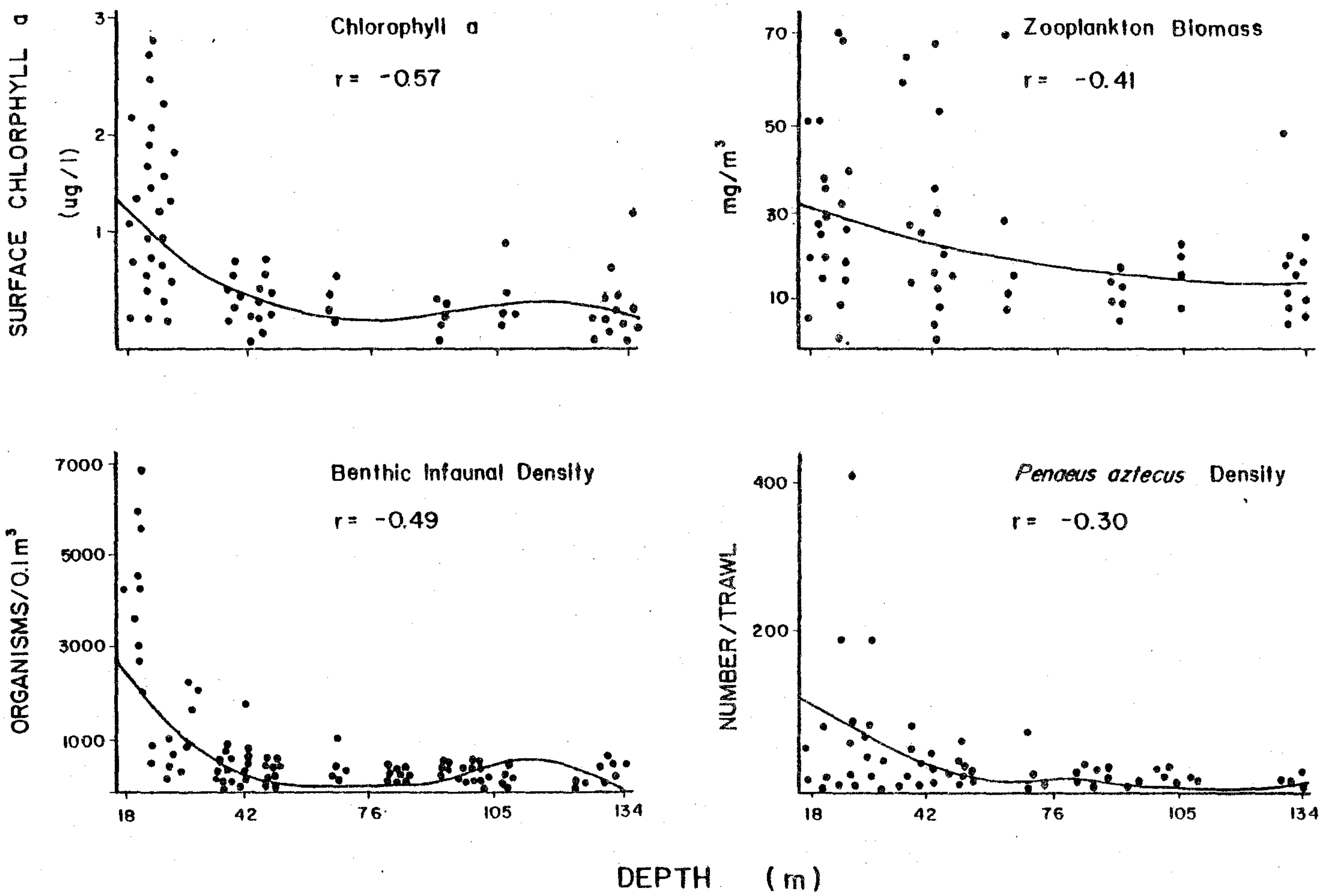

Figure 5. Plots of chlorophyll a, zooplankton biomass, benthic infaunal density, and *Penaeus aztecus* density (shrimp) against water depth (m) for the South Texas outer continental shelf study period. Correlation coefficients (r) are indicated for each plot.

producer biomass decreases with depth (*i.e.* distance from shore) and that there are also gradients observed for zooplankton biomass, macroinfaunal densities and epifaunal shrimp densities. These changes with depth suggest that the inner-shelf region is a much more dynamic area than the waters closer to the shelf break. In addition, many of the rivers mentioned above enter the Texas shelf waters through well-developed estuaries. These estuaries undoubtedly have an important impact on the outer coastal zone which may be manifested in some of the gradients observed in Figure 5.

TROPHIC COUPLING

For many years immense amounts of information have been accumulating on primary production, zooplankton abundance and the distribution of benthic organisms in important fishing areas. Despite these data bases, it is very difficult to describe quantitatively the links between primary production and fish yields. A few plausible attempts to quantify these links have been provided by Steele (1974) for the North Sea ecosystem and Mills and Fournier (in press) for the Scotian shelf system. Even without complete data bases, the comparison of regions like the North Sea, the Scotian Shelf, and the northwestern Gulf of Mexico Shelf, could offer insight into the general structure of marine ecosystems and pinpoint deficiencies in our understanding of them. Of most concern in this manuscript is the need to take a hard look at the hypothesis that, despite geographical differences, most coastal ecosystems with productive fisheries have similarly constructed food webs (Dickie 1972; Mills 1975).

The presence of isothermal conditions from the surface waters to the seafloor during much of the year allows for a great deal of interaction between two dynamic communities in the inner-shelf region of the Texas coast: 1) a benthic community consisting of those organisms living in or on the sediment or near the sediment-water interface; and 2) a pelagic community consisting of those organisms drifting, floating, or swimming in the overlying waters. Because of their interactions, the boundaries of these two communities are not clear. Many nekton, for example, deposit eggs which become part of the benthic community, while the larvae and adults are members of the pelagic community. Conversely, numerous benthic species produce eggs which float in the water column, hatch into planktonic larvae and become dispersed by currents before settling permanently to the bottom.

In addition to the above interactions, demersal fishes swim into the pelagic zone to feed on plankton while the benthos depends upon the continual "rain" of materials (*e.g.* algae, fecal pellets, detritus) from the overlying waters for nourishment. It is quite clear that in inner-shelf waters, where mixing occurs, resulting in a relatively homogenous water column, the discrimination between pelagic and benthic components is very obscure and trophic coupling becomes very important.

The nearshore subtidal region of the Texas coast with its many interacting communities is the site of several major fisheries including penaeid shrimp (*Penaeus* spp.). As a result of the recent observations on the south Texas shelf, we feel it is imperative to examine some of the biological trends of this region and relate them to a fishery of immense economic importance, in order to delineate the deficiencies in our understanding.

Outside the bays and estuaries, the shrimp fishery extends to approximately 80 m (262.5 ft) depth on the shelf, with maxima in yield obtained well inside this range. Annual shrimp landing reports (NOAA/NMFS Gulf Coast Shrimp Data, Annual Summaries) indicate that for the reporting area (Statistical Area #20) similar to STOCS stations monitored during the BLM funded study, an annual average of 5.7×10^6 kg (12.7×10^6 lb) of shrimp were landed for the years 1975-1976. This represented a mean value of 18 million dollars for that period to the commercial fishery.

For purposes of developing a conceptual model, a single station centered in the middle of the fishery reporting area described above, which was monitored on almost a monthly basis for the period 1976-1977 will be focused upon. This station, identified at Station 1 of Transect II in Figure 1 was located off Aransas Pass Inlet in approximately 22 m (72.3 ft) water depth.

Primary production for Texas inner-shelf waters as characterized by the above station was somewhat bimodal on an annual basis with peaks in the spring and fall (Figure 6). Annual estimates of production based upon chlorophyll a measures converted to carbon equivalents according to methods of Ryther and Yentsch (1957) indicated that these waters produced a mean of approximately 103 g C/m^2/yr (Figure 7).

Macrozooplankton biomass on the Texas shelf averaged approximately 3.566 g/m^2 wet weight over the sampling interval. Assuming a turnover ratio of 7 (Steele 1974), annual production of the macrozooplankton was estimated to be 25 g/m^2/yr. Since the water column was usually fairly homogeneous and the zooplankton tows often did not reach the bottom, plus sampling bias from net clogging, it is likely that the number for production estimate could be doubled to 50 g/m^2/yr for purposes of this model. Assuming approximately a 6% conversion between wet weight and carbon content of metazoans (Rowe, personal communication) the carbon equivalent of zooplankton production was estimated to be 3 g C/m^2/yr (Figure 7).

Information on the neuston component of the planktonic community indicated that an additional 0.21 g C/m^2/yr could be assumed for the macroplankton production from these surface animals. Standing crop of microplankton was calculated to be 465 mg/m^2 wet weight. Annual production was estimated as 10 times the standing crop. With the conversion to carbon content mentioned above, this resulted in approximately 0.9 g C/m^2/yr. Therefore, the total production estimate for the zooplankton component of the food web on the inner Texas shelf is approximately 4.1 g C/m^2/yr (Figure 7).

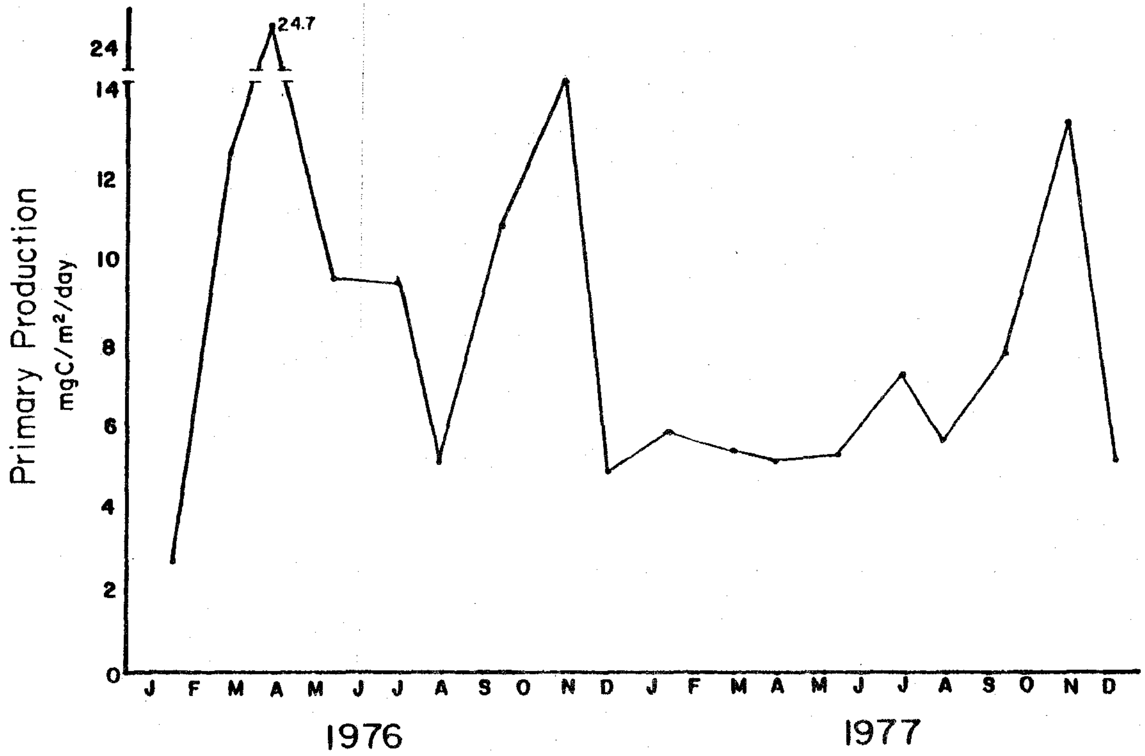

Figure 6. The 2-yr cycle of primary production (carbon fixation) for Texas coastal waters between 1976 and 1977. Calculations according to methods of Ryther and Yentsch (1957) using chlorophyll data.

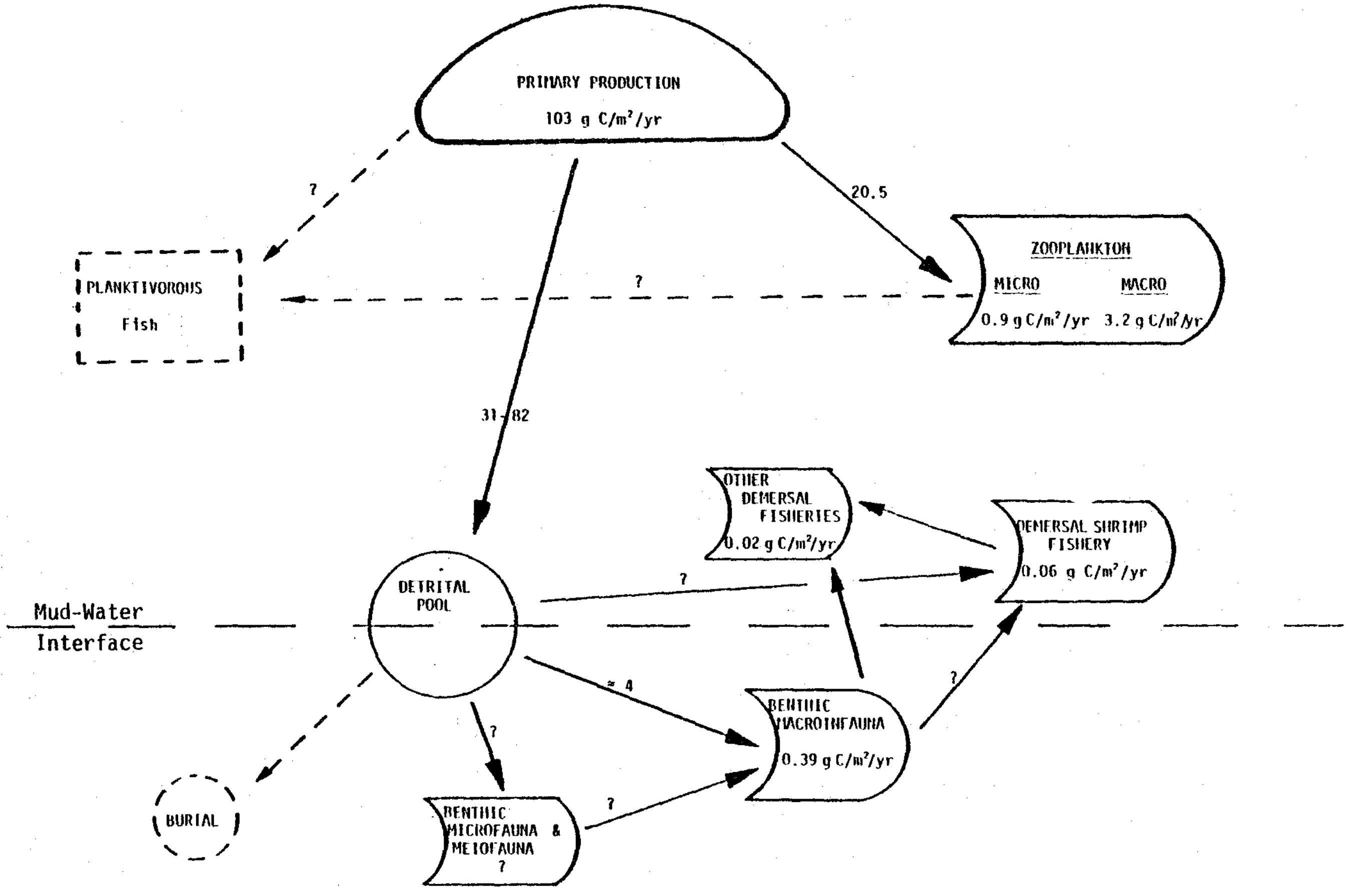

Figure 7. Conceptual model of a coastal food web for south Texas inner-shelf waters. All material flows represent g C/m^2/yr.

If we assume a minimum transfer efficiency of 20% (very conservative) between primary producers and the zooplankton, then 20.5 g C/m^2/yr (Figure 7) would be required to support the zooplankton. This transfer of carbon results in approximately 82 g C/m^2/yr of primary production remaining. Mills and Fournier (in press) indicated that, contrasted with the North Sea ecosystem (Steele 1974), they found that the majority of primary production for the coastal ecosystem on the Scotian Shelf was diverted to the demersal fisheries. This may very well also be the case for the Gulf coastal ecosystem. The bottom waters appear to support greater amounts of primary producers than the surface or mid depths during the majority of the time (Kamykowski and Milton 1980).

The amount of pelagic fisheries biomass directly supported by primary producers on the Texas inner shelf is unknown. From the amount of zooplankton production observed, however, one would have to assume that the pelagic fisheries is small. The Texas inner-shelf ecosystem is probably characterized as a system where the majority of primary production is input directly to the bottom waters and benthos.

Information from Steele (1974) indicated that 30% of the primary production is transported to the benthos in the North Sea ecosystem. From the above facts, and assuming there are no major links to pelagic fisheries other than zooplankton, it would appear that almost 80% of this production reaches the benthos in the Texas coastal waters. This is probably an over-estimation but the real number is certainly greater than the 30% estimated for the North Sea.

To further illustrate the input to the bottom, the data on nepheloid layer dynamics (Kamykowski and Batterton 1979), not only demonstrate the presence of a prevalent nepheloid layer, at least during the summer months, but also illustrate the presence of peak chlorophyll layers in the bottom waters as well as peaks in nitrogen represented by ammonia (Figure 8). These peaks of primary producer biomass, as well as greater than 1% light transmission at these depths, suggest the possibility of photosynthesis taking place. ^{14}C experiments confirm this. The organic carbon production at depth, plus the direct input to the benthos of detritus both from the nepheloid layer and the upper portions of the water column, presumably can provide a sizable nutritional source for demersal trophic links. In addition to the primary producer biomass in bottom waters, there appears to be a considerable amount of nutrient regeneration as illustrated by the ammonia concentrations (Figure 8).

Estimates of benthic infaunal biomass in this region of the Texas inner-shelf range between 0.5 g/m^2 (STOCS study) and 2.4 g/m^2 (Rowe *et al.* 1974). Assuming a turnover ratio of approximately 4.5 (Nichols 1978), 0.39 g C/m^2/yr are produced by the infaunal benthos (Figure 7).

Shrimp fisheries yeilds (NOAA/NMFS Gulf Coast Shrimp Data, Annual Summaries) were used to estimate the production of shrimp on an annual basis for the inner-shelf waters. Utilizing the suggested conversions to obtain the heads-on weight and assuming a turnover ratio of approximately 0.8 (Caillouet, NMFS, personal communication), the commercial fishery catch represented approximately

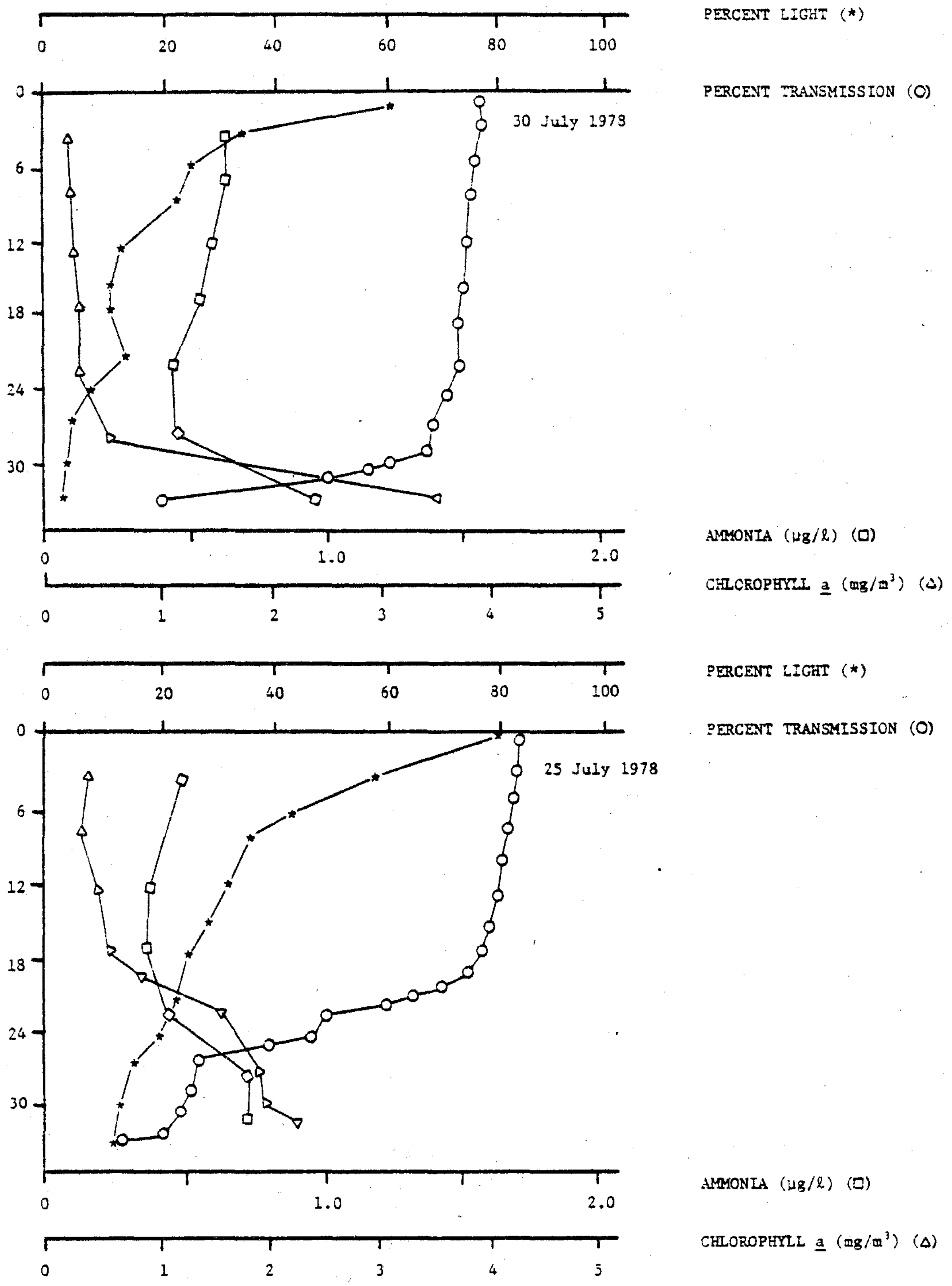

Figure 8. Depth profiles of percent light, transmissometry, chlorophyll a and ammonia nitrogen concentrations for two cruises off the Texas coast (33 m water depth) during 1978 (From Kamykowski and Batterton 1979).

0.03 g $C/m^2/yr$ of shrimp production. Since these catch statistics did not include the juvenile portion of the shelf population, this estimate could conservatively be increased to at least 0.04 g $C/m^2/yr$ (Figure 7).

Data from the STOCS study indicated that an additional 0.02 g $C/m^2/yr$ of other demersal species was produced on the inner shelf. The combination of these data with the shrimp production estimates illustrated that approximately 0.06 g $C/m^2/yr$ was produced by the fauna living in the bottom waters of the Texas shelf. Comparing this trophic level to the infaunal production and assuming a 10% transfer efficiency, it would appear that there is not enough of a food source to support the demersal component of the inner-shelf food web.

The alternative to an infaunal-demersal fishery trophic link is a detrital based trophic web for many of the commercially important species, including the shrimp. The data on primary production plus the peak concentrations of chlorophyll in the bottom waters along with a relatively small amount of pelagic secondary production would tend to support this conclusion.

If the Texas inner shelf trophically revolves around a detrital food web, one of several questions concerns where the benthos fit into this trophic scheme, especially since they do not appear to have the biomass to alone support the observed production at higher trophic levels. A possible hypothesis for the role of the benthos takes into account the dynamics of the nepheloid layer. Rhoads *et al.* (1974) pointed out that the concentration of suspended solids in many estuaries and coastal waters is higher in the bottom waters than at the surface, especially where the water column passes over muds that have undergone intensive bioturbation.

The nepheloid layer is most prevalent in Texas coastal waters during the summer when surface primary production is at a low (Figure 6). Under circumstances like these the bottom serves as a nutrient reservoir and may dampen the effects of surface productivity cycles. The influencing factors in the maintenance of the nepheloid layer with its associated nutrients, plant biomass and detritus are potentially the benthic infauna as well as macroepifaunal species, such as penaeid shrimp, which may disturb and otherwise bioturbate the bottom sediments.

The recycling and release of nutrients as well as sediment detritus to the water column depend largely on the ease with which the muddy sea floor can be resuspended. Bioturbation and current turbulence control this process (Rhoads *et al.* 1974). Primary productivity in turn provides plankters to the bottom waters through surface sedimentation. Both living and dead plankters plus associated microorganisms produce detrital food for demersal consumers including shrimp populations. Thus, benthic infauna do not necessarily provide all of the direct food source for an important fishery such as the shrimp, but rather supplement the demersal consumer's diet and indirectly provide alternative nutritional sources through their bioturbation activities and the maintenance of a very productive zone in the near-shelf bottom waters.

In turn, the extremely high densities of shrimp on the Gulf of Mexico shelf, as indicated by the successful fishery, probably have a direct effect on the smaller benthic infaunal biomasses observed for these waters as contrasted to Atlantic coastal waters (Rowe *et al.* 1974). The predation pressure of the shrimp plus their physical feeding activities may serve as influential factors in maintaining infaunal organisms at relatively smaller sizes with possible higher turnover ratios than even assumed here.

From the preceding exercise, it is obvious that the coastal waters of the Gulf of Mexico are extremely productive and that this production is influenced by many factors. It is suggested that much of this production is diverted directly to the benthos and that the major regional fisheries, such as shrimp, receive much of their nutrition from a detrital food web. Determining the mechanisms of this food web and the exact role of such components as the benthos is an extremely important task for future research. It would appear that this ecosystem, and its food webs leading to major commercial fisheries, is certainly different in structure than, for example, the system described by Steele (1974) for the North Sea. This points to the need for detailed regional studies before generalizations and predictive models can be constructed for important fisheries and related factors such as impacts from environmental disturbances.

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BARRIER ISLANDS AND THEIR MANAGEMENT AS SIGNIFICANT ECOSYSTEMS

Edward T. LaRoe[1]

ABSTRACT

Barrier islands and beaches are significant ecosystems which share common features. The complex interrelation of ecology and geomorphology which characterizes barrier islands is probably unique among ecosystems. The ecologic and economic benefits provided by barrier islands, especially the related estuarine systems which they create, are also significant. And finally, the hazards to, and the ecological stresses from, development on barrier islands are substantial. Resource managers must address these problems before the resource can be successfully managed and the benefits which barrier islands provide retained.

INTRODUCTION

Barrier islands are dominant geologic and ecologic features along much of the East and Gulf coasts of the United States. Together with the West Coast barrier beach formation, they share common characteristics, features, benefits, and needs for management. I would like to discuss in general terms those features which distinguish barrier islands and beaches as significant ecosystems and which, not coincidentally, pose the difficult problems which the managers and users of barrier islands must face.

Barrier islands have very characteristic shapes: they are elongate, thin structures, parallel to the shoreline, formed of unconsolidated sediments (usually sand). Individual islands may range up to tens of kilometers long, and are usually less than a few kilometers wide. They often occur in long chains, separated from each other by narrow inlets like beads on a necklace. They are separated from the mainland by estuaries and wetlands, which may range in size from narrow lagoons to the extensive sounds over 50 kilometers (27 mi) wide such as those in North Carolina.

In the United States, barrier islands range from New England, down the Atlantic coast, around the Gulf of Mexico, to Texas. They are generally

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located in areas with low sloping coastal plains and moderate tidal range. They are best developed along the South Atlantic coast, and form almost half of the Gulf of Mexico shoreline. Typical barrier islands include relatively undeveloped ones, such as Sapelo Island and the Core Banks; Chincoteague, Padre Island and Cape Hatteras, which are primarily used for recreational purposes; and severely perturbed areas such as Marco Island, Atlantic City, Galveston Island and Florida's big mistake, Miami Beach. While true barrier islands do not exist on the Pacific Coast, a similar feature occurs there--the barrier beach. Barrier beaches are elongate, thin peninsulas, such as the Silver Strand which creates San Diego Bay, or Long Beach, which forms Willapa Bay; they share similar characteristics with barrier islands.

FUNCTIONS OF BARRIER ISLANDS

Barrier islands are important for several reasons. They form the first line of defense for the mainland against winter storms and hurricanes--they are truly a barrier to those storms. They are also important because they provide for the creation of estuarine ecosystems. And finally, they provide a unique ecosystem in themselves.

BARRIER ISLANDS AND DEFENSE AGAINST ENERGY STRESSES

Barrier islands are dominated by energy stresses. Exceptional wave force, wind and tidal energies, and ocean flooding are the predominant factors which shape and regulate the barrier island ecosystem. As a result of these forces, barrier islands are extremely mobile and dynamic systems, constantly subject to change. Seasonal and other regular cyclic fluctuations in wave patterns and intensity combine with irregular ocean storms and hurricanes to form and reform barrier island profiles. The beaches and dunes migrate in response to these fluctuations. Storm overwash periodically carries sand onto the island, leaving substantial deposits of new sediments. The result is that, morphologically, the islands are in a continual state of flux. While we generally recognize the great impact that hurricanes have on barrier islands, I should emphasize that because of wave periodicity and duration, seasonal winter storms can play an equally important role in shaping the islands.

It might be tempting to conclude, given the dynamic nature of barrier islands, that these forces lead to great instability. While this may be correct in terms of man's needs for development, ecologically the contrary is true. It is the dynamic nature of the barrier island system that makes it stable. The island beaches offer little resistance to storm waves, and effectively absorb and dissipate the tremendous forces which confront them. This confrontation with the sea's storms is their most characteristic feature.

In the natural system, storm waves frequently breach the island dunes and flood the island. As waves wash over the dunes during storms, they carry sand and shell onto the island and distribute them across the grasslands, marshes, and even into the estuary behind. Storm overwash, therefore, actually contributes new sediments to the islands. In this fashion, overwash serves to maintain the island by supplying sand from the beach and offshore areas for new dune growth, adding to the island's elevation, and extending the island laterally into the estuary.

Soils characteristic of barrier islands are generally immature. Sandy soils predominate, and are perpetuated by the frequent overwash. Ocean flooding tends to carry finer sediments into lagoons. Sandy soils provide rapid absorption of water, except in deflation plains where the sand may be wind-scoured to the water table. They are also prone to problems of ground-water contamination, either by excessive drawdown leading to salt-water intrusion, or by septic tank waste disposal.

BARRIER ISLAND ECOSYSTEMS

The barrier island fauna and flora not only reflect, but also depend upon, the overwash and immature sandy soils. Progressing inland from the ocean, the first plants are hardy grasses such as sea oats (*Uniola paniculata*) and salt meadow cordgrass (*Spartina patens*). Both grasses are well adapted to flooding and overwash, and will quickly grow even if completely buried by sand. Regular overwash serves to maintain these productive, early successional forms. On smaller or frequently-flooded barrier islands, these grasses may be the dominant vegetation across the island. However, protection from overwash allows the development of later successional stages which may displace, at least partly, the hardy and productive grasslands, so that on larger, more protected islands, shrubs and forested woodlands can develop. The largest barrier islands are known for the development of maritime forests.

Barrier island ecosystems are generally biologically depauperate, with fairly simple food webs; this results in part from the periodic stress (which keeps them in an early successional stage), as well as from the reduced complexity associated with all insular systems. Characteristic of island ecosystems generally, special populations or subspecies, particularly of mammals (such as deer), are frequently found on barrier islands. Many of these are now endangered. Larger predators are generally absent. In response to the dynamic beach conditions, the beach fauna *per se*, is largely composed of annuals. The short life span and rapid turnover lead to swift recolonization of the beach sands following perturbation.

ESTUARIES CREATED BY BARRIER ISLANDS

When we discuss barrier islands, we tend to focus on the extensive beach and dune systems and their interaction with the ocean. In doing so, we frequently overlook the great importance of barrier islands in creating and maintaining the extensive network of highly productive estuaries and wetlands along our coast. As a physical barrier, the islands protect both the estuaries and the mainland from the high energy forces. The semi-enclosed lagoons they form permit mixing of ocean and fresh waters and allow the development of estuarine conditions. The physical protection provided allows the development of lower-energy tidal wetlands and extensive marshes. These estuaries and wetlands are among the most important benefits of barrier islands.

The lagoons and estuaries are connected to the sea by inlets. These inlets form a pathway for the transportation of sand and sediments from inland rivers to the coastal beaches, of marine organisms between coastal and estuarine waters, and of man's products from port to port. Like the islands, the inlets themselves are unstable. Responding to hydrologic pressures, changing sea levels, man's impacts, and other forces, the inlets migrate freely, shoaling in at one place or time, and breaching the islands in low or vulnerable places to form new passes at some other time. The channel depth is seldom constant.

The barrier islands and inlets are both substantially affected by the flow and availability of sand. The sand is subject to two major kinds of movement: an onshore/offshore cyclic migration, where it is alternately stored in offshore submerged sandbars or the onshore beach and dune system; and a littoral drift which moves the sand along-shore, parallel to the shoreline. This littoral drift may be cyclic, but generally imparts a net flow of sand along the beach in one direction. Interruption of either type of movement can alter the natural sand balance, causing widespread erosion or accretion of sand on the beach or in the inlet.

MAN'S IMPACTS

The final feature of barrier islands is their strong appeal to man and their vulnerability to his influence. Man is attracted to barrier islands for a variety of reasons--for recreation and aesthetic pursuit, for agricultural and forestry uses, and for real estate development. From the first efforts at colonizing the United States--Sir Walter Raleigh's settlement at Roanoke 400 yr ago--to the most recent large-scale developments, man has attempted to settle the barrier islands. And as with so many of his efforts, while he attempts to use and modify the barrier islands for his own benefit, he winds up, at great public cost, destroying the resource.

The very feature which maintains the islands--their dynamic nature which allows them to yield and reform under the wave stress--is hostile to man's objectives. Flooding and overwash, which sustain the islands, are inimical to man's presence and his structures. Development must be accompanied by static conditions. Through bulkheads, seawalls, groins, and dune stabilization efforts, man has tried to impose an artificial stability on the islands. And while man has accomplished little of a long-term nature, his efforts to stabilize the islands have, in fact, caused the loss of their natural defensive capability, causing severe perturbations in island ecology and geomorphology. Erosion has increased and beaches have narrowed. Where conditions have been temporarily stabilized, ecological succession has accelerated, leading to biota less tolerant of--and less capable of recolonizing after--storm flooding and overwash. Displacement of the dunes and dune vegetation by homes and roads destroys the natural sand storage repositories, as well as the main features of defense. This leads to further erosion and damages.

For his navigational use, man has attempted, also, to stabilize the inlets between islands. The groins and jetties, which are the primary tool for inlet stabilization, have led to substantial downcurrent erosion problems when sediment transport is interrupted. The channels themselves must be maintained by continuous dredging, which has ecologic and economic impacts of its own. In some areas where additional navigational access has been desired, new channels have been cut through barrier islands, leading to widescale changes in sediment flow along the beach and in the stability of estuarine waters behind the island.

Reports on the effects of livestock grazing on barrier islands are mixed. However, feral animals, especially hogs, have substantially altered the ecosystem on some islands. This has special significance to the U.S. Fish and Wildlife Service; some barrier island refuges have been managed as hunting preserves where the population of feral hogs has been deliberately maintained--to the great detriment of some of the unusual, if not unique, native species and the natural ecosystem.

In addition to the losses in the natural ecosystem, the development by man of barrier islands is accompanied by other losses to: loss of life and property, and great economic loss. Man's development is often followed by--indeed, is the cause of--substantial beach erosion. For example, 43% of Florida's beaches are undergoing erosion, with 17% undergoing erosion that is considered "critical". These figures may be considered typical for the Atlantic and Gulf coast. Much of this critical erosion is directly associated with the effects of man's development.

When erosion occurs, man's development is threatened. Costly protective structures--jetties, groins, and sea-walls--are often constructed; even beach renourishment is attempted. Such remedies are not only terribly expensive, but only temporary in effect. Beach restoration effort, which costs about $1,000,000 or more per mile, must be repeated cyclically. Man's efforts to stabilize the moving sands by physical structures often interfere with natural processes, destroying the natural defensive properties and causing more long-term harm than benefit.

Poor development practices also result in exorbitant flood and wind damage and loss of life as well as beach erosion. Most barrier islands are low enough to be regularly covered by flood waters from winter storms and hurricanes. The hazards of flooding and erosion are exacerbated by the problems of access from and evacuation to the mainland. Barrier island development is not only costly to begin with, but extremely vulnerable after completion.

Regrettably, development on barrier islands is often subsidized--directly or indirectly--by government. Because of the high costs associated with such development--freshwater supplies are usually very limited and need to be piped in from the mainland, the sandy soil and high water table precludes the widespread use of septic tanks, and the problem of providing a bridge or causeway from the mainland for access to the island are just three factors causing high costs--barrier islands would often not be developed without Federal and State grants or construction projects, much less Federal permits. These costs are often borne by taxpayers as a whole, not just future island residents.

MANAGEMENT PRINCIPLES

The concern for the adverse ecological impacts, the hazards to life and property, and the long-term costs associated with development of barrier islands, suggests that the first rule of development for barrier islands is that they should not be developed. Public and private efforts to protect and preserve barrier islands need to be increased, for this provides the long-term solution. Unfortunately, this is a very costly and time-consuming process. While we have succeeded in acquiring and protecting some significant barrier island systems during the last three decades, there is still so much to be done that we cannot hope for preservation of all yet undeveloped barrier islands.

Where development does occur, several management principles can be applied to reduce the adverse impacts and high costs. The following suggestions are offered as factors to consider in the design, review, or approval of development on barrier islands and beaches.

1. Recognize and protect the important parts and processes of the island system. Understand, for example, the relationships of the beach and dunes to the long-term survival of the island forest, marshes and estuary.
    a. Do not attempt to stabilize unstable beaches, foredunes, and inlets. Their strength, their benefits as a barrier, lie in their ability to migrate and, in so doing, effectively absorb the sea's energy.
    b. Protect stabilized and conditionally-stabilized dunes. Do not clear them of vegetation, which would lead to erosion. Provide elevated walkways to protect the dunes and dune vegetation.

    c. Treat chains of barrier islands as a single system. Recognize that sand is transported by littoral drift from one island to another. Interruptions, such as groins, jetties, and artificial inlets, can have substantial adverse downstream effects.

2. Utilize a combination of zoning, site restrictions, and performance standards to provide effective protection of the system. The use of such non-structural solutions is preferred to the use of structural solutions for the problems of erosion and flooding.

    a. Prohibit development on beaches and unconsolidated dunes. The free movement of these sands is essential to prevent erosion and to maintain the island's defenses; while the sands will move, buildings cannot. While limited construction on the beach will not usually harm the beach (although under certain circumstances it can lead to erosion), it is practically impossible to avoid damage to the structures. The best way to avoid conflict--and the damage--is to prohibit placing the structures there altogether.

    b. Prohibit construction on the foredune. Man's activities here almost always lead to increased erosion and break down the barrier island defense against energy stresses.

    c. Prohibit development in brackish or interior freshwater wetlands. These have high ecological value as habitat, nursery sites, and sources of productivity. In addition the interior wetlands are a recharge area for the island aquifer. Avoid fill or drainage ditches in these areas.

    d. Require that all development be secured to adequate pilings and constructed at an elevation above the 100 yr flood level. This will reduce damage from flooding and storm winds.

    e. Prohibit the large-scale removal of vegetation, especially sand stabilizing species. Confine the removal of vegetation to just those areas needed for development. Require that denuded areas be quickly revegetated with native species of plants.

3. Design and provide adequate services to support the island population, while avoiding or reducing adverse impacts on the island. Since most services will be provided from the mainland, this requires careful planning.

    a. Plan services--particularly roads, sewers, and water--so that they complement one another, by being designed to accommodate the same projected population. This prevents the tendency to use an excess of one service as force for more growth, which strains other services, and results in continued, cyclical expansion of each service.

b. Although some fresh water may be available on the island, for urban scale development, fresh water will usually have to be brought from the mainland. Excess withdrawal from the shallow island aquifer can lead to saltwater intrusion. In addition, sensitive, sand-stabilizing plants are unable to compensate for lowered groundwater; thus, as the water table is lowered, the plants die, leading to increased erosion.

c. Require central sewage treatment. Septic tanks in the sandy soil do not provide adequate treatment; they can lead to eutrophication in the interior wetlands, and to contamination of groundwaters and estuarine resources (such as oysters). Treatment facilities and holding ponds should not be built on the island unless they can be constructed above the 100 yr flood plain.

d. Construct, roads, bridges, and causeways, both to and from the island, above the 100 yr flood level. This is necessary to allow for evacuation from and emergency access to the island during hurricanes or other severe storms.

e. Limit the projected population, through zoning, transferable development rights, or other means, to that which can be safely evacuated given 12-h notice of impending storm. This is a function of the carrying capacity of the roads and bridges.

f. Require that roads and bridges to the island provide for adequate water flow and exchange within the estuary, so that the natural pattern of salinity and currents are not altered.

g. Ensure that the costs of providing the necessary services are borne by the developer, not the taxpayer. This, itself, will serve to avoid much damage, because in many cases development would be infeasible if it were not for public subsidies.

Most of the adverse effects of man's activities have not generally been foreseen or desired. Yet, by attempting to impose an artificial stability on the system, man's activities strike directly at the nature of the island's defense system. As a result, barrier islands, which are resilient enough to survive the enormous assaults by nature, are extremely vulnerable to the effects of man; and man's stresses have had greater impact on the ecology and geomorphology of barrier islands than have those of nature.

While careful planning and control can avoid or reduce some of these impacts, it is regrettable that we could not have profitted from the lesson of Sir Walter Raleigh 400 yr ago, and abandoned all efforts to develop on barrier islands.

AN OVERVIEW OF LEGAL ASPECTS OF THE PERMITTING PROCESS

James T. B. Tripp[1]

ABSTRACT

The task of managing and protecting coastal resources, as well as freshwater wetlands, from exploitative uses is enormous. The U.S. Fish and Wildlife Service and National Marine Fisheries Service bear heavy responsibility under various programs to conserve those resources. Several new approaches to carrying out this mandate are suggested, which would allow for more effective resource management by such agencies.

First, the Fish and Wildlife Service should develop broad policy positions on critical issues which arise during the Section 404 permitting process. For example, permits for non-water dependent uses, such as housing, highways, most Soil Conservation projects and others, should be routinely opposed. In connection with certain coastal dependent activities, such as oil and gas exploration, the emphasis should be on development, with appropriate experts, of a technically sound policy relating to technology-forcing alternatives.

Second, the Fish and Wildlife Service should increasingly emphasize preventative actions to protect high quality coastal resources, rather than reacting to exploitative proposals. Where such high quality coastal resources are found, the Fish and Wildlife Service should prepare reports with management plans for those resources. In developing long-term management proposals for critical coastal resources, the Service can make use of a host of planning tools, including Section 404 predesignation, the Flood Disaster Protection Act, national seashores, scenic rivers, wildlife refuges, wilderness areas and mitigation.

Third, enhancement of coastal resources, such as coordinated planning for the Mouth of the Colorado River Project in Texas and the Atchafalaya Basin and the Mississippi River Delta in Louisiana, should be given high priority. This means working closely with a small number of expert coastal and delta geologists, hydrologists, and resource biologists.

The Fish and Wildlife Service is overwhelmed by the task facing it through the 404 and other permitting programs, in part because the Service

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has traditionally played a largely reactive role, emphasizing review of individual permit applications, Corps planning reports and EIS documents. An alternative approach would focus on developing policy positions on activities, working with outside experts in identifying technology-forcing alternatives, and emphasizing preventative efforts. In order to do this, the Fish and Wildlife Service must put together a broader interdisciplinary team in each area or regional office. The Service should have on its staff, hydrologists, water quality experts, economists and others, in addition to biologists. Without such experts, the Service is at an enormous disadvantage *vis-a-vis* the Corps, and other development-oriented agencies and many private applicants.

MANAGING IMPACTS OF PETROLEUM DEVELOPMENT IN BRACKISH MARSHES

William L. Longley[1] and Rodney G. Jackson[2]

ABSTRACT

Petroleum development operations in wetlands are partitioned into seven phases and the activities are described for each phase. Environmental effects are discussed in terms of: vegetation and consumer losses; increases in dissolved, particulate, and toxic materials; and modifications of hydrology. Suggestions for minimization of impacts are presented. Changes in the water flow regimes of wetlands lead to the most significant alterations; thus, the land manager must concentrate his efforts on maintenance of these water flows during all petroleum development operations.

INTRODUCTION

Petroleum development in the Gulf coast began near Beaumont, Texas in 1901. Development commenced soon after in Louisiana, but it was not until the 1930's that the equipment and technology had progressed enough to allow extensive exploration and production along the Gulf coast wetlands (Davis 1973). By 1971, petroleum exploration and production along the Gulf coast was extensive; Gusey and Maturgo (1971) reported more than 14,000 gas and oil wells in the Louisiana coastal marshes and more than 18,000 well completions offshore of Louisiana and Texas.

During this period, Gulf coast wetland areas shrank. Gagliano and van Beek (1970) estimated that 42.7 km^2/yr (16.5 mi^2/yr) of Louisiana wetland were converted to other types of land or water units. Some of this change was due to natural erosion and subsidence. Craig *et al.* (1979:141) calculated that this represented 35% of the net land loss. Gagliano (1973:90) estimated that 25% of the change could be attributed to petroleum industry dredging. The remaining portion of the net decrease (40%) was due to drainage, dredging, filling, and impoundment for agriculture, industry, navigation, and residential development. These studies were made in Louisiana and cannot

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be directly extended to all Gulf coast states. However, Chapman (1967) has presented figures that indicated wetland loss in other Gulf coastal areas. It is clear that a considerable portion of the decline in wetland area is related to society's use of wetland regions for transportation, development, and energy production.

Energy policy is currently undergoing a substantial change in this Nation. As a result of this change, petroleum activities in Gulf coastal wetlands are bound to increase. For wise management of our renewable resources, it is sensible to consider methods and standards of operation of oil and gas development that conserve our wetland ecosystems.

This study (Longley *et al.* 1978) was conducted for the Coastal Ecosystems Project of the Biological Services Program, U.S. Fish and Wildlife Service. Other studies that include consideration of the impacts of oil and gas activities are Conner *et al.* (1976), Darnell (1976), Clark (1977), and Clark and Terrell (1978).

OIL AND GAS ACTIVITIES

Oil and gas activities may be divided into seven phases: pre-exploration; access to the site; site preparation and operation; placement and operation of production facilities; installation and maintenance of lines; spills and cleanup; and site shutdown and restoration.

PRE-EXPLORATION

Pre-exploration activities involve broad reconnaissance or site-specific measurements. Broad reconnaissance methods include inspection of aerial and satellite photos, magnetometer surveys, and other indirect measures. These require little if any direct site contact.

Site-specific methods include gravity surveys and seismic techniques. Gravity surveys require a surveyor to carry and make field measurements with a simple instrument sensitive to differences in gravitational field. There is a minimum of vehicle movement from location to location during gravity surveys.

Seismic methods usually require a series of explosive charges that are set off parallel to a string of seismic detectors. The reflected vibrations from subsurface formations are recorded and allow the formations to be mapped. Seismic surveys are usually undertaken in a series of long straight lines. Vehicles may traverse a line several times to: survey and place markers; drill shot holes or plow-in explosive cord; place detectors; retrieve shot tubes and detectors, and fill shot holes. In dry areas, trucks may be used to transport equipment. Marsh buggies are used in wetland areas. Most buggies use large low-pressure rubber tires. In Louisiana, track-laying vehicles with wide treads are also used. There are at least two and often three vehicles involved with any shot line.

Point-charge explosives may be placed in shot holes 15 to 120 m (50 to 394 ft) deep and 75 to 350 m (296 to 1148 ft) apart. Some seismic surveyors now use explosive cord, burying it the length of the shot line with a vehicle-mounted "vibrating knife". This requires less equipment than point-charge methods and can result in very little surface disturbance.

ACCESS TO SITE

The two methods of gaining access to a well site in wetlands are constructing a roadway from the upland and dredging a canal from open water or an existing canal. At some locations, a combination of these access methods is used. In wetlands with firm substrates, a board road may be constructed. This consists of two or three layers of boards, each perpendicular to the previous layer, placed directly on the marsh surface. Board roads are often temporary and may be removed when movement of heavy equipment has ceased.

In waterlogged soils or areas subject to frequent inundation, a leveed road may be built. A dragline is used to scoop material from the marsh surface parallel to the road. The leveed material is shaped and allowed to dry, and a roadway is constructed on the levee top. If heavy loads are expected, the roadway may have board layers. If the road is to become permanent, the top may be capped with shell or crushed rock.

Canals to well sites are usually 2 to 3 m (6.6 to 9.8 ft) deep and about 20 m (66 ft) wide. Dredging is most often done by a barge-mounted dragline. The spoil is placed on both sides of the canal to form continuous levees. The distance of the spoil piles from the canal edge depends upon the boom length of the dragline.

Spoil itself is quite variable in composition. When heaped, it may spread over a wide area, then shrink and compact upon drying. The foundation sediment upon which spoil is placed may be weak and result in continuing maintenance problems for canals. Vessel movement through canals causes bank erosion. The erosion results in gradual widening of the canals and recurrent maintenance dredging requirements.

SITE PREPARATION AND OPERATION

In wetland areas, the actual drilling site is small. In areas where levee or board roads have been built, ring levees are constructed; all operations take place on the board-covered marsh floor. The levee is 1.5 to 2 m (4.9 to 6.6 ft) high and is built with borrowed sediment from outside the leveed area. Just inside the levee, a sump is dug all around the well site. This collects runoff and water that leaks through the levee.

Maximum size for ring levees is about 120 by 120 m (394 by 394 ft). There may be subcompartments constructed within the ring levee for temporary storage of drilling muds and cuttings. When portable steel mud containers are used, the well site may be smaller.

In dredged locations, the well site is an enlarged extension of the dredged channel and may be 40 m (131 ft) wide and up to 120 m (394 ft) long. No other levees are built because drilling fluids are usually contained in barges.

Auxiliary services to the well site include temporary gas lines and water wells that may be drilled on-site. Alternatively, all water and fuel may be trucked or barged in. Much equipment is transported by truck or barge. After drilling begins, traffic continues to move 24 h a day until the well is completed.

Drilling itself has little direct effect on the environment unless a blowout or accidental spill occurs. Solid and liquid wastes are usually hauled off-site. Drill cuttings may remain or be removed. Drilling fluids can pose disposal problems. Some fluids contain components clearly unacceptable for disposal in wetlands; others, although not toxic, can present the same problems for wetlands as fill material from dredging.

Drilling is a short-term operation , rarely taking more than 90 days. After drilling is completed, much of the equipment is removed and production or shutdown and restoration occurs.

PLACEMENT AND OPERATION OF PRODUCTION FACILITIES

Production facilities include flowlines, equipment at the wellhead, and centralized treatment equipment. Flowlines carry natural gas, crude, or both from the wellhead to the centralized equipment. Flowlines are pipes 7 to 10 cm (3 to 4 in) in diameter and are rarely more than a few kilometers long. In relatively stable marsh soils, flowlines may be plowed into the soil, placed in a ditch and covered with earth, or placed along the levee edge. In very wet, unstable soils, flowlines may be placed directly upon the marsh and allowed to sink into the soil. At dredged locations, flowlines may be buried in the bottom or elevated on pilings above water.

Wellhead production equipment may consist of separators, heaters, treaters, or pumps. Most of this equipment is necessary to keep wells operating economically as the resource is depleted. At leveed locations, these devices are placed on concrete slabs on the levee floor; at dredged sites, they may be placed on the wooden or steel wellhead platforms, on other platforms built nearby, or on the bank. These devices require little space and only rarely cause serious problems.

Most centralized facilities are placed on solid soil, near or at the edge of the wetlands. Occasionally this equipment will be mounted on large barges or placed in leveed areas. Centralized equipment includes freewater knockout tanks, skimmers, separators, pumps, compressors, burning pits, temporary saltwater disposal tanks, and tank batteries. This equipment is used to separate natural gas and crude oil, to remove water and sediment from crude oil, to temporarily hold produced water and sediment for disposal, and to store crude until it is transported. In some places brine, if it meets water quality standards, may be released directly into wetlands or water bodies. Where it cannot be released, brine may be reinjected into the earth for disposal. In older fields, brine may be reinjected with other fluids to improve petroleum recovery.

With the start of production at the well site, vehicle or vessel activity is high while equipment is placed and the well is treated. Activity is very low after production begins. Wells are checked visually every few days, and periodic maintenance occurs on production equipment and the well itself. At the centralized site, there is daily activity such as maintaining the production equipment, preparing the stored petroleum for transport, and disposing of the waste materials. Production activities often last for decades; but after the equipment is placed and operating, very little new environmental disruption occurs.

INSTALLATION AND MAINTENANCE OF LINES

In moderately firm wetland soils, pipelines are often constructed by the "push" method. A pipeline-laying barge is positioned and a long, continuous string of pipe is constructed, attached to a series of floats. The pipeline is directed into a narrow, shallow canal dug along the pipeline route and is pushed through the canal as each section of pipe is added at the barge. McGinnis *et al.* (1972) report that pipelines up to 76 cm (30 in) in diameter and sections up to 24 km (15 mi) long may be constructed in this manner. The pipeline canal may be kept to a minimum size using this technique, often 1.2 to 1.8 m (4 to 6 ft) deep and 2.6 to 3.1 m (8 to 10 ft) wide.

After the pipe has been pushed the length of the canal, the floats are removed and the line sinks to the canal bottom. Buggy-mounted backhoes may be used to backfill the canal. It is sometimes impossible to completely refill the ditch with excavated soil because it dries and may shrink up to 50%.

In some areas the soil is so unstable that a dragline on timber mats or a buggymounted backhoe cannot be used to dig the push canal. The "flotation" technique may then be used, where a dredge excavates a canal wide enough for the lay barge. The barge traverses the length of the canal, laying the pipe behind it. This method poses the same environmental problems as canals for well access and tends to be used less frequently since the development of the "push" technique.

Pump or compressor stations may be built along the pipeline route. At major collection points these stations may require several hectares of land for placement. Booster stations are smaller in size and require only a few hundred square meters. Pipeline constructors often avoid placing pump stations in wetland soils because of poor foundation materials for construction. However, leveed, pilemounted, and bargemounted pump stations may be built when wetland areas cannot be avoided.

After a pipeline is constructed, there is little activity along it except for periodic inspection, usually from low-flying aircraft. At pump stations the low level of activity involves maintaining and operating the pumps and pipeline. Periodic maintenance on pipelines may include site inspections and replacement of electrodes to prevent electrolysis. Pipeline leaks are detected quickly since new pipelines have automatic valves that close when pressures drop suddenly. Like production equipment, pipelines may function for dozens of years with only minimum maintenance.

SPILLS AND CLEANUP

Cleanup operations may occur at any time. The first priority is to isolate the spilled fluids because buoyant petroleum materials spread quickly as thin films. When the spill is isolated, as much petroleum is skimmed off as possible. In wetland areas, it is usually desirable to cut and remove or even burn oil-soaked vegetation so that the petroleum adhering to the vegetation does not spread later. Vehicular traffic and trampling of vegetation outside but adjacent to the affected area may sometimes cause as much disruption to the wetlands as the original spill.

SITE SHUTDOWN AND RESTORATION

Termination of production at the well site involves pulling the tubing and downhole equipment and plugging and removing the wellhead equipment. A small truck- or barge-mounted rig is necessary. Sometimes a small amount of dredging is required to allow barge entry.

At leveed sites the board pad is removed and sometimes the levees are breeched. Completely removing levees and elevated roads and returning land elevations to prior levels is rarely undertaken. At dredged sites the canal is abandoned, though occasionally a plug is placed across the canal mouth.

In some instances, surface landowners are happy to have roads, levees, and canals on their property. In other cases, petroleum developers will try to satisfy the requests of surface land owners for restoration. Making cuts in levees and even placing plugs in canals is usually not cost-prohibitive. However, the cost of completely refilling canals is usually high because of the effort involved and the need for extra soil after levee banks have dried and compacted.

If an entire field has ceased production, centralized equipment will be removed. The same is true for pumping and booster stations. Pipelines themselves are left in the ground when they are abandoned.

Revegetation is sometimes undertaken at the request of the landowner. Because of rapid natural reestablishment of vegetation in some marsh areas, artificial revegetation is not always necessary. However, areas prone to erosion from major currents, vehicle or vessel movement, or animal activity (cattle walkways, for example) may require stabilization, fertilization, and planting.

IMPACTS OF OPERATIONS

LOSS OF VEGETATION

Vegetation losses occur during all phases of oil and gas activity because of (1) movements of work crews and vehicles and (2) placement of sundry facilities. Pre-exploration activities typically involve small areas, but the damage may become significant if vehicular movement is not carefully controlled.

Total areas affected during site access, wellsite preparation, pipeline installation, and placement of production facilities are primarily dependent on dimensions of construction easements and rights-of-way.

Prediction of the effects of spills (and subsequent cleanup) is difficult because of many compounding factors. The area covered may be dependent on topography, duration of the release, presence of water bodies and currents, prevailing winds, and tidal cycle. The resultant die-back of vegetation is a function of the type of material spilled and the degree of movement of men, marsh buggies, airboats, barges, outboards, and other cleanup equipment over and through marsh areas.

Losses and gains in vegetation during site shutdown are quite variable, and depend on the degree of earthmoving accomplished and the amount of revegetation effort.

Minimization of Losses

The most obvious way to minimize total areal losses is to reduce dimensions of roads, canals, wellsites, padsites, and pipeline rights-of-way.

This can best be accomplished at meetings held prior to any field work. The land manager and permittee (or his contractor) should agree to all plans, including mitigation and restoration, before field work commences.

The following suggestions may successfully accomplish a reduction in total area impacted: 1) utilize directional drilling whenever possible; 2) establish and restrict pipelines to a reasonable "corridor"; 3) encourage the "push" method rather than "flotation" method of pipeline installation ; 4) require the use of wooden mats for draglines and other tracked vehicles; 5) encourage the use of portable steel tanks for drilling mud rather than excavating mud pits; 6) place small flowlines on the surface, preferably adjacent to existing roads or canals; 7) restrict work crews and vehicles to narrow easements; and 8) regulate the number of passes by vehicles (and the retracing of paths) as appropriate.

Several additional methods and techniques may be employed to reduce the severity of vegetation losses. The land manager should design (and completely familiarize contractors with) a spill contingency plan. All contractors should maintain adequate fire suppressant equipment. Although fire *per se* may not kill vegetation, any unplanned burn may alter a management scheme. The land manager, by avoiding the use of heavy equipment during wet seasons, may prevent unnecessary disruption of root systems. Revegetation efforts and double-ditching techniques will usually accelerate regrowth following disturbances; however, double-ditching may not be economically justified in cases where distinct soil horizons do not exist.

LOSS OF CONSUMERS

The destruction of nests, beds, dens, or individuals may occur during all phases of oil and gas activities because of 1) crushing by work crews and vehicles and 2) placement of various facilities. Pre-exploration operations are usually the least damaging, but losses may be significant if vehicular movement and harassment or poaching are rampant. Primacord blasting in shallow water has been postulated as a cause of fish kills and other losses, but this is usually difficult to verify.

The total biomass lost during any phase of activity is a function of several variables: 1) the total area modified by construction, easements, and rights-of-way; 2) timing of the activity; and 3) the degree of harassment or poaching. In the case of spills, another variable must be included: the efficacy of containment and clean-up operations.

The effect of site shutdown on consumers is site-specific. Although common strategies and techniques may generally improve the area for some consumers, aquatic species may be lost when water bodies are filled. It may be judicious to retain some open water bodies to increase diversity.

Displacement of organisms is usually minor during pre-exploration; temporary during site access, installation of lines, placement of production facilities, spills, and site shutdown; and continual during drilling (3 mo) and production (up to 30 yr).

Minimization of Losses

The seven guidelines to reduce the areal extent of vegetation losses (see previous section) are also applicable to consumers. Several additional methods and techniques may be employed to reduce the severity of consumer losses: 1) Access alignments and permanent facilities should avoid existing concentrations of fauna. If rookeries, dens, or nests are encountered during operations, the contractor should notify the land manager before proceeding. (The manager can partially control this potential problem by regulating the timing of operations.) When primacord is used in open water bodies, a warning blast may scare consumers from the area. 2) Contractors should be completely familiar with a spill contingency plan developed by the land manager; the plan should include the use of scaring devices, prohibition of harmful dispersants, and floating barricades ("booms") where applicable. 3) Site shutdown allows a manager to utilize innovative strategies (*e.g.* construction and maintenance of denning platforms). It must be emphasized that the proper time to reach agreement on mitigation and compensation matters is prior to initial field work, even though it may be advantageous to postpone details of renovation plans until just prior to shutdown.

INCREASES IN DISSOLVED MATERIALS

Varying quantities of dissolved nutrients are returned to open water bodies as a result of earthmoving activities. If the concentrations of nutrients are adequate, and other environmental parameters are conducive, an algae bloom may occur. The phenomenon is usually temporary and insignificant in comparison to other impacts of oil and gas activities. However, if the bloom has a sufficient biochemical oxygen demand, fish and other aquatic organisms may perish.

During drilling operations, the marsh is subjected to a wide variety of compounds in drilling mud, sump discharge, and wastes from vehicles and equipment. The kinds and amounts of these materials, and hence their effects, are site-specific. Consequences may involve vegetation or consumers (over a short or long period of time) and, therefore, could range from insignificant to highly significant.

Brine disposal may result in the most serious increase in dissolved materials. Aquatic species are more capable of coping with gradual rather than sudden changes in salinity. Larval and juvenile stages of aquatic fauna are quite susceptible to high-salinity stress; stunted growth may occur. Affected plants may exhibit very low germination rates. The impact of brine effluent depends upon the duration of discharge, quantity released, ionic concentrations, and brine temperatures. Introduction of brine of high salt content, atypical ion distribution, and high temperature, stresses even salt-tolerant species to a point where survival is not possible.

Detergents and other petroleum dispersants will be treated in the section discussing toxic materials.

Minimization of Effects

Impacts from additions of dissolved materials may be reduced by implementing the following guidelines: 1) contain drilling muds (and components) in metal containers; 2) require proper storage, handling, and disposal of all chemicals used by contractors; 3) prohibit brine disposal in the open marsh; and 4) place plugs in canals or ditches whenever possible to prevent brine discharge into larger water bodies; a similar result can be achieved by dredging the connection to an existing canal last.

ADDITION OF PARTICULATE MATERIAL

Small, usually insignificant, changes in particulate matter occur due to vehicular traffic in the marsh during all phases of oil and gas activities.

Larger additions of particulate material result from earth-moving operations during site access, wellsite construction, installation of lines, placement of production facilities, and site shutdown or restoration. The effects are typically short-term and localized; however, prevailing water velocities and circulation patterns may provide exceptions to this generalization.

Erosion of soil, especially canal banks and spoil deposits, may have serious and long-term consequences. (Boat and barge traffic accelerate the rate of erosion and resuspended materials from the canal bottom.) The increased turbidity leads to a decrease in the suitability of standing water as habitat for phytoplankton, fishes, and aquatic invertebrates.

During drilling activities the adjacent marsh may be subjected to a variety of particulate materials used in drilling muds. Upon termination of drilling, residual mud may exist in an open mud pit, it frequently remains until final site shutdown commences.

Straw or other absorbent materials may be spread over a marsh surface during spill cleanup operations. The oil-soaked materials are usually burned

Minimization of Effects

Turbidity problems may be reduced by implementing the following procedures: 1) construct temporary plugs during canal dredging and line installation; 2) prevent spoil from being deposited too close to the edge of the canal; 3) employ containment levees, turbidity curtains or screens when possible; 4) place adequate bulkheading or riprap where necessary (especially at crossings); 5) enforce speed limits on water traffic; and 6) initiate revegetation efforts following all construction activities; waiting until site shutdown is frequently too late.

Drilling mud problems can be reduced by 1) requiring the use of portable mud tanks, 2) prohibiting the disposal of mud (and mud components) in the marsh, and 3) requiring the removal of all excess mud and components immediately after completion of drilling activities.

The land manager should always insist on proper storage, handling, and removal of all construction materials; extra care must be taken to avoid the introduction of harmful materials during spill cleanup operations.

ADDITION OF TOXIC MATERIALS

A marsh may be subjected to a wide variety of toxic materials in drilling mud, sump discharges, and wastes from vehicles and equipment. The types and quantities of toxic materials are site-specific. Impacts of addition of toxic materials may involve vegetation or consumers (over a short or long period of time) and therefore, could range from insignificant to highly significant.

The maintenance of rights-of-way, wellsites, and production facilities may involve the use of herbicides or pesticides. These toxic materials must be used selectively.

Toxic substances found in spilled materials are also site-specific. Consequences depend primarily upon the composition and size of the spill. Topography, prevailing winds, tides, and water currents are important modifiers of the effects. Toxicity to the biota also depends on the ambient temperature and salinity, and the life form or life stage that is exposed.

Minimization of Effects

Damages from toxic materials may be reduced by implementing the following guidelines: 1) require proper storage, handling, and disposal of all materials and wastes in order to prevent leakage into the marsh; 2) regulate and monitor "burning pit" operations; 3) require proper maintenance and repair of all treatment and processing equipment that could release toxic materials to the marsh; and 4) regulate the kind, rate, method, and time of application of herbicides and pesticides.

In addition to these guidelines the land manager should design (and completely familiarize contractors with) a spill contingency plan. The plan should include storage sites of necessary spill containment and removal equipment. Emphasis must be placed on the importance of immediate containment of spilled material; utilize booms, straw, plugs, and other materials. Avoid the introduction of additional toxic materials (*e.g.* detergents, dispersants, emulsifiers) during spill cleanup operations.

CHANGES IN WATER FLOW REGIMES

Changes in water flow regimes can cause extreme and long-lasting effects on marshes. Moreover, all phases of oil and gas development have the potential to change water flow characteristics by altering topographic features of the marsh. Depressions range in size from ruts caused by vehicle wheels to wide canals for access and pipelines; elevations range in size from insignificant piles of sundry materials to many hectares of spoil deposits. In general, effects on water regimes may be categorized into changes in the rate of flows, duration of flows, and frequency of flows.

Ruts and Small Depressions

The depth and number of ruts created by marsh vehicles are dependent upon the total number of trips and the degree to which vehicles retrace existing tracks. Deep ruts resulting from retraced trails will form surface depressions allowing the movement of water and, if deep enough, may result in standing bodies of water during wet seasons. The orientation and depth of the depressions determine whether they 1) remain for long periods of time and 2) alter the water regime of a given area of land by increasing or decreasing the frequency of submergence or emergence, average depth, and duration of submergence. Ruts parallel and subject to the tidal flux may increase the frequency of submergence or emergence; those perpendicular to tidal water movement may decrease the frequency. Areas dominated by marsh-hay cordgrass (*Spartina alterniflora*) may be replaced by stands of American three-square (*Scirpus americana*) or other water-tolerant species when the frequency and/or duration of submergence decreases.

The depressions can contribute to faster runoff of surface and standing water in localized areas. Thus, the duration of submergence and the average depth of water in nearby areas are decreased, while the frequency of submergence or emergence is increased. If vehicle tracks occur in areas of the marsh where isolated ponds exist, intramarsh circulation could be affected. Depressions could connect individual water bodies and increase the intermixing of their contents. The total area affected is site-specific and usually small when compared to 1) the remaining area of brackish marsh or 2) the effects of canal excavation.

Canals and Levees

Pipeline canals that are adequately backfilled or plugged may have temporary localized effects on circulation patterns, but they do not result in permanent long continuous canals and spoil ridges. Water movement patterns remain essentially unchanged following restoration procedures. The effects of staggered borrow pits and discontinuous spoil deposits, are, likewise, localized and relatively small. Of greater significance to the hydrological regime of the brackish marsh are the 1) construction of leveed access roads, and 2) dredging of access and pipeline canals and subsequent spoil deposition. Leveed roadways and open canals bordered by continuous spoil levees generate a complex of interactions which may facilitate changes in the marsh's freshwater sheetflow from the uplands and facilitate rapid marsh drainage. The result may be a lower water table under the affected marsh surface, and eventual drier conditions in high marsh areas.

Simultaneously, open canals may allow increased intrusion of more saline estuarine waters further inland. The pattern and height of spoil placement are the most important factors that determine if the salt water is contained within a localized zone or inundates extensive areas. Waterflow in the canal depends upon canal location and orientation in the marsh, the influence of tidal waters, and the portion of the canal in question. Long, straight sections of the canal, especially with tidal influence, may show an increase in the volume of water exchange compared to the preconstruction conditions. Often the net result is increased water salinity in the marsh. Increased water salinity eventually results in increased soil salt concentrations that can have physiological implications on plant assemblages.

Continuous levees may also block or redirect freshwater sheetflow or small drainage pathways. The result may be that wetter conditions (and perhaps standing water) prevail on one side of the levee, while the opposite side is drier. Drainage, impoundment, and introduction of stronger tidal forces (if estuarine areas are close enough to affect brackish marsh sites) may thus cause extensive changes in the duration of water submergence, average water depth, and frequency of substrate aeration.

If the net outcome of canals and levees is drier and more saline soil in a given marsh area, marshhay cordgrass is given a competitive advantage over most other marsh plants. The other major plant group, composed primarily of sedges and rushes, is a particularly significant food source for many waterfowl species and furbearers. Reduction of this plant component decreases the area's habitat suitability for these consumers. Drier conditions also result in decreased phytoplankton and benthic algae production as well as decreased food and cover for aquatic invertebrates and small fishes. Secondary consumer groups (predatory mammals and raptors) might be adversely affected if the alteration were extensive enough. The magnitude of alterations described above varies according to canal dimensions, number of canals, canal orientation relative to freshwater and saltwater sources, levee orientation and placement, the hydrologic gradient of the watershed, and other site-specific characteristics.

Minimization of Water Flow Alterations

Negative impacts due to vehicular movement can be reduced by adhering to the following guidelines: 1) use existing roadways whenever possible; 2) travel in naturally high areas - avoid alignments through swales or depressions; 3) prohibit vehicles from crossing unprotected levees; 4) regulate the number of vehicle trips over the same trail depending on soil conditions - in soft areas, retracing of trails should be avoided; and 5) balloon-tired vehicles are preferable to tracked vehicles.

Disruption of water regimes by construction of leveed roadways can be reduced by implementing the following suggestions: 1) choose alignments judiciously after considering all natural phenomena and land use goals; align roads parallel rather than perpendicular to surface waterflow; 2) stagger borrow pits to prevent formation of long continuous ditches along roadways or ring levees; and 3) avoid crossing drainages; if crossings are unavoidable, adequate culverts, bridges, and bulkheads can maintain waterflows.

Many methods exist for reducing the impacts of canal construction: 1) choose alignments with extreme care; make them short and straight where possible, avoiding natural creeks, bayous, and swales; 2) design access canals to prevent water stagnation; avoid having deepest portions at distal end; 3) carefully consider spoil-disposal sites, patterns, and techniques; selectively employ retaining structures, turbidity control, distinct mounds and levees, broadcasting spoil (to counteract subsidence); 4) where crossings of other watercourses are necessary, use adequate plugs and bulkheading; plugs every 400 to 500 m may be beneficial in long straight pipeline canals; 5) the "push" method of pipeline installation is preferable to the "flotation" method; and 6) back-filling of ditches should be accomplished as soon as possible; shrinkage of spoil is thereby reduced, and waterflows are re-established sooner.

Innovative planning can accomplish many benefits during shutdown and restoration activities. Although it may be preferable to simply restore all areas to their previous elevations, it could be more beneficial to enhance waterfowl and wildlife habitat by converting an area to an impoundment or stock pond, retaining scattered high areas for loafing and sunning. Such enhancement strategy usually requires much forethought (typically during the planning of site access).

OVERVIEW

Petroleum exploration and extraction operations produce two obvious levels of ecological effects in marsh ecosystems. The first level involves the radical change or complete removal of a given parcel of the system. This type of alteration is the most evident and the most predictable. Individual and cumulative perturbations of the substrate and floral components of wetlands will lead to changes in the fauna. These changes are predictable because major interdependent relationships between these elements of the system are known.

If the isolated alterations are few and of small magnitude, the functioning of the ecosystem is not impaired. However, each roadway, well-pad site, pipeline corridor, line installation, treatment and storage complex, pumping station, and other such facility removes supporting habitat within the immediate site as well as modifies, and perhaps degrades, nearby habitats for sensitive species. Unrestrained growth and development of an oil field maximizes habitat fragmentation, which can radically alter the ecological character of the ecosystem as indicated by changes in its biotic diversity, dispersion, and abundance. Not only is wildlife habitat removed directly through facility placement and site alterations, but the intrusion of man, his activities, and facilities into previously undisturbed wildlands alter additional habitat areas and trigger behavioral changes or range-abandonment by sensitive faunal species. Widely scattered single facilities may cause only minor changes in regular movements, but as development densities, disturbances, and intrusions increase, intolerant wildlife species abandon areas, even though other aspects of supporting habitat remain adequate. Dislocated individuals may relocate to other suitable, unoccupied habitats, if available. Such incremental losses are individually small, but the cumulative effects inherent to development of a major field can be quite significant.

The pristine wetlands inherently experience natural fluctuations in various components, and they contain compensating mechanisms to accommodate such fluxes. It is only when threshold levels of critical linkages or components are reached that the ecosystem changes noticeably. This, of course, represents the second level of ecological impacts. Unfortunately, these ecosystem threshold levels are unknown.

Water is the major factor in maintaining marsh systems. Salt marshes and fresh marshes depend primarily on inputs of a single type of water; saline and fresh, respectively. Brackish marshes and delta marshes characteristically receive inputs of both water types, although not in equal proportions. The movement of water through the system is the important force driving and controlling the wetlands. This fact must always receive consideration from the decision-maker. Because roads, levees, and canals alter water flows, they are considered to be the source of the most important impacts at the ecosystem level. Indeed, they often become the boundaries separating two ecosystems.

The effects of man-induced landforms on the ecosystem are not nearly as predictable as their impacts on the small specific sites they occupy. Two reasons for this lack of predictability are apparent. First, the ecosystems include a larger area and events occur over a longer time scale than do the alterations. Although the man-made features resulting from oil and gas activities are manifested in weeks or months, the natural phenomena of an ecosystem (periodic flooding and fires, rainfall patterns, succession, subsidence, and others) occur over periods of years, decades, or centuries. Second, the orientation of canals, levees, and roadways is such that the water flows of the ecosystems do not experience complete major changes; "all or none" situations are few. This means a relatively long period of time must pass before natural fluxes or cycles encounter these partial alterations. By the end of such a time period, additional or different alterations have frequently occurred in or near the ecosystem.

These facts indicate that the way to maintain an ecosystem during petroleum exploration and extraction, then, is to manage the ecosystem. But the dilemma is unavoidable; management decisions are typically concerned with relatively small areas and must occur over a short time scale; moreover, there is insufficient time to observe the wisdom of the choices, as reflected by long-term changes. It would be advantageous and highly desirable for the land manager to have, before major petroleum operations occur, a development plan for an entire oil or gas field. Presently, this does not and cannot occur. Drilling and extraction decisions are intermittent and based on cumulative information. Each new well provides data which are utilized in the decision of whether to drill another; in addition, the degree of speculation varies with the decision maker, the price of petroleum products, and other factors. Thus, there is no reason to expect this dilemma to change in the near future.

Different large-scale factors frequently confound management problems. Man-induced or natural phenomena that occur over a large region are constantly interacting with the ecosystems found in that region. Examples include the Gulf Intracoastal Waterway, channelization of the Mississippi River and other shipping lanes, large-scale subsidence, periodic fires, or flooding, and altered sediment and river-water input. Such features are affected by, and have influence on, the petroleum exploration and extraction processes.

Thus, the existence *per se* of a maze of canals or levees in a given wetland area represents a loss of land habitat. More important, by providing a route of intrusion, it makes possible an additional impact; complete ecosystem conversion. The Sabine National Wildlife Refuge is one example of such a situation. The waters of the Sabine and Calcasieu Lakes became increasingly saline due to channelization of shipping lanes. The existing network of canals on the Refuge provides an open passage for these waters into and through the parts of the Refuge. Areas that were fresh marsh are now brackish marsh. The Delta National Wildlife Refuge is another case where primary focus must be on regional phenomena. Any alteration which serves to isolate the "inner ponds" of the delta accelerates the loss of subaerial land habitat. The rate of subsidence in this area is great; therefore the existence of the delta ecosystem is dependent upon periodic flooding and its concomitant deposition of new sediments.

These regional phenomena cannot be completely controlled. Management must face the situation and make intermittent (sometimes daily) decisions concerning petroleum activities. It appears that an optimum strategy would be to consider and categorize all pertinent phenomena, commencing with long-term regional types, ranging downward through the ecosystems, and culminating in specific sites of concern. These long-term phenomena, along with the land-use goals of the particular area, must be kept in the foreground as periodic management decisions are made.

Methods of reducing significant impacts from oil and gas operations can be categorized into: 1) minimizing total habitat losses during each phase of petroleum activities; 2) maintaining adequate major water flows for the particular wetland ecosystem; and 3) providing for restoration of landforms and conditions after petroleum operations have terminated.

The first category, minimizing habitat loss, can be attained by encouraging preferred methodologies (*e.g.* the "push" method of pipeline installation, double-ditching techniques, directional drilling, and revegetation). Standardization of maximum dimensions would also be helpful for management.

The second category, maintaining waterflows, requires knowledge of the water regimes of the entire region, ecosystem, and site. Risk-laden decisions must be made if site-specific information concerning sheetflow and drainage are lacking. In planning for maintenance of existing water flows, it would be prudent to assume that the density of canals, levees, and roadways in a given area will increase. This assumption will likely force implementation of measures which may appear to be very conservative, but which later allow the maintenance of water flows in the midst of increased petroleum development.

The final category, providing for restoration or mitigation, also requires much forethought. In most cases, stipulations and provisions must be composed many years before restoration or mitigation actions actually occur. Consideration of long-term phenomena and land-use goals will influence the stipulations concerning spoil disposal techniques and patterns, isolation (or filling) of obsolete canals, removal of levees or roads, and construction of wildlife enhancement structures.

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STATE-FEDERAL RELATIONS IN THE COASTAL ZONE

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INTRODUCTION

The coastal zone has become the focal point of the most bitter conflicts being waged between Federal and State agencies. Until the issues of control over and responsibility for coastal resources have been settled, the conflict will continue. The comparative newness of many programs has resulted in uncertainty over which governmental unit will be responsible for which function. A major effort to clarify these matters will take place in the courts, and it is vital that those involved know what the issues are and how they may be resolved. The successful accomplishment of any task depends on the equipment with which it is undertaken. Federal employees working within the coastal zone often attempt to do their jobs without full cognizance of the tools they have been given. Many times, the laws which have been enacted are allowed to hinder rather than help accomplish a goal, but better understanding of laws and their implementation would improve the situation. There are certain statutes and regulations which affect every project undertaken and should be given particular attention. This paper briefly summarizes current developments in laws which affect U.S. Fish and Wildlife Service (FWS) efforts and efficiency in the coastal zone.

Every project initiated by the FWS is oriented toward a specific goal. That goal, which is stated in the Fish and Wildlife Coordination Act (FWCA) and has echoed through Fish and Wildlife laws since the first treaty was signed, is the protection and preservation of wildlife and habitat. The method of accomplishing this and the philosophy behind the statutes have changed drastically in the ensuing years, but the basic goal has lived on. The Fish and Wildlife laws are essentially the laws which will guide us in the methods and manner of operation, and give us the focus, the intent, of FWS. Other laws, however, must be taken into account. Laws must be made to mesh because the Congress gives little thought to the consistent operation of all the laws passed. So many laws are in direct opposition to each other that a balancing act is required to effect the goals of one law without defeating the purpose of another.

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MIGRATORY BIRD TREATY ACT

The first and strongest of the wildlife laws is the Migratory Bird Treaty Act (MBTA)(Ch. 128, 52, 40 Stat. 755) passed in 1916 to implement the terms of the treaties with Great Britain and Canada and in later years signed with Mexico and Japan. This Act can be the most effective weapon in the battle against destruction of habitat. Because it is based on these treaties, it surpasses the importance of other statutes which Congress may enact. The basic ranking of legal importance in declining order is constitution, treaties, and statutes; this means that as long as it does not affect anyone's constitutional rights, an expression of the MBTA will take precedence over laws. This makes the MBTA a very effective tool.

The MBTA, which construes the work "take" to mean "pursue, hunt, shoot, capture, collect, kill", or any attempt to do so, has been used to prevent the baiting of fields in *U.S. vs. Reese*, 27 F. Supp. 833 (W.D. Tenn. 1939), and the use of lead shot in the hunting of migratory waterfowl (see 41 Fed. Reg. 31386, 28 July 1976). An act which prohibits any taking of migratory birds with no requirement of scienter (guilty knowledge) can be used to much greater advantage.

Two recent cases indicate that the courts are willing to accept the utilization of the MBTA in cases where pollution killed migratory birds without the intent or even the knowledge of the actors. In the first of these cases, *United States vs. FMC*, 572 F 2d 902 (2d Cir. 1978), a pesticide manufacturer was charged with violations of the MBTA for bird deaths from carbofuran residue in a holding pond. The court's instruction to the jury included a reminder that awareness of wrongdoing and the intent to kill the birds were not elements of the offense, and if they found that the birds were killed by products eliminated by the FMC plant, they had to return a guilty verdict. The strict liability construction probably will be limited by a cost-benefit balancing or a direct causation requirement. Even if this should happen, however, the FMC case will be a valuable precedent. In *United States vs. Corbin Farm Service*, 444 F. Supp. 510 (E.D. Cal. 1978), affirmed in part 578 F 2d 259 (9th Cir. 1978), the defendants were charged with the death of approximately 1,100 American widgeon (*Mareca americana*) as a result of spraying FURADAN 4 on an alfalfa field. These cases indicate that if migratory waterfowl will be harmed, degradation resulting from construction and channelization projects could be a violation of the MBTA.

PROPERTY CLAUSE

This new dimension to the MBTA provides an additional means to accomplish FWS objectives in the coastal zone. Another old favorite, the Property Clause, U.S.C.A. Const. Art. 4, S3, Cl, 2, has recently gained greater efficacy in providing protection to Federal projects. The Supreme Court examined the scope of the Property Clause in *Kleppe vs. New Mexico*, 426 U.S. 529, 96 S. CT. 2285, 29 L.Ed. 2d 34 (1976). The court in *Kleppe* held that a State agency acting in accordance with a New Mexico law could be prevented from removing wild burros from Federal lands in light of proper exercise of congressional power under the Property Clause. This line of reasoning was taken a step further in *U.S. vs. Brown* (522 F. 2d 817, 1977) where the court found that the Property Clause permits Congress to enact legislation protecting Federal lands from "spillover" effects from activities occurring on nonfederal public lands or waters. State laws allowing hunting on waters within a National Park were overridden under the Supremacy Clause by Federal regulations protecting wildlife and visitors on the land. If other courts agree with the *Brown* reasoning, it is possible that activities on public areas adjacent to refuges in the coastal zone can be prohibited if they have an adverse effect on the purposes for which the Federal land is held.

COASTAL ZONE MANAGEMENT PROBLEMS

Continual conflict in the coastal zone is due to a question which arises with some frequency: "Who owns the marshes and beach areas?". The answer is difficult not only because State laws vary, but because there are three discrete portions of the area known generally as the "beach". The area between mean high tide and mean low tide is usually referred to as the foreshore. The beginning of vegetation denotes the dune line, and beyond that are the uplands. The majority of coastal States do not allow private ownership of the foreshore, holding that area in trust for the use of the general public. Although public use once was defined in terms of fishing and rights of navigation, recent decisions include recreational activities as an important element of that use. The dry sand area which is upbeach of the foreshore is subject to private ownership in most States; this creates the problem of beach access. Only when public roads are constructed through the two tiers of privately owned beach can potential users approach the public use area without trespass.

Each state dictates whether its beaches can be reached by the public, either through laws allowing ownership of every beach segment or by constructing means of entry to the public areas through privately owned lands. The Federal government has a minimal impact on beach access; it can acquire the foreshore from the State or private owners and create recreation areas, or acquire property landward of the dune line and use the Property Clause to provide a basis for controlling activity on the foreshore. The Coastal Zone Management Act (CZMA) now offers grants to coastal States to acquire lands "to provide access to public beaches and other public coastal areas of environmental, recreational, historical, aesthetic, ecological, or cultural value, and for the preservation of islands" (CZMA Section 315 [2]).

The problem of administrative responsibility in marshes adjacent to wildlife refuges frustrates project leaders and law enforcement personnel in most coastal areas. Ownership of tidal marshes is controlled by the same laws which prescribe ownership of the foreshore. On refuges in those States which prohibit private ownership of the area from mean high tide to mean low tide, an anomalous situation exists where the Federal government does not own the land, but Federal agents are the only ones there to enforce the law. Violators have questioned the authority of FWS agents to enforce Title 50 regulations on land held in trust for the public. Due to controverted authority, enforcement in marsh areas is a continual vexation; however, the *Browne* and *Kleppe* decisions may be used to facilitate administration of those lands. In ordinary situations, regulations controlling activities on Federal land suffice; however, in critical circumstances, when the regulation is to protect Federal property, the court in *Kleppe* observes that "the Property Clause is broad enough to reach beyond territorial limits" (426 U.S. at 528, 96 S. Ct. At 2291).

COASTAL ZONE MANAGEMENT ACT

Crucial to effective management of resources in the coastal zone is an understanding of the CZMA and the problems it has spawned. Congress enacted the CZMA, 16 U.S.C. §§ 1451-1464 as amended in 1976, in an attempt to encourage preservation and protection of the Nation's coastal zone. Because zoning is historically a function of State police powers, the act includes certain incentives to encourage coastal States to participate in the development and implementation of comprehensive coastal management programs. Although not quite half of the affected States have approved programs, the CMZA still has the potential to affect Federal activities in every State in the coastal zone. In spite of Section 304 (1) of CZMA, which provides that "excluded from the coastal zone are lands the use of which is held in trust by the Federal government, its officers, or agents", activities of Federal agencies must be consistent with State programs. The controversy over the exact meaning of "Federal consistency" rages unabated. State and Federal agencies charged with protecting the coastal zone are finding it difficult to coordinate their efforts.

The CZMA requires Federal activities in the coastal zone to be consistent with approved State plans to the "maximum extent practicable" when those activities affect the resources within that state's designated coastal boundary (CZMA § 307 [c] - [d], 16 U.S.C. § 1456 [c] - [d][1976]). Federal approval of State coastal plans is contingent on the consideration of national interests. In this way, Congress sought to allay Federal agency concerns while allowing States greater authority over Federal activities. A negative Federal agency response resulted from fear that parochial interests expressed in the plans would undermine the success of Federal programs. Consternation increased with the realization that Federal actions taking place outside a State's coastal boundary, which significantly affect resources within the coastal zone, must also be consistent.

Section 307 (c)(1) requires all Federal agencies conducting or supporting activities directly affecting the coastal zone to determine whether those activities are consistent with the State program. Part (c)(3) of the same section, which applies to applicants for Federal permits or licenses, provides for the State to make a consistency determination. Under § 307 (c)(3) no Federal license or permit may be granted until the State has concurred with the applicant's certification. The Department of Commerce interpreted the Section 307 (c)(1) phrase "directly affecting" to mean "significantly" affecting the coastal zone and was challenged by the Justice Department. The National Oceanic and Atmospheric Administration (NOAA) regulations published 25 June 1979, retreated from the position that the effects be significant, and returned to the earlier phrasing of "direct effect". The new regulations do not attempt to define "direct effect" noting that it was the determination of the Justice Department that the plain language of the statute should control, and that the issue is essentially one of fact to be decided on a case by case basis.

A major State-Federal confrontation which resulted from the matter of consistency determination reached a critical stage in May 1979 with negative declarations filed by the Department of the Interior (DOI) with California and Massachusetts in regard to preleasing activities on OCS Lease Sales 48 and 42, respectively. Prelease activities include: 1) call for nominations and comments; 2) tentative tract selection; 3) environmental statements; and 4) consultation with governors. DOI has taken the position that prelease sale activities do not directly affect the resources in the coastal zone. "Directly" is being interpreted as meaning "without intervening cause (DOI letter of 22 June 1979 to Executive Office of Environmental Affairs, Boston, Massachusetts).

The California Coastal Commission notified Secretary Andrus that California has a serious disagreement with Interior's determination that preleasing activities in preparation for OCS Sale 48 do not directly affect the California coastal zone. The filing of a serious disagreement initiates mediation by the Secretary of Commerce (CZMA § 307 [b]). There is no formal arbitration, but merely a forum provided for the parties to work toward a compromise solution rather than having the issues decided by the court. The discord between California and DOI results from an interpretation of the statute, not a conflict over provisions in the State coastal plan; therefore, no solution will be completely satisfactory to both parties. This case is the first to test the meaning of "Federal activities", and will set the groundwork not only for other preleasing actions, but for the many planning activities carried on in preparation for Federal licenses and permits. California's position is that Section 307 (c)(1) and (c)(3) requirements be met; DOI insists that in the presale leasing situation if a negative declaration is made under (c)(1), then the applicant will have to make a consistency determination under (c)(3), and in every case, at least one consistency determination will be made. Mediation by the Secretary of Commerce is scheduled to begin in late September or early October (1979) with little hope given the possibility of an earlier resolution.

STATE COASTAL ZONE MANAGEMENT PROGRAMS

Among the issues causing conflict in the coastal zone are State Coastal Zone Management Program policies, wetlands protection, and approval of local plans. Section 302 requires three broad classes of program policies: resource protection, management of coastal development, and simplification of government processes (CZMA § 302 [h]). Using these broad classes, States must develop specific policies which provide a framework for the implementation of the program. Expressly singled out for policy statements are uses of or impacts on wetlands and floodplains within the coastal zone. These policies must operate to minimize the destruction, loss, or degradation of wetlands and preserve and enhance their natural values in accordance with Presidential Executive Order 11990. Presidential Executive Order 11988 pertaining to floodplains must be implemented through policies which reduce risks of flood loss, mitigate the impact of floods on human safety, health, and welfare, and preserve the natural beneficial values served by floodplains.

The policies formulated by the State planning team must provide (1) a clear understanding of the content of the program, especially in identifying those who will be affected by the program and how, and 2) a clear sense of direction and predictability for decision makers who must take actions pursuant to or consistent with the management program (*Federal Register* Vol. 44, 61, 28 March 1979). Notwithstanding this directive, vague policy statements and ambiguous standards characterize many of the State programs. For example, Alabama's coastal board has produced a creditable plan which is now beginning the final review process; however, the policies lack specificity. The plan makes references to the product of studies which have not been formulated, and as a result, the data needed to support policies in the program are not available. A particularly difficult situation arises with the question of enforcement of these policies. States tend to favor the less menacing "should" to ease their programs past watchful local governments while the Federal agencies reviewing the plan would prefer the stronger "shall". Federal agencies insist that "should" cannot insure the predictability dictated by the statute. The question of what actually will be done in approving and denying permits is too often left unanswered.

Lack of consideration of Executive Orders 11988 and 11990 has resulted in no control over freshwater wetlands within the coastal zone. Without control of "spillover effects", areas affecting migratory waterfowl and the State's designated critical areas are left vulnerable. The Executive Orders are directed toward Federal agencies; however, the argument is made that not only Federal activities are addressed, but also the Federal funding of State projects such as their coastal plans. The DOI, for one, is making every effort to establish the link between freshwater and coastal systems that will require States to expand their protection to include freshwater systems contiguous to coastal wetlands. The statute requires State control over salt marshes and wetlands, but leaves protection of watersheds and riverine systems optional (§ 305 [b][2]). DOI maintains that the wetlands should be treated as a single nonseverable ecosystem and has implored Office of Coastal Zone Management (OCZM) to insure adequate control over the entire system prior to program approval. When the CZMA comes before the legislature in October for reauthorization, DOI will attempt to have this portion of the statute amended to include contiguous freshwater systems within the coastal boundary.

Because Federal actions must be consistent with State coastal programs, CZMA provides for a review of all State plans by affected agencies. Ideally, the Federal agencies and State planning groups should have been working closely long before the Final Environmental Impact Statement (FEIS) is produced. In this way, the Federal agencies can make their interests known and be aware of what will be expected of them under the approved plan. Some States, Alaska and North Carolina among them, are utilizing local plans as the basis for the operation of the State plan. The adoption of these local plans subsequent to State program approval effectively circumvents the Federal review process. Although local plans are not required to be consistent with the State plans, many have been delegated enforcement powers and this can lead to uncertainty and inconsistency. Extreme divergence in local policies may make it impossible for Federal agencies to maintain consistency. DOI has taken the position that these local programs, adopted subsequent to State plan approval, are additional controls and authorities and must go through the formal amendment process.

State coastal planners are in the unenviable position of having to create a plan which satisfies environmentalists and Federal agencies as well as developers and local governments. The unsettled interpretation of Section 307 (f) has caused a problem for the States by polarizing developers and environmentalists. Section 307 (f) reads as follows: "Notwithstanding any other provision of this title, nothing in this title shall in any way affect any requirement (1) established by the Federal Water Pollution Control Act, as amended, or the Clean Air Act, as amended, or (2) established by the Federal Government or by any State or local government pursuant to such Acts. Such requirements shall be incorporated in any program developed pursuant to this title and shall be the water pollution control and air pollution control requirements applicable to such programs."

SECTION 404 OF THE FEDERAL WATER POLLUTION CONTROL ACT

The Environmental Protection Agency (EPA) issued a memorandum in July 1978 which indicates that State planners must incorporate the guidelines in § 404 (b)(1) of the Federal Water Pollution Control Act (FWPCA), 33, U.S.C.A. § 1344, or be ineligible for program approval. The memorandum makes it clear that because an application is consistent with the State program, it does not make it necessary for Federal agencies to issue a permit. Although the State may certify the permit, agencies need not if the request is not in accord with Federal regulations. In May 1979 the Solicitor, DOI, issued a memorandum consistent with the EPA position. When the Delaware coastal board presented its FEIS, DOI included in its program comments a statement of this position. Delaware's planners and OCZM had determined that because the portion of the planning document which included implementation of § 404 (b)(1) provisions is the subject of a court action, it would be wise to eliminate that requirement. The condition was found to be too restrictive by a lower court, and is now being interpreted by the State Supreme Court. Although the issue of water quality is still undecided, Delaware's program has been approved.

The CZMA is due for reauthorization in October and the DOI will recommend modification of many sections over which disputes have arisen. These recommendations may not result in the changes DOI finds necessary, and some problems with CZMA may continue. The best method of dealing with these continuing problems is to work with the States, draft Memoranda of Understanding which define each agency's responsibilities, get involved with the planning and implementation of the programs, and, above all, monitor the program carefully. OCZM has not published criteria for evaluation, but a familiarity with the State plan will aid in discerning patterns of noncompliance.

IMPLEMENTATION OF THE FISH AND WILDLIFE COORDINATION ACT

A very important wildlife law, the Fish and Wildlife Coordination Act (FWCA) as it was originally passed in 1934 has been called a "remarkably forward-looking piece of legislation" (The Evolution of National Wildlife Law 1977 page 193). The Act called for the development of wildlife habitat and an investigation into the causes and prevention of water pollution. With only two mandatory provisions, the FWCA turned out to be a fairly toothless little law; it required consultation with the Bureau of Fisheries before construction of any dam, and the availability of impounded waters of any dam "for fish-culture stations and migratory birds resting and nesting areas. . . not inconsistent with the primary use of the waters" (Act of 10 March 1934, Ch. 55, 53[a], 48 Stat. 401). When the amendments made in 1946 did not meet the expectations of the bill's supporters, another attempt to strengthen the law was made in 1958. The result of these two efforts was the requirement that Federal agencies contemplating major water development projects, such as dams and channelization projects, give "full consideration" to the reports and recommendations of the FWS and of State wildlife agencies. Wildlife agencies can recommend that permits, including Corps of Engineers permits issued under § 404 of the FWPCA, be denied for several water-related activities. Unfortunately, the Corps is not required to heed the counsel of the wildlife agencies.

To remedy this situation, President Carter, in July 1978, issued a Water Policy memorandum directing the Secretary of Interior in cooperation with the Secretary of Commerce to promulgate regulations defining the requirements and procedures that must be met for fully complying with the Fish and Wildlife Coordination Act (FWCA)(16 U.S.C.A. §§ 661-667e [1970]). The proposed rules issued 18 May 1979 address the relationship of the FWCA to the National Environmental Policy Act (NEPA), which was contemplated as an amendment to the FWCA when first considered, and to other environmental review requirements. The proposed rules are predicated on the basis that "the FWCA is more than a mere consultative responsibility; it is an affirmative mandate to action agencies, of which consultation with wildlife agencies is only a part." Federal Regulations Volume 44 (98), page 29301, Section 410.21, as proposed, calls for equal consideration of wildlife resource values in project planning. Acting agencies are required to involve wildlife agencies from the beginning of a project. Compliance with the equal consideration mandate requires:

(1) Consultation between action agencies (or applicants to them) and wildlife agencies on measures necessary to conserve wildlife in project planning, construction, and operation;

(2) Reporting by wildlife agencies on the effects of the project and its alternatives upon wildlife resources and on measures recommended to conserve wildlife resources in connection with the project and its alternatives;

(3) Full consideration by the action agencies of measures recommended to conserve wildlife resources, both with regard to the project and its alternatives; and,

(4) Implementation of justifiable conservation measures.

Fortification of the Fish and Wildlife Coordination Act will help eliminate many of the frustrations FWS employees experience in coastal projects. A recent court opinion provides a vivid example. The decision in the case of *The Avoyelles Sportsmen's League Inc. vs. Alexander* (C.A. 78-1428, W.D. la) held that the clearing of wetlands to convert bottomland into farmland is subject to permit under the FWPCA "even where no earth (other than *de minimis*) is moved." The Corps had based its determination that no § 404 permit was necessary by invoking the normal farming or silviculture exemption (§ 404 [f][1][A]) and the fact that no earth (other than *de minimis*) was moved. The court ruled that the clearing of 8,097 ha (20,000 ac) of bottomland to plant soybeans was not the normal farming or silviculture activity contemplated by § 404 (f)(A). The word "normal" was held to connote an established and continuing activity. The court found that the clearing activities fall under § 404 (f)(2) which takes away the exemption for those activities which change the use of the land. Those activities which would be excepted under 404 (f)(1)(A) are denied the exemption if they are part of an effort to convert a wetland area to another use which will reduce the reach, or impair the flow or circulation of, the water. The *de minimis* argument was rejected in this case as an attempt by the Corps to ignore the purposes of the act and apply "engineering and construction methodology and theory to an environmental problem, totally frustrating the purposes of the Clean Water Act" (*Avoyelles* at 17).

CONCLUSION

Until the major issues of responsibility in the coastal zone are settled, Federal-State relations will be difficult. Never will the situation be completely smooth because too many factors - economic and jurisdictional, among others - create tension. Awareness of wildlife laws and current legal trends is an important factor in successfully dealing with State and other Federal agencies.

ADAPTIVE ENVIRONMENTAL ASSESSMENT AND MANAGEMENT:

AN OVERVIEW

Carroll L. Cordes[1]

INTRODUCTION

Coastal resource managers and others concerned with protecting fish and wildlife and their habitats are primarily involved in the environmental assessment process in a reactive review role. The tendency is to object to development in general and to hold out for an environmental *status quo* whenever possible. Such a posture is not unexpected since planned developments are primarily designed within an economic context and rarely include a thorough consideration of environmental uncertainties. What often results are confrontations among representatives of various interest groups, most of whom had no opportunity to participate in the original project design. Subsequent attempts to modify a project are almost always strongly opposed, and conflict resolution is rarely achieved. Thus, many projects offering legitimate social benefits are delayed and unique opportunities for enhancing natural resources are lost.

These problems largely result because contemporary methods for evaluating effects of planned projects or management policies on environmental resources are inappropriate. It is clear that new approaches must be developed and implemented if environmental amenities and values are to appropriately be considered in public decisions. One such approach is that of "adaptive environmental assessment and management" described by Holling (1978).

CONCEPT OF ADAPTIVE ASSESSMENT AND MANAGEMENT

The concept of adaptive assessment and management is built upon four basic properties which determine how ecosystems respond to change (Holling 1978). The first is that system components are interlinked in a selective way; each part is not intimately connected to every other part. Therefore, in conducting an environmental assessment study, it is not necessary to measure everything. Qualitative measures of structural features (who connects to whom), for example, are considered to be more important than measures of

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population size for a long list of species. The method of adaptive assessment additionally puts emphasis on identifying those parts of the system which are sensitive to change or management and those which are not. The identification of sensitive components is aided by the process of model building and testing which are essential ingredients in the adaptive assessment methodologies.

The second property is that ecosystems are composed of a mosaic of interlocked spatial elements that differ in their biophysical characteristics. It is this spatial diversity that makes it difficult to project where environmental impacts will occur and how intense they will be. Although the degree of spatial heterogeneity will differ from one system to another, it is not safe to assume that impacts will be gradually diminished over space. In many cases it is difficult to relate impacts and problems to the location of a development. For example, while the local environmental impacts of a pipeline project can be identified, the induced effect of the invasion of capital and of construction workers on communities remote from the pipeline site can have dramatic social consequences that cause unexpected impacts greater than the pipeline itself.

Ecosystems have more than one stability region and the change from one equilibrium phase to another occurs suddenly. This third property stresses that sharp shifts in behavior are natural for ecosystems and implies that removal of a disturbance or project impact does not guarantee a system will return to its original predisturbance condition. A variety of field studies have clearly demonstrated this multiequilibrium property (Glendening 1952; Niering and Goodwin 1974; Bazykin 1975; Jones 1975).

The final property supporting the concept of adaptive assessment and management is that ecosystems are not static but are in a state of continual change. Some changes result from internal processes or mechanisms (*e.g.* competition) while others are caused by outside events (*e.g.* floods and fires). These dynamic changes contribute to the structure, diversity, and resilience of ecological systems. Thus, any management policy or development which aims to reduce system variability can lead to the gradual loss of system resilience through relaxation of selection pressure. The adaptive approach to environmental assessment recognizes that environmental quality is not necessarily achieved by eliminating change.

A central theme of the adaptive approach is that the future is uncertain. For environmental assessment this means the unexpected can be expected. It is impossible, and not even necessary, to measure everything in an assessment study; and the unmeasured variables or components which are also affected by man's activities will produce unexpected changes in those that are being examined. Further, since most or all project impacts are consequences of disturbances not previously experienced by the natural system, observations made prior to project construction or completion cannot reveal what these impacts may eventually be. Thus, environmental assessments cannot be predictions in any real sense. The philosophy of the adaptive approach is that environmental assessment should be an ongoing investigation, not a one-time prediction, of impacts.

PROCEDURES AND TECHNIQUES

The methodology of adaptive assessment and management is organized around a series of structured workshops designed to systematically analyze a resource management problem or proposed development project. Workshop participants include key individuals and decision-makers associated with the proposed plan or project, subject area specialists (*e.g.* ecologists, wildlife managers, fishery biologists, hydrologists, economists) and a core group of two or three analysts and one or two supportive staff members. The core group is responsible for coordinating the workshops and insuring that the project representatives, specialists, managers, and decision-makers are all involved in the problem analysis and evaluation.

Workshops are held in some neutral location where everyone is removed from normal responsibilities and work pressures. The duration of a workshop is typically five days, in order to keep everyone focused on the problem.

The first workshop is the most important, because it is then that the problem is clearly identified, focused, and bounded. All the "key players" are present and a concerted effort is made to classify impacts, define crucial information needs, describe alternative actions, and develop the framework and crude working version of a model--usually a computer-simulation model. The core group handles the mechanics of model building and insures that all steps in the process are clearly understood by the workshop participants. Thus, at the very beginning of the study or project evaluation, all of the key interest groups are represented and all of the study or evaluation elements are jointly considered and integrated. The model constructed during the first workshop represents the collective thinking of the whole group and provides a perspective which allows conflicting interest groups to look beyond their own concerns. Even this first draft model is a powerful tool for exploring the significance of unknown relationships, evaluating the ecological or socioeconomic implications of different management scenarios or project alternatives, and for identifying specific areas for additional research and data collection.

The first workshop is followed by a period of consolidation. The core group refines and tests the model, while the other participants gather those additional data which the initial model explorations indicated were crucial. Subsequent workshops are held to further define management or project objectives, construct alternative operational policies, and explore environmental uncertainties. Some of these subsequent workshops may largely involve scientists when the goal is critical review of underlying assumptions. Others will involve mostly managers when the issue concerns operational feasibility. And when the purpose is to insure relevance and understanding, some workshops will involve only decision-makers. In every case a period of consolidation follows the workshop. The number of workshops held and the time interval between each will largely depend on the nature of the problem at hand, the availability of pertinent information and the time frame for decision-making.

Communication is given high priority in the adaptive assessment and management process, wherein each user determines the level of detail most appropriate for his needs. Emphasis is placed on having dialogue between developers and resource managers continue throughout the development process. The goal is to design projects or management strategies with enough adaptive flexibility to benefit from information feedback and to make the best use of the environment.

USE OF THE ADAPTIVE APPROACH IN THE U.S. FISH AND WILDLIFE SERVICE

The U.S. Fish and Wildlife Service has established an adaptive assessment core group in Ft. Collins, Colorado, as part of the Western Energy and Land Use Team (Office of Biological Services). The group is responsible for applying and evaluating the methodologies of adaptive assessment in relation to Service resource problems. Two applications of the adaptive approach have been completed. The approach was used to evaluate resource policies and to develop a master plan and environmental impact document for the Charles M. Russell National Wildlife Range in Montana. The second application involved use of adaptive methodologies in identifying those water-related problems most affecting fish and wildlife resources in the Sacramento-San Joaquin River systems. In both cases the adaptive approach was considered to be a viable alternative to traditional assessment techniques.

CONCLUSIONS

The methodologies of adaptive environmental assessment and management insure that environmental dimensions are integrated as equal elements with economic and social considerations at the very beginning of the development or management design process. Alternative management policies and development plans are generated in an atmosphere of open communication between developers and resource managers and each alternative is collectively assessed for its environmental, economic, and social consequences. Flexibility is encouraged in project designs and management strategies so they may be adapted to unexpected ecological events and adjusted to benefit from information feedback throughout the development process.

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ECOLOGICAL VALUES OF SELECTED COASTAL HABITATS

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INTRODUCTION

Nearshore coastal waters make up less than 1% of the world's oceans yet it is in this fringe that are found the most productive ecosystems in the world. Estuaries producing at their minimum rate per acre still equal the most productive agricultural areas. At a maximum rate, an estuary can outproduce agricultural land by a factor of two. There is no doubt that the coastal zone contains the most valuable and diverse grouping of natural resources in many states.

The pressure imposed by rapid industrial and population growth in these states demands intelligent control and management of coastal regions. Knowledge of the functions and ecological values of these nearshore ecosystems is essential for decision makers to properly manage them, while maintaining conditions for the continued productive uses of coastal resources.

This paper outlines the ecological values ascribed to selected coastal habitats of the south Texas coast. Not all categories of coastal ecosystems can be covered within the scope of this paper. Those included are barrier islands, wind tidal flats and mud flats, wetlands, vegetated tidelands, mangrove swamps, and seagrass systems. While each habitat is dealt with separately, one must keep in mind that no single part of a coastal ecosystem operates independently of any other. Each coastal ecosystem should be understood with respect to the functioning of its parts and the unity of its whole as well as the interrelatedness to other habitats in the overall coastal zone.

BARRIER ISLANDS

Barrier islands are mobile features--they constantly move and change shape in response to changes in tidal level, currents, sediment supply and storms. Padre and Mustang Islands are part of a chain of barrier islands that stretch 200 mi (321.8 km) along the Texas coast from the Brazos River to the Rio Grande. The chain of islands is broken intermittently by passes both natural and artificial. These natural passes occur in areas of higher tidal range and where large rivers empty into bays and estuaries sufficient to maintain an open pass.

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Important in the shaping of land forms and transporting of sand, along Padre and Mustang Islands, is the role of the wind. Winds are strong and predominantly onshore, with a yearly average of 6 mph from the east-southeast.

Hurricanes are another agent acting on the Texas barrier chain. During surges of high water, both before and after the storm passage, low parts of the islands are washed over. Passes cut by hurricanes usually close by sand deposition within a short time, but the washover areas remain low and are commonly reopened by subsequent storms.

Dating shells along the Texas coast indicates that the barrier islands have been growing for about 5,000 yr. Some parts of the barrier chain (Matagorda and San Jose Islands) have been prograding seaward whereas some have remained stationary (Mustang Island and northern Padre Island), while others are moving landward by erosion (south Padre Island). Shoreline erosion of 1,000 ft (0.34 km) in less than 100 yr can be documented in South Padre Island.

The principal sources for nearshore sediment are rivers, particularly the Mississippi and secondarily the Rio Grande, which transport sand directly into the Gulf of Mexico. Sand is moved along the coast by currents, wave action and wind. Beach sand is also moved onshore and offshore by the actions of waves, tides, and currents.

In high energy waves during hurricanes and severe storms, sand is eroded from the beach and deposited offshore in submerged sand bars. During periods of calmer weather low energy waves gradually move sand from the sand bars and deposit it back on the beaches. Under normal conditions the beach is made of a nearly flat backshore, which after its full development is above normal wave activity, and a sloping foreshore washed daily by waves.

Along most of the barrier islands landward of the beach is a ridge of vegetated dunes. Dunes are composed of windblown sand from the beach. The sand is deposited towards the top of the beach and a foredune gradually forms. They become higher and wider as additions of sand continue. Foredunes form where vegetation and other obstacles such as drift lines and debris cause deposition of windblown sand. The vegetation is an important factor in determining the size, shape, and stability of the foredunes. The leaves and stems of the plants obstruct the wind and reduce the velocity needed for sand transport. The sand then deposits around the vegetation. These pioneer plants, such as the railroad vine (*Ipomoea pes-caprae*) and sea oats (*Uniola paniculatum*) are able to produce stems and roots in response to being covered by sand and grow more rapidly than the rate of sand deposition. Those plants without this ability will not facilitate sandbinding and the sand movement continues.

Where foredunes have been cut back by wave action leaving an unvegetated dune of loose sand, strong onshore winds may initiate a blowout formation. Blowouts may also develop where stabilizing vegetation has been damaged or destroyed by natural causes (drought or fire) or by human interference (grazing, clearing or heavy pedestrian or vehicular traffic). Unless the gaps in the foredune system are repaired by sand accumulations colonized by stabilizing vegetation, the blowouts increase in size and migrate inland under the influence of the prevailing winds.

The low areas left behind migrating dune fields, the deflation flats, are the expansive grasslands that make up the majority of the interior of the barrier islands. They are marked by a series of low ridges, small dunes, and troughs. While frontal dunes remain fluid, the back dunes become stabilized and rather permanent features.

The bay margin of the barrier island is marked by wind tidal flats, which are occasionally covered by the waters of Corpus Christi Bay and Laguna Madre. In other areas on the estuarine side the barrier islands support marshes and mangrove swamps which provide essential habitat for many forms of life and supply basic nutrients to coastal ecosystems.

The stable ecology of a barrier island depends on the maintenance and perpetuation of a dune system. The entire barrier island, as described above, forms a protective barrier for the Texas coast which was recently made more apparent by the IXTOC I well blowout in the Gulf of Mexico.

- The dunes are the frontal defense against the forces of wind and waves as well as the means by which the islands move and grow. Foredunes act as barriers against the action of waves and tides and are a source of sand for the beach during periods of erosion. Vegetated foredunes are inherently flexible. If part of a dune is damaged by storm waves, the remaining vegetation traps sand blown from the beach and the dune is reformed, thus rebuilding protection against future wave attacks.

- The dune vegetation traps windblown sand, anchors sand already in the dunes, acts as a buffer against wind erosion, and helps maintain dune stability.

- The foredunes protect areas behind them from wave damage and salt water intrusion during storms.

- Barrier islands prevent windblown sand from filling vegetated flats in adjacent lagoons, estuaries and bays, and their presence helps insure the perpetuation of the highly productive estuaries on their landward sides.

- Barrier islands provide unique habitat for flora and fauna and host unique wildlife, some species and subspecies of which are endemic to barrier islands, and, in particular, south Texas barrier islands.

For a review of the physical forces shaping the barrier islands of north and central Padre Island, Texas, see Hunter *et al.* (1972). Clark (1974) and Clark *et al.* (1977) discuss the ecology and ecological values of barrier islands.

WIND TIDAL FLATS AND MUD FLATS

On the bayward and lagoonal sides of barrier island chains and in shallow water areas associated with *Spartina alterniflora* marshes or mangrove swamps, wind tidal flats and mud flats are present. These areas are situated below mean low tide, where water only intermittently covers the land, and are exposed on low range tides as unvegetated expanses of mud or sand (Clark 1974). These areas are subject to extremes in salinity and temperature, both air and water.

Fluctuations in these systems are influenced primarily by winds. During the summer, in south Texas, the prevailing onshore winds generate a current flowing to the north, driving water off the wind tidal flats and lowering the lagoon water level. In the winter, the winds predominate from the north causing a strong current to the south raising water levels in the lagoon and inundating the wind tidal flats (Mathewson *et al.* 1975).

Wind tidal flats and mud flats are often unappreciated because their values are not visible (Clark 1974). Deevey (1970) argued that mud, the essential habitat of essential microorganisms, is just as important as water to the economy of the planet. Since mud is an integral part of coastal ecosystems, the following ecological values ascribed to muddy sediments in tidal flats pertain as well to estuarine sediments of marshes and swamps.

- Muds perform roles in the global cycles of nitrogen and sulfur. There is impressive evidence for the importance of coastal anaerobic muds to the continued normal functioning of nitrogen and sulfur (Gosselink *et al.* 1974). Completion of the cycles requires microbial action in a reducing environment. Certain microbial forms containing the enzyme hydrogenase, the essential catalyst of interconversion, occur only in muddy environments that are lacking in free oxygen (Deevey 1970).

The sediments of mud flats, wind tidal flats, and tidal marshes are ideally suited for this function. Tidal waters carry nutrients along with dissolved particulate matter to the sediment surface where they diffuse through a thin layer of oxidized sediment to the anaerobic zone below. Nitrogen of biological origin is oxidized to nitrate in the oxidized layer, diffuses into the reduced zone, and is reduced to nitrogen, eventually escaping to the atmosphere. Flooded marshes appear to be uniquely adapted for denitrification and may also be extremely valuable for treatment of inorganic nitrogen wastes (Gosselink *et al.* 1974). Studies in flooded swamp and marsh soils (Patrick *et al.* 1971) have shown substantial loss of inorganic nitrogen by denitrification in the anaerobic zone. The sulfur cycle, in the same way, depends on the reduction of sulfate in anaerobic muds to sulfur and sulfides. The perpetuation of organic compounds as renewable resources depends on the performance of microorganisms in oxidation-reduction cycles than link air, water, and mud (Deevey 1970).

- Estuarine sediments have a large capacity to buffer nutrient changes and the associated ecosystems have evolved adaptations to high nutrient levels

(Gosselink *et al.* 1974). Nutrient rich effluents entering a marsh are effectively trapped by tidal circulation (Bowden 1967) and eventually assimilated into the productive biological system. Pomeroy *et al.* (1972) have shown that the phosphate recycling system is so large and homeostatic in Georgia estuaries and marsh sediments that the level of phosphate in those waters varies little throughout the year, despite variations in input. Studies in Louisiana by Ho *et al.* (1970) showed the same patterns. The sediments act as both source and sink, effectively buffering large additions of phosphate to the estuarine system.

- Mud flats and wind tidal flats provide feeding habitats for birds at low tide and fishes at high tide. For example, the red drum (*Sciaenops ocellata*) feeds in shallow marsh areas, moving about with its head lowered and its tail occasionally out of the water (Overstreet and Heard 1978).

- In many estuaries, mud flats and wind tidal flats produce a high yield of shellfishes (Clark 1974), such as eastern oysters (*Crassostrea virginica*), quahog clam (*Mercenaria campechiensis*), and razor clam (*Solen viridis*).

WETLANDS

The definition of "wetlands" in the U.S. Fish and Wildlife Service, October 1977 Draft "Classification of Wetlands and Deep-Water Habitats of the United States" includes those areas periodically inundated by tides or potentially inundated by tides. This general definition includes two categories distinguished by Clark (1974) as true wetlands--those higher areas above main high tide but below the yearly high storm mark; and the vegetated tidelands--the area between mean high tide and mean low tide.

The ecological values of wetlands were summarized by Clark (1974) and are listed briefly as follows:

- Wetlands cleanse runoff water and regulate its flow into estuaries, serving as a buffer between fresh and saline waters. (This role may be of major importance.)

- Wetlands absorb storm waters and help reduce coastal flooding to a degree. (This role may also be of major importance.)

- They take up, convert, and store basic nutrients to the coastal ecosystem. (This value generally lower than the vegetated tidelands.)

- They provide essential habitat for certain coastal birds and animals. (This value is also generally lower than vegetated tidelands.)

VEGETATED TIDELANDS

Vegetated tidelands, areas between mean high tide and mean low tide, include a wide range of salt tolerant plants, the most prominent of which are grasses, mangroves, and rushes. It is difficult and unreasonable to distinguish ecological values for selected types of vegetative tidelands. Numerous functions are performed and shared by different habitat types. The ecological values listed in this section are pertinent to most coastal vegetated tidelands, but more specifically to *Spartina alterniflora* marshes which have been studied most extensively. (Specifics of mangrove swamps will be detailed in the following section.)

- Vegetated tidelands are the vehicle for storage and transfer of nutrients from upland sources which are partially used and recycled within the tidelands system, but ultimately transported into the coastal waters to provide basic nutrients for the coastal food web system (Clark 1974).

- Marshes and marsh vegetation perform a key role in converting inorganic compounds (nutrients) and sunlight into stored energy of plant tissue (Clark 1974). Many of the real values of the marshes are not recognized or accrue some distance from the marsh itself (Gosselink *et al.* 1974). Teal (1962) estimated that 45% of the net primary production of a Georgia *Spartina alterniflora* marsh was flushed into the adjacent bay by tidal action. Odum and de la Cruz (1967) estimated that the net export of organic matter from 62 ac (25.2 ha) of such marsh was 100 lb (45 kg) and 310 lb (140 kg) on a neap and spring tidal cycle, respectively. Stove *et al.* (1971) estimated that well over one half of the total production of organic matter in a Gulf coast estuary originated from the surrounding marshes. In this way coastal marshes and other shallow water production areas (reefs, seaweed, and seagrass beds) all over the world export mineral and organic nutrients that support much of the production of the adjacent estuarine and coastal waters (E. P. Odum 1971). For a listing of references concerning marsh productivity see U.S. Fish and Wildlife Service (1977).

A study of primary production in a *Spartina alterniflora* marsh of interest to the south Texas area because of nearly subtropical conditions and low tidal energy, which distinguish Gulf coast marshes from Atlantic coast marshes, was that done by Kirby and Gosselink (1976) in Louisiana. Tides were approximately 25 h in periodicity and 50 cm (19.7 in)in amplitude. The water levels in the bay were strongly influenced by winds--high in spring and summer when southerly winds predominated and low in winter when northerly winds occurred. Total biomass remained relatively constant although proportions of live and dead plant material varied throughout the year. Living material increased through spring to a peak in September followed by a rapid death of above ground portions to minimum standing crop in December. There was considerably more dead (standing or attached) vegetation than live on the marsh throughout the year except in late summer. In early spring, rising temperatures and high waters resulted in increased consumer activity and strong flushing of the marsh surface. Detritus carried from the marsh by flooding tides accumulated along banks in April and May. From qualitative observations, it was concluded that large amounts of detritus were exported from the marsh into adjacent bay waters. De la Cruz (1973) estimated a net export of 340 g m^{-2} yr^{-1} of particulate organic matter which was 21% of the net production estimated by Smalley (1959) for that marsh. De la Cruz did not estimate dissolved organics which Odum *et al.* (1972) reported as much as 25% of the dry weight of vegetation which can be leached from the plant tissues during the first few days after plant death. Kirby and Gosselink (1976) estimated an export of 70% of the net production from the streamside marsh they studied and noted an increase in production with decreasing latitude. Based on percent coverage from infrared aerial photographs, they estimated a production for Louisiana Gulf coast salt marshes as 1,176 g m^{-2} yr^{-1}.

● The productive vegetation of tidal marshes provides the foundation for the estuarine detrital-based food web. When dead leaves and stems enter water and are broken down by bacteria, they leave the storage component of the energy cycle and as small particles of organic detritus become food of fiddler crabs, worms, snails, mussels, and myriads of larval stages of fish and shellfish of estuarine waters. Once detritus enters the estuary, it rapidly loses its identity due to breakdown by physical forces and microorganisms, perhaps enhanced by the activities of larger animals (Welsh 1973). A variety of estuarine organisms, including some species of fish (de la Cruz 1965; Odum 1970; Wass and Wright 1969) have been found to use detritus as food or at least be a potential user (Darnell 1967; Frankenburg and Smith 1967; Jorgensen 1966; Qasim and Sankaranarayanan 1972; Teal 1962). Copepods use the microorganisms on detrital particles as food (Heinle *et al.* 1974) and there is evidence for a food chain involving detritus, copepods, mysids, and striped bass (*Morone saxatilis*) larvae.

A study by Heinle *et al.* (1977) provided evidence to support the hypothesis that detritus is rapidly incorporated into higher trophic levels. Seasonal pulsing of flows from tidal marshes resulted in similarly pulsed production of zooplankton in some estuaries. The timing of the production of copepods based on a detrital food source was such that year-to-year variations in amount may have been an important factor in the survival of anadromous fish larvae. Contributions by marshes to the pool of organic material available for consumption by organisms have been measured all along the Atlantic coast. Earlier studies suggested a substantial part of the annual production of marsh grasses was exported to adjacent estuaries (Teal 1962; de la Cruz 1965; Williams 1966). More recent measures on a poorly flooded tidal marsh suggest little export of organic matter from some marshes, while others scoured by ice and storms contribute all of their standing crop to the estuary (Heinle and Flemmer 1976).

The importance of detrital material was pointed out as one of the factors for a reduced abundance of macroinvertebrates in a comparative study of a *Spartina alterniflora* marsh, an open bay area, and an area in which intertidal vegetation was permanently eliminated by alteration of the natural area for development. Five species (*Penaeus aztecus, P. setiferus, P. duorarum, Palaemonetes* sp. and *Callinectes sapidus*) were more abundant in the marsh area than in the upland canal area (Trent *et al.* 1976).

- Tidal vegetation and the creeks interconnecting the marsh system provide habitat for feeding, spawning, or protection. It is well-documented and now generally recognized that marshes serve as nursery grounds for commercially important fishes and shellfishes (Gosselink *et al.* 1974). McHugh (1966) estimates that two-thirds of the cash value of species harvested on the Atlantic and Gulf coasts are "estuarine dependent". Many fishes feed in the shallow marsh areas, for example, the red drum, *Sciaenops ocellata* in the northern Gulf of Mexico (Overstreet and Heard 1978). Some species (*e.g.* blue crab, *Callinectes sapidus*; juvenile shrimp, *Penaeus* spp.; finfishes) move in and out of the marsh actively while others (*e.g.* copepods, larval fish and invertebrates) are passively carried in and out with the tides. The marsh vegetation and creeks provide habitat for these species. In a study of an altered natural area for a canal development, the permanent elimination of intertidal vegetation was cited as one of the factors as accounting for a reduced abundance in shrimp (*Penaeus aztecus*, *P. setiferus*, *P. duorarum*, and *Palaemonetes pugio*) and blue crab (Trent *et al.* 1976). Marshes are generally recognized as important habitats for migratory birds. For example, almost the entire North American population of the snow goose and blue goose (both same species *Chen caerulescens*) are dependent on the marshes of the Texas and Louisiana coasts for their wintering grounds (Gosselink *et al.* 1974).

- Vegetated tidelands remove toxic material and excess nutrients from estuarine waters (Clark 1974). Marshes have the capacity to treat run-off waters and possibly under controlled conditions pretreated effluents may be polished within them (Gosselink *et al.* 1974). A marsh of 1,000 ac (404.7 ha) may be capable of purifying nitrogenous wastes of a town of 20,000 or more people (Clark 1974). An important contribution by estuaries and marshes in waste treatment is tertiary treatment to remove and recycle inorganic nutrients. Untreated organic wastes (secondary treatment), however, greatly stresses any natural aquatic system but especially marshlands (Gosselink *et al.* 1974). Although vegetated tidelands can assimilate a reasonable amount of contaminants, they do have a limit and so must be protected from gross pollution from both land runoff and estuarine sources, in particular, from oil and toxic substances (Clark 1974). The vitality of a marsh or swamp depends on the quality and quantity of freshwater inflows that it receives from drainage of adjacent shores. The pattern of drainage from land, as well as the system of creeks that removes water from the marshes and the existing pattern of tidal flushing, should be preserved in an unaltered way for optimal ecosystem conditions (Clark 1974). Eutrophic conditions in upland canals combined with inadequate water exchange and high nutrient levels contributed to the lower abundance of shrimp and crabs (Trent *et al.* 1976) contrasted to natural *Spartina alterniflora* marshes in West Bay, Galveston, Texas.

- The sediments of vegetated tidelands serve roles in the global cycles of nitrogen and sulfur as discussed in the section on wind tidal flats and mud flats.

- Sediment and other inert suspended materials are mechanically and chemically removed from the water and deposited in the marsh or swamp. The intertidal vegetation thus reduces sedimentation of channels or shellfish beds and serves to stabilize shorelines and prevent erosion.

- Vegetated tidelands form an important buffer against storms. They absorb the enormous energy of storm waves and act as a reservoir for coastal storm waters, thus reducing damage further inland as well as the severity of flooding (Clark 1974; Gosselink *et al.* 1974).

MANGROVE SWAMPS

Mangrove swamps, another marsh type habitat, are more specifically defined vegetated tidelands. Much of the information from the preceding section of vegetated tidelands is equally applicable to mangrove swamps with differences in basic vegetative types. Also, many mangrove swamps of the south Texas coast are fringed with dense stands of *Spartina alterniflora* and the distinctions between the two habitat types, as well as their ecological values, are difficult to delineate.

Most of the literature concerning mangrove swamps is derived from studies in tropical areas, and, in particular, Florida. Black mangrove (*Avicennia germinans*) occurs sporadically in the northern Gulf of Mexico in Texas and Florida and along with other species of mangrove forms extensive swamps in the Florida Everglades and Florida Keys. Along the south Texas coast, black mangrove forms extensive swamps on Harbor Island in Redfish Bay but also occurs in scattered locations in Corpus Christi and Aransas Bays and in the Upper and Lower Laguna Madre.

Information detailing the ecological processes of south Texas mangrove swamps is minimal. Although the following ecological values of mangrove systems were obtained from literature pertaining primarily to Florida mangrove swamps, the basic processes are assumed to be applicable.

- Mangroves are well-known for their land building characteristics (Davis 1940; Savage 1972a; Clark 1974; and Hanlon *et al.* 1975). The red and black mangrove root systems and their associated biota act to capture, accumulate and stabilize sediments suspended in the intertidal waters. Through a series of successional stages, red and black mangroves are replaced by a new flora composed of salt-loving shrubs and herbs which rarely experience inundation by salt water. This dynamic process often loses ground to natural events such as hurricanes and freezes. Man-made disturbances can also change the course of this process either by direct destruction (*i.e.* dredging and filling) or indirectly by interrupting the supply of suspended material which is the basis of this landbuilding process.

The black mangrove holds greatest promise for a program of shoreline stabilization because of its broad latitudinal range, tolerance of adverse soil conditions, extensive early root system, and ease of transplanting (Savage 1972b). *Avicennia* can survive some inundation of pumped materials by sprouting and is known to have recovered from extensive hurricane and freeze damage (Savage 1972b).

- Another major function of mangrove swamps is the transport of energy made available to the estuary and its inhabitants in the form of leaves and twigs which are degraded by organisms. This process has been investigated in the red mangrove (Heald 1971; W. E. Odum 1971), and there is every reason to believe that *Avicennia* leaves also serve as "energy transport" mechanisms (Savage 1972a). The fallen leaves of the mangroves collect between the roots and begin to decompose. In the system studied, 95% of the annual mangrove leaf production eventually entered the aquatic system. Decomposition was accomplished by bacteria and fungi, which produce detritus. The detritus of mangrove origin accounted for 35 to 60% of the suspended material in estuarine waters. Most of the other detrital material was derived from the seagrasses. Detritus and detritus-associated microorganisms serve as the basis of the estuarine food web. Small invertebrates, nematodes, crabs, and shrimp feed on the detritus and in turn are eaten by larger predators including commercial and game fish.

- Definitive studies have outlined the role of mangrove swamps to commercial and sports fisheries (Heald and Odum 1969; Heald 1971; W. E. Odum 1971). The commercial shrimp of the Dry Tortugas are dependent on the mangroves as a nursery ground (Idyll 1965; Kutkuhn 1966; Idyll *et al.* 1968; Sastrakusumah 1971). Other commercially valuable species rely on mangrove swamps as a nursery and feeding ground--striped mullet (*Mugil cephalus*), gray snapper (*Lutjanus griseus*), red drum (*Sciaenops ocellata*), blue crab (*Callinectes sapidus*), tarpon (*Megalops atlantica*), snook (*Centropmus undecimalis*) and spotted seatrout (*Cynoscion nebulosus*) (Heald and Odum 1969; Snedaker and Lugo 1973).

- Mangrove swamps provide refuge for countless land and water animals, including migratory birds (Hanlon *et al.* 1975).

- Mangroves protect coastlines against the force of storms (tropical depressions and hurricanes) and act as a natural barrier to erosion (Hanlon *et al.* 1975).

SEAGRASS SYSTEMS

In shallow bay waters at depths 1 to 5 ft (30.5 to 152 cm) extensive colonies of submerged seagrass beds occur. These seagrass systems are strongly influenced by tides, salinity, water temperature, wave action, and water turbidity. They prosper in quiet, protected waters of healthy estuaries. The five seagrass species found on the Texas coast are turtlegrass (*Thalassia testudinum*), widgeon grass (*Ruppia maritima*), shoalgrass (*Halodule wrightii*), manatee grass (*Syringodium filiforme*), and clover grass (*Halophila engelmannii*). The seagrass systems of the south Texas coast are perhaps the most extensively studied of the coastal ecosystems in the area (Moore 1963; Odum 1963; McMillan and Moseley 1967; Seagle 1969a and 1969b; Zimmerman 1969; Rickner 1975; Edwards 1976; Merkord 1978). General reviews of seagrasses and research on seagrass systems are available in den Hartog (1970), Zieman (1970), McRoy (1973), Phillips (1974, 1978), and Thayer *et al.* (1975).

- Seagrasses are widely distributed in coastal areas and are one of the most productive shallow-water ecosystems in the sea (McRoy and McMillan 1977; Thayer *et al.* 1975; Phillips 1978). The high productivity of the seagrass habitat and the prominent role of the grass itself has been shown by Odum (1957), Odum *et al.* (1959), Phillips (1960), and Jones (1968). Wetzel (1964) and Jones (1968) found that benthic plants normally contribute more to inshore productivity than do phytoplankton. Representative values of annual production of *Thalassia* in the Caribbean range from 88 to 4,000 g C m^{-2} and for *Zostera* range from 6 to 1,200 g C m^{-2} (Phillips 1978).

- Seagrasses and components of seagrass systems contribute significantly to the carbon cycle. In addition to providing a substrate for epiphytic floral production, seagrasses excrete a considerable quantity of dissolved organic carbon into the water, which is then available for uptake by other local plants or for export offshore (Phillips 1978).

- A few animals feed directly on marine grasses such as turtles, manatees, a few fishes, and some sea urchins (Hanlon and Voss 1975). Shoalgrass is the principal food item of redhead (*Aythya americana*) and pintail (*Anas acuta*) and supplements the diet of lesser scaup (*Aythya affinis*) in the Laguna Madre, Texas (McMahan 1968). Although only few species feed directly on seagrasses, or on the epiphytes associated with them, seagrass detritus, or more specifically, the microorganisms associated with seagrass decomposition, are considered the most important food source for detritivores in the seagrass-based food web (Fenchel 1977; Tenore 1977; Thayer *et al.* 1975). Although the exact mechanisms of seagrass energy transfer through intermediate consumer levels to commercially important fisheries are not known, studies (Young *et al.* 1975; Young and Young 1977) have shown the importance of small opportunistic benthic studies living in grasses as prey for decapod crustacean predators that are considered "translators" of energy from the macrobenthos to higher level consumers in studies of seagrass beds (Young and Young 1978). Seagrasses are essential elements of the estuarine ecosystem, particularly in systems where marshes are reduced or absent. They provide a substantial amount of primary productivity, and some grass beds are potentially as productive in terms of detrital nutrients as salt marshes.

- Seagrass leaves greatly increase the amount of surface available for the attachment of plants and animals, thus increasing the diversity and productivity of the seagrass beds (Humm 1964; Nagle 1968; Hanlon and Voss 1976) and supplying food to grazing animals (Clark 1974). Comparative productivity studies on oxygen change or ^{14}C uptake measurements have shown that epiphytes can make significant contributions to the total primary productivity of aquatic systems. Penhale (1977) found that the average annual standing crop of eelgrass and its epiphytes was 105.0 g dry wt m^{-2} and approximately 25% of this was epiphytes. Of the average yearly biomass, 23.5% was epiphytes. With primary production rates of 0.27 to 1.80 mg C h^{-1} and from 0.23 to 1.53 mg C (g dry wt)$^{-1}h^{-1}$ for epiphytes, there was no doubt that the epiphytes attached to *Zostera marina* play an important role in the primary production cycle of the seagrass community. Penhale (1977) estimated epiphytes contributed 24% of the yearly biomass and 18% of the total productivity of the seagrass bed.

- Seagrasses provide physical refuge from predation for certain fishes and invertebrates (Carr and Adams 1973; Kikuchi 1974; Hanlon and Voss 1975; Reise 1977) and serve as nursery areas for innumerable important commercial, non-commercial and sports fishes and invertebrates including Florida pompano (*Trachinotus carolinus*), snapper, snook, and spiny lobster (*Panulirus argus*) (Clark 1974; Hanlon and Voss 1975). Simmons (1957) found seagrasses to be important in the Laguna Madre, Texas, serving as spawning grounds and habitat for a large number of organisms. Seagrasses attract a diverse and prolific biota and often create unique opportunities for the existence of certain species (*e.g.* the tiny larval stages of estuarine scallops must attach to grass blades to survive, and the species can exist only where there are grasses; Clark 1974). Seagrass beds also provide feeding habitats. Overstreet and Heard (1978) reported grass beds as an important community in which red drum (*Sciaenops ocellata*), especially preadults, feed.

- Seagrass systems provide wildlife habitat, in particular, wintering areas for waterfowl. Redhead, pintail, and lesser scaup utilize the Laguna Madre, Texas, in large numbers (McMahan 1969). Seventy-eight (78) percent of the entire population of the North American redhead wintered in Laguna Madre in 1951-1954 (Weller 1964).

- The sediments of seagrass systems perform similar functions to those of tidal marshes in nutrient cycling and global cycles of nitrogen, sulfur, and phosphorus. The plants themselves absorb phosphorus, nitrogen, sulfur, and carbon through the roots, and to some extent through the leaves, pumping them into the water where they can be used by epiphytes and phytoplankton. Bacteria absorb nutrients from the water, while acting on the detritus, and enrich it with nitrogen and phosphorus. At the same time the seagrasses excrete dissolved organic carbon into the water column (Phillips 1978).

- Seagrasses trap and stabilize sediment (Burrell and Schubel 1977; Orth 1977; Clark 1974) in which they grow and continue to collect and hold within their root structures the suspended particles that drop out as water slows in passing over the beds. The grass bed itself may collect enough sediment to be significantly elevated toward the surface and therefore toward the source of light (Clark 1974). The rhizomes and roots form dense extensive networks in the substrate which effectually bind the bottom muds and sands together and prohibit or greatly reduce erosion from waves or tidal currents (Hanlon and Voss 1975).

PRICING THE PRICELESS

Studies have been made to estimate the values of natural coastal wetlands. One by Gosselink *et al.* (1974) determined a monetary evaluation based on 1) by-product production (fisheries, etc.); 2) potential for aquaculture development; 3) waste assimilation; and 4) total "life-support" value in terms of the "work of nature" as a function of primary production. All of these were calculated in terms of a) annual return and b) an income-capitalized value. The values in \$/acre determined were :1a) 11; 1b) 2,000; 2a) 1,000; 2b) 20,000; 3a) 2,500; 3b) 50,000; 4a) 4,100; and 4b) 82,000. This methodology has come under severe attack by Shabman and Batie (1977) who pointed out conceptual problems in the "life support" values and the evaluation of direct wetland services citing the lack of comparable market values and improper application of economic principles. Their criticism, however, failed to document how proper economic analysis should be done.

The importance of the above exercise is that economists and planners have finally begun to find ways to deal with the intangible and price the priceless in an attempt to develop guidelines for the maintenance of a high-quality environment. With the acreage of pre-colonial United States wetlands already more than half lost to destruction, prices and ecological values of coastal ecosystems must be seriously considered so that our precious coastal resources and commodities remain productive.

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APPENDIX A

LIST OF WORKSHOP ATTENDEES

Name	Affiliation
Art Anderson	USFWS, Albuquerque, N.M.
Rick Barcelona	USFWS, Albuquerque, N.M.
Michael S. Brim	USFWS, Panama City, Fl.
Elaine Bunce	USFWS, Slidell, La.
Ken Butts	USFWS, Aransas NWR, Tx.
Robert Chabreck	Louisiana State Univ., Baton Rouge, La.
Brian R. Chapman	Corpus Christi State Univ., Corpus Christi, Tx.
Carroll Cordes	USFWS, Slidell, La.
John Day	Louisiana State Univ., Baton Rouge, La.
Judy Dedmon	USFWS, Atlanta Ga.
Armando de la Cruz	Mississippi State Univ., MS.
Joe Ellis	USFWS, Albuquerque, N.M.
R. Warren Flint	UTMSI/PAML, Port Aransas, Tx.
Paul L. Fore	USFWS, Albuquerque, N.M.
Johnny D. French	USFWS, Corpus Christi, Tx.
Nicholas Funicelli	USFWS, Austin, Tx.
Terry Gonzalez	USFWS, Aransas NWR, Tx.
Bill Hawthorne	USFWS, Albuquerque, N.M.
Lewis G. Helm	USFWS, Albuquerque, N.M.
Ronald E. Hood	USFWS, Atlanta, Ga.
Rod Jackson	USFWS, Galveston, Tx.
Carol Justice	USFWS, Albuquerque, N.M.
Joe Kathrein	USFWS, Albuquerque, N.M.
Wayne Kewley	USFWS, Galveston, Tx.
James B. Kirkwood	USFWS, Atlanta, Ga.
Claude Lard	USFWS, Victoria, Tx.
Edward T. LaRoe	Coastal Society, Tallahassee, Fl.
William Longley	General Land Office, Austin, Tx.
Harold Loyacano	USFWS, NSTL, Ms.
John McClain	USFWS, Austin, Tx.
Don Meineke	USFWS, Corpus Christi, Tx.
Carlos Mendoza	USFWS, Galveston, Tx.
Suzanne Nair	USFWS, Washington, D.C.
Jim Neal	USFWS, Albuquerque, N.M.
Floyd Nudi	USFWS, Albuquerque, N.M.
Patrick L. Parker	UTMSI/PAML Port Aransas, Tx.
Roy Perez	USFWS, Corpus Christi, Tx.
Leslie Peterson	USFWS, Brazoria/San Bernard NWR, Tx.
Russ Peterson	USFWS, Galveston, Tx.
Ron Phillips	Seattle Pacific Univ., Seattle, Wa.
Warren Pulich Jr.	UTMSI/PAML, Port Aransas, Tx.
Nancy N. Rabalais	UTMSI/PAML, Port Aransas, Tx.
Charlie Sanchez	USFWS, Albuquerque, N.M.

ATTENDEES (cont.'d)

Name	Affiliation
Bob Schumacher	USFWS, McAllen, Tx.
Glenn Sekavec	USFWS, Albuquerque, N.M.
Wayne A. Shifflett	USFWS, Attwater P.C. NWR, Tx.
Lorna Sicarello	USFWS, Panama City, Fla.
Paul Smith	USFWS, NSTL, Ms.
Sam Spiller	USFWS, Corpus Christi, Tx.
Stephen Talbot	USFWS, Albuquerque, N.M.
Joyce Teerling	USFWS, Lafayette, La.
James Tripp	Environmental Defense Fund, New York, N.Y.
Steve Van Ripper	USFWS, Aransas NWR, Tx.
Lou Villanova	USFWS, Atlanta, Ga.
Paul Vohs	USFWS, Stillwater, Ok.
Dick Wade	USFWS, Atlanta, Ga.
Fred Werner	USFWS, Galveston, Tx.
Donald Wohlschlag	UTMSI/PAML, Port Aransas, Tx.
Jack Woolstenhulme	USFWS, Albuquerque, N.M.
Paul Yakupzack	USFWS, Lafayette, La.
Ken Ystesund	USFWS, Albuquerque, N.M.

APPENDIX B

AGENDA

U.S. FISH AND WILDLIFE SERVICE
GULF OF MEXICO COASTAL ECOSYSTEMS WORKSHOP

4-7 September 1979
University of Texas
Port Aransas Marine Laboratory

TUESDAY, SEPTEMBER 4, 1979

2:00 - 5:00	Registration
5:00 - 7:00	Dinner
7:00 -10:00	Resource Films and Smoker

WEDNESDAY, SEPTEMBER 5, 1979

7:00 - 8:00	Breakfast
8:00 - 8:15	Registration
8:15 - 8:30	Workshop Introduction - Paul L. Fore
8:30 - 9:10	Effects of Impoundments on Coastal Fish and Wildlife Resources Bob Chabreck - Louisiana State University
9:10 - 9:50	Effects of Altered Freshwater Inflow on Estuarine Systems Neal Armstrong - University of Texas at Austin
9:50 -10:30	The Contribution of Wooded Swamps and Bottomland Forests to Estuarine Productivity John Day - Louisiana State University
10:30 -10:45	COFFEE BREAK
10:45 -11:25	Recent Advances in Our Understanding of Marsh Ecology Armando de la Cruz - Mississippi State University
11:25 -12:05	The Role of Sea Grasses in Estuarine Systems Ronald Phillips - Seattle Pacific College

12:30 - 6:30	SACK LUNCH & FIELD TRIPS Field trips - Coastal Ecosystems and Current Environmental Impacts (Choice) a. Estuarine habitats in the vicinity of Port Aransas (seagrass beds, saltmarshes, mangrove swamps)-by boat. b. Barrier island and hypersalinity lagoon (Mustang Island, Padre Island National Seashore and Laguna Madre)-by car.
6:30 - 7:30	Dinner
8:00 -	Mexican oil spill FWS update Jack Woolstenhulme (IXTOC I Oil Spill Coordinator) Charlie Sanchez (Regional Pollution Response Coordinator) Roy Perez (Field Supervisor, Corpus Christi Field Office) Audience Participation and Discussion

THURSDAY, SEPTEMBER 6, 1979

6:30 - 8:00	Coastal Bird Field Trip (Optional)
7:00 - 8:30	Breakfast
8:40 - 9:20	Studies of Freshwater Needs of Fish and Wildlife Resources in Nueces/Corpus Christi Bay, Texas Nicholas Funicelli - Fish and Wildlife, Austin
9:20 -10:00	The Ecology of a Hypersaline Lagoon-The Laguna Madre Warren Pulich - University of Texas, Port Aransas Marine Lab
10:00 -10:15	COFFEE BREAK
10:15 -10:55	Ecology of the Texas Gulf Shelf-Estuarine Implications Warren Flint - University of Texas, Port Aransas Marine Lab
10:55 -11:35	Urban Planning on Barrier Islands Ted LaRoe - Florida Bureau of Coastal Zone Planning
12:00 - 5:30	SACK LUNCH AND FIELD TRIPS Coastal Ecosystems and Related Environmental Impacts Alternate groups from Wednesday

6:00 - 7:30	Dinner
8:00 -	An Overview of Legal Aspects of the Permitting Process James T. Tripp - Environmental Defense Fund, New York

FRIDAY, SEPTEMBER 7, 1979

7:00 - 8:30	Breakfast
8:40 - 9:20	Management of Oil and Gas Operations on the Coast William Longley - Texas General Land Office, Austin Rod Jackson - USFWS - Galveston
9:20 -10:00	State and Federal Regulations and Management of Coastal Zones Judy Dedmon - USFWS, Atlanta, Georgia
10:00 -10:15	COFFEE BREAK
10:15 -10:55	Adaptive Environmental Assessment and Management Carroll Cordes - FWS, Slidell, Louisiana
10:55 -11:35	Ecological Values of Selected Coastal Habitats Nancy N. Rabalais - University of Texas, Port Aransas Marine Lab
11:35 -12:00	Wrap-up and Evaluation Joseph W. Kathrein, USFWS, Albuquerque, New Mexico
12:00	LUNCH (Cafeteria)

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16. Abstract (Limit: 200 words)

Proceedings contain the formal presentations from the Gulf of Mexico Coastal Ecosystems Workshop, which was sponsored by the U.S. Fish and Wildlife Service. Purpose of the workshop was to provide information to coastal decision-makers on recent developments in coastal ecology related to assessing the impact of human activities on fish and wildlife resources. Topics discussed include the ecological value of marsh impoundments, freshwater inflow requirements in Corpus Christi Bay, legal aspects of permitting process, productivity of seagrasses with an extensive bibliography, ecology of the hypersaline Laguna Madre, dynamics of Gulf of Mexico off the Texas coast, contributions of wooded swamps to estuarine productivity, management of barrier islands, oil and gas development in coastal marshes, state and Federal relations in the coastal zone, adaptive environmental assessment as a management tool, and the ecological role of selected coastal habitats.

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