ESTUARY-SEA ECOLOGICAL INTERACTIONS: A THEORETICAL FRAMEWORK FOR THE MANAGEMENT OF COASTAL ENVIRONMENT

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INTRODUCTION

The Mexican coast of the Gulf of Mexico supports human activities that are increasing in variety and intensity. This coast is significant in terms of its economic, social and environmental values, including port activities, fishing production, agricultural and petroleum industries, tourism, urban-commercial expansion and pollutant cycling. Many of its uses and resources result in conflict of interests because they are “common property” and the effects of human activities are mostly felt in lagoon-estuary ecosystems, which are formed in environments that were deposited prior to sea intrusion.

In many cases coastal management practices are marked by activities that are reactive or short term, *ad hoc* and generally not integrated with different levels of government or users, resulting in fragmented management proposals, particularly at sub-regional scale (Cicin-Sain and Knecht 1998; Zárate Lomelí and Yáñez-Arancibia 2003). With a functional approach to ecology, successful lagoon-estuary management, clastic coastal depositional environments, together with the water “mixing areas”, begins with understanding estuary-sea ecological interactions, and requires decision-making based on their physical characteristics and biological processes, integrating “seasonal ecological pulses” with economic and social coastal development.

In the case of great latitudinal extensions (*ca*. 3,200 km from Tamaulipas to Quintana Roo) that contain numerous types of coastal environments, environmental management and planning (*i.e*., SEMARNAT, INE, PROFEPA, CNA) is daily confronted with the dilemma of formulating management policies and practices with fragmented or difficult to access environmental data, or available only for a limited number of ecosystems. At the same time there is no integrated macro/meso scale understanding of the functional structure of the Gulf coasts, its estuary-sea interactions or the processes that modulate these interactions from the hydrological basins to the estuarine deltas on the neritic continental shelf (Fig. 14.1). Therefore, any discussion of coastal ecological interactions implies: 1) an understanding of the connections between land, sea, atmosphere and epicontinental waters; 2) an understanding functional structure and reciprocal interdependence between the main components of the coastal zone; 3) an understanding linkages between coastal plain wetlands and the continental shelf through estuary outlets; and 4) interpreting the ecological meaning of the mixing zone and the size of exports in relation to the import of materials and energy.

In this chapter, the value of understanding the functional structure of the coastal zone of the Gulf of Mexico will be demonstrated through geomorphologic, climatic-meteorological, hydrodynamic and biological understanding of representative but contrasting ecosystems. Understanding these concepts and processes are fundamental with regard to environmental management and management practices if they are to be based on both integrated biological and physical attributes (for example, fluvial discharge, climatic seasonality, biodiversity, estuarine metabolism, among others), and ecological processes in seasonal pulses, which determine natural productivity in the coastal zone (Fig. 14.2). The main objective is to compare ecological processes along a latitudinal gradient, between oligo- and mesohaline wetlands and the

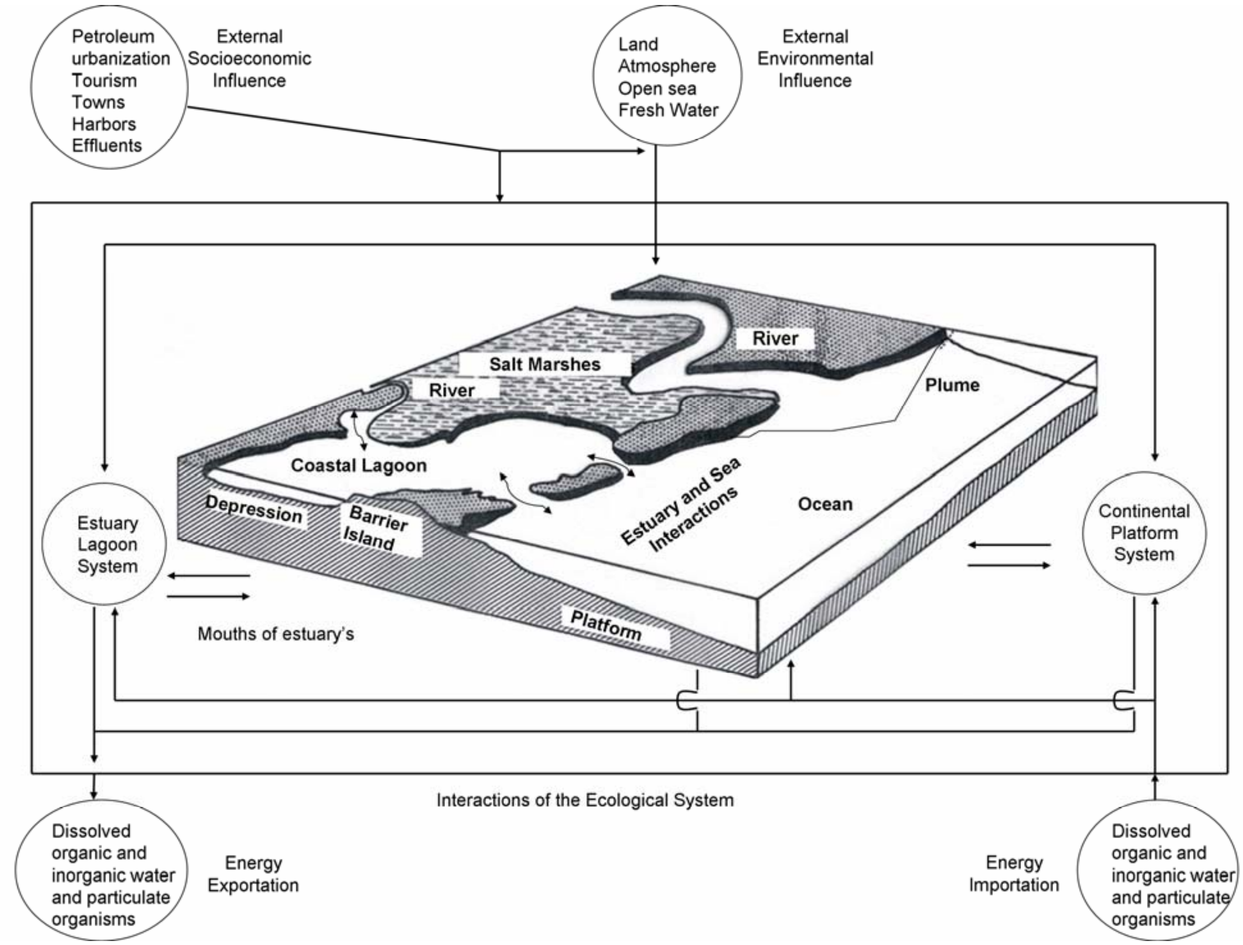


Fig. 14.1. Conceptual model illustrating components of the coastal zone ecosystem. The arrows indicate the direction of the interactions. The "estuarine mouths" are the primary factor in estuary-sea ecological interactions. Barrier islands are interrupted by estuarine mouths; where the river and sea meet also constitutes an estuarine mouth. In this subsystem, active exchange of water, pollutants, nutrients, organic matter, sediments and organisms occurs. Connectivity involves mixing and transport processes, extent of the estuarine plume, migratory movements, variations in biodiversity and abundance, ontogenetic changes in biological cycles, trophic dynamics, physical-chemical changes, and changes in productivity. Modified from Yáñez-Arancibia (1986).

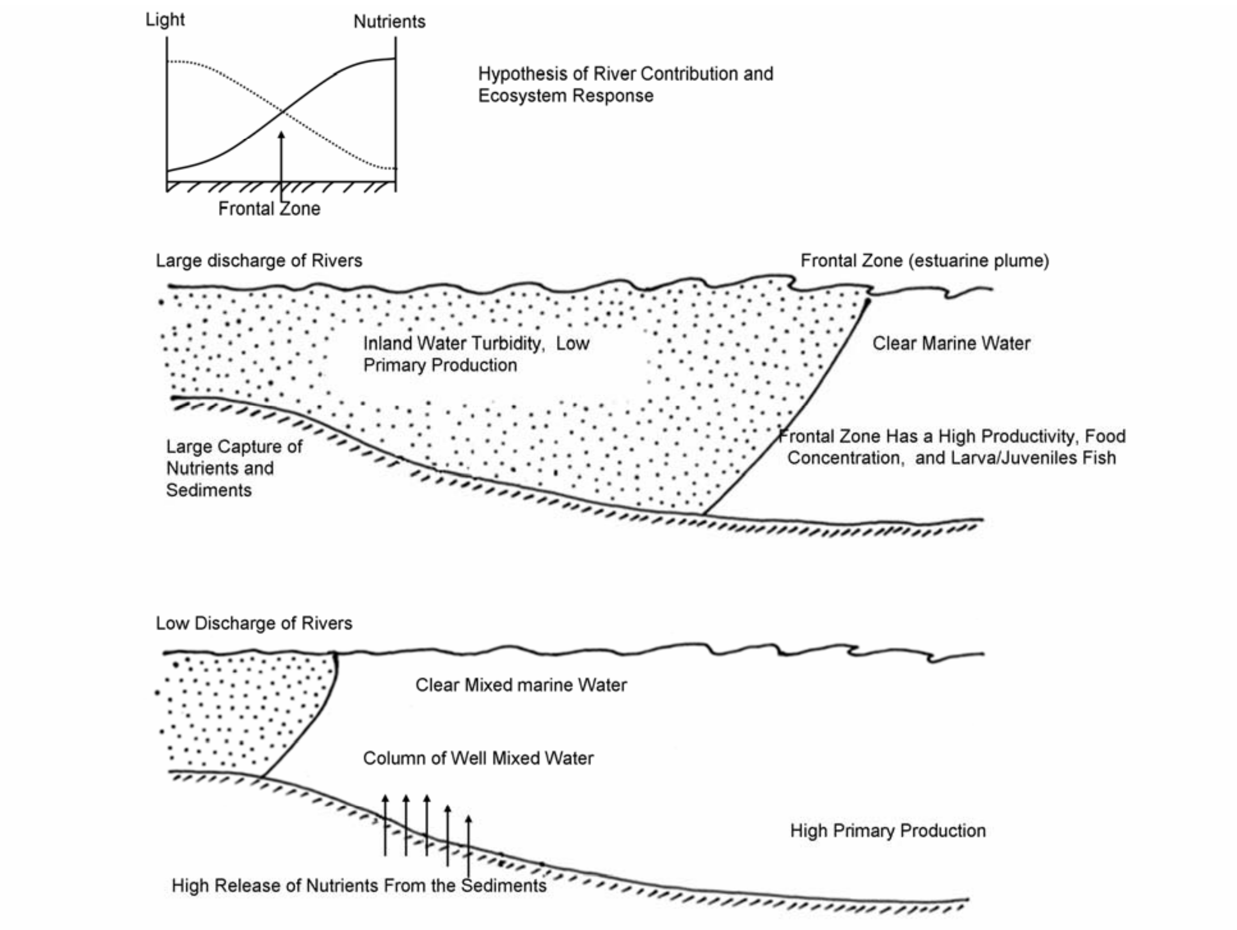


Fig. 14.2. Hypothesis of the contribution of rivers and coastal ecosystem response. Larvae, young and adult fishes and macroinvertebrates use the open and protected water system and the gradient estuarine plume front, as essential habitats, before and after their movement toward the wetlands or the continental shelf. Environmental factors and their extremes condition the ecological functioning of the estuarine-lagoon systems.

continental shelf, highlighting the function of estuarine mouths in estuary-sea ecological interactions.

BRIEF DEFINITIONS TO UNDERSTAND ESTUARY-SEA ECOLOGICAL INTERACTIONS

In order to obtain an environmental diagnosis, and with management purposes aimed at the public sector and decision makers, ideally the borders of coastal areas should be defined by the areal extent of the relevant interactions, including physical, biological, economic, social and legal-normative factors, among others. For the purposes of this chapter the following terms are very briefly defined so the reader can understand estuary-sea ecological interactions: a) coastal zone; b) estuary; c) coastal lagoon; d) estuarine-lagoon system; e) clastic depositional environment; f) facies; g) estuarine plume; and h) environmental pulses.

COASTAL ZONE

Because functional criteria should be established, we consider a coastal zone as a wide ecoregion with intense physical, biological and socioeconomic interactions with dynamic exchanges of energy and materials between the continent, freshwater, atmosphere and adjacent sea. Generally it includes the coastal plain, the lower river basin, hydrophytic wetlands, mangroves, low flooded jungle, dunes, coastal lagoons, estuaries, beaches and the estuarine plume on the neritic continental shelf. In practice, and for management purposes within a legal framework, both Mexico and the United States incorporate municipalities and counties as the geopolitical borders on the continent, and the continental shelf as an extension towards the sea. In Mexico, the 20 m wide Zona Federal Marítimo Terestre (Land Sea Federal Zone ; ZOFEMAT) is included as a small strip within this concept of coastal zone. (Chua and Pauly 1989; Chua and Scura 1992; Yáñez-Arancibia 1999, 2003; Yáñez-Arancibia and Day 2003).

COASTAL PLAIN

The coastal plain is the set of natural attributes at ecosystem and resource levels that are geographically located on the plains alongside the coastline and extending inland to where the flat physiography and marsh and lake vegetation are well represented. Coverage of the coastal plain is modified by effects of natural seasonal flooding. This coastal sub-region: a) contains important wetlands; b) structures diverse critical habitats for specific flora and fauna; c) retains the flow of water and recharges groundwater; d) modulates the balance between freshwater and brackish wetlands depending on the tidal regime and volume of freshwater discharge; e) buffers the lower river basin before reaching the sea, f) acts as a filter controlling water quality, retaining nutrients, sediments, pollutants and diminishing eutrophication; and g) sustains important economic activities in the coastal zone. (Yáñez-Arancibia 1986; Day *et al*. 1989).

ESTUARY

Hydrodynamically, an estuary an entrance of the sea that floods a river valley, where freshwater and seawater mix and dilute. It is the meeting of epicontinental waters that generates “estuarine conditions”. From a geological perspective, it is a clastic coastal depositional environment that receives fluvial and marine sediments, with facies influenced by tides, waves and river discharge. In an integrated understanding of an estuary, the gradients and water dilution and mixing (hydrodynamics) are supplemented with sedimentary environment gradients (environmental geology facies) (Officer 1976; Kjerfve 1978; Yáñez-Arancibia 1987; Boyd *et al.* 1992; Dalrymple *et al.* 1992; Dyer and Orth 1994; Harris *et al.* 2002; Harris and Heap 2003). Using this oceanographic definition, estuaries and deltas are not differentiated, although obviously there are variations regarding their physical processes (Lauff 1967; Yáñez-Arancibia 1987; David and Kjerfve 1998).

COASTAL LAGOON

Geomorphologically, a coastal lagoon is a coastal depression below the mean high tide level, in permanent or ephemeral contact with the sea, and presents some kind of barrier; with or without fluvial contribution and with sedimentary facies determined by the tides, waves, coastal currents and river discharge (Bird 1968; Lankford 1977; Lasserre and Postma 1982; Yáñez-Arancibia 1987; Boyd *et al.* 1992; Kjerfve 1994; David and Kjerfve 1998; Harris *et al.* 2002). Due to the meeting of freshwater and seawater, "estuarine conditions" are found in this geomorphologic depression.

ESTUARINE-LAGOON SYSTEM

Ecologically, an estuarine-lagoon system is a depression connected to the coastal plain and the sea. It is a hydrodynamic and geomorphologic zone of mixing and interactions, where gradients of primary aquatic productivity, salinity, turbidity, sedimentary facies and biodiversity prevail, in the presence of a great variability in "seasonal pulses", conditioned by winds, river discharge, tides and coastal currents. Flora and fauna are morphophysiologically well adapted to environmental variability and natural productivity, and seasonal biological cycles of interaction between the oligohaline wetlands and adjacent sea (Day and Yáñez-Arancibia 1982; Yáñez-Arancibia 1987; Day *et al.* 1989; Kjerfve 1994).

CLASTIC COASTAL DEPOSIT ENVIRONMENT (CCDE)

This is a coastal area where sediments derived from land and/or marine sources accumulate (Kjerfve 1994; Harris and Heap 2003). Rocky coasts, erosive cliffs, beaches and dunes are excluded from this chapter. Two main types of CCDE are: CCDE-1, environments that receive a large contribution of sediments and actively prograde toward the sea (i.e., deltas, flood plains, out tides); and CCDE-2, environments that have a small supply of sediments with geomorphic characteristics associated with Holocene sea level rise and whose paleovalley is completely filled with sediment (Bird 1968; Boyd *et al*. 1992; Harris *et al.* 2002). Variation in average sea level, relative amounts of land/sea sediment contributions, and size of the receptor basin, determine the variability and persistence of estuary-sea ecological interactions (Yáñez-Arancibia and Day 1982, 1988).

FACIES

Facies are defined as a set of geomorphic and sedimentological attributes that are diagnostic elements in a sedimentary environment and its physical, chemical and biological processes. On their own, individual facies have little interpretive value. However, when they are analyzed in conjunction with different sedimentary environments, on both horizontal and vertical scales, the strength of interpretation is much stronger and the set of facies suggests generalizations for a certain type of depositional environment (Yáñez-Arancibia and Day 1982), for example, intertidal flood plains, sand banks, brackish tide pools, mangroves and jungles subject to flooding, wetlands with grasslands, muddy middle basins, barrier islands, estuarine mouths and inflow-outflow tidal deltas. Moreover, from a management perspective, it is important to emphasize that the concept of "facie" is used in this chapter as an analogy of the set of factors in an ecological "habitat", in most clastic coastal depositional environments, in the sense of Day *et al.* (1989, 1997) and Kjerfve (1994).

ESTUARINE PLUME

The estuarine plume is defined as the area on the continental shelf that is influenced by "estuarine conditions". It is characterized by salinities of <35 psu, high turbidity, high availability of particulate and dissolved organic and inorganic compounds, and the greatest primary aquatic production of the continental shelf is generated in estuarine front zone. Its size and seasonality depend on the width and dynamics of the estuarine mouths, river discharge, tides, coastal currents and wind regime (Figs. 14.2 and 14.5a). This plume is highly correlated with delta systems and its primary productivity is an indicator of environmental sustainability of the deltas and their correlation with demersal fisheries (Pauly 1986; Day *et al.* 1997; Cardoch *et al.* 2002).

ENVIRONMENTAL PULSES

Environmental pulses are events with a hierarchical distribution expressed in seasonality of external and internal contributions of both energy and materials in the coastal zone. These pulses are not constant, but occur as contributions taking place on different temporal and spatial scales (Table 14.1, Fig.14.4). These pulse events produce benefits on different ecological scales and are integrated into the functional structure of the coastal zone; therefore environmental pulses are ecological pulses. The greatest importance of these events lies in their impact on large sedimentary deposits in coastal systems and the large spatial changes in geomorphology that can be found. The most frequent events have a very important role in maintaining saline gradient, contributing nutrients, stabilizing habitats, regulating biological processes, and determining recruitment by species dependent on or associated with estuarine conditions (Yánez-Arancibia and Pauly 1986; Yáñez-Arancibia *et al.* 1991; Day *et al.* 1997; Sánchez-Gil and Yáñez-Arancibia 1997). Lagoon-estuarine systems have always faced natural changes from diurnal pulses,(i.e., productivity), daily pulses (i.e., tides), decadal pulses (e.g., El Niño), or longer (i.e., sea level rise/fall), and more recently, anthropogenic actions that induce an additional pressure with sediment pulses, nutrient enrichment, hypoxia and the greenhouse effect.

THE ENVIRONMENTAL SETTING

Coastal dunes and estuaries have been part of the geological record during at least the last 200 x10^6 years (Schroeder and Wiseman 1999). However, modern lagoon-estuarine systems are of recent profile, formed in the last 5,000 to 6,000 years during stabilization of the interglacial period in middle Holocene, that followed sea level rise at the end of the Pleistocene (Kjerfve 1978, 1994). The physiography and hydrodynamics of these systems are highly variable, and in the Gulf of Mexico it is a clear expression of coastal biological organization conditioned by geomorphology (Bianchi *et al.* 1999; Kumpf *et al.* 1999; Yáñez-Arancibia 2003a). The Gulf of Mexico basin began forming in the late Triassic (~200 x 10^6 years ago).

Since the Holocene, estuarine sediments have been derived from: a) fluvial sources; b) coastline erosion; c) marine sources; d) wind sources; and e) biological sources. The composition and distribution of sedimentary facies are a result of: a) type and quantity of sedimentary

Table 14.1. Time scale of events and pulses in deltaic systems, and effects of evident ecological impacts applied to the Grijalva/Usumacinta (PCdGU and LTdU) and Papaloapan (LAdP) delta systems.

Event	Time Scale	Impacts
Drastic changes river course	1,000 yr	Delta lobe formation Net progress of the deltaic continental mass
Great floods	50-100 yr	Severe channel cutting. Scattered depressions and fissures form Large sedimentary deposits
Great storms	5-20 yr	Large sedimentary deposits Deltaic coastal erosion Increased aquatic and wetland productivity Increased aquatic marine productivity in adjacent areas
Average river flow	Annual	Increased sedimentary deposits Decreased salinity Hydraulic balance of the delta Nutrient contribution Ecological integrity of habitats Immigration/emigration of estuarine fauna Increased primary and secondary production in the delta and adjacent sea
Normal storm events (cold fronts and tropical storms)	Weekly	Increased sedimentary deposits River bank erosion and river flooding Deltaic coastal erosion Organism transport Net material transport.
Tides	Daily	Wetland productivity drainage Hydraulic balance of the delta

material available for deposition; b) hydrodynamic processes; and c) basin geometry. The suite of sedimentary environments present is normally associated with the characteristics of the sand barrier that protects them from the sea, the estuarine mouth that links estuarine waters with the ocean, the dynamics of the inflow of rivers, normally located at the head of the estuarine system, and the shallow edge all along the coastline where coastal erosion occurs.

Generally speaking, estuarine circulation is the result of four dominant processes: a) net supply of freshwater to the system; b) local momentum transferred by winds; c) variability of the estuarine mouth caused by coastal ocean processes; and d) coastal currents combined with tide and wave action (Kjerfve 1978, 1994).

The general geomorphology of clastic coastal depositional environments is affected by the relative importance of waves and tides, that control the quantity, nature, distribution and transport of sediments along the coast. A significant wave train generates active transportation of sediments along the coast, producing parallel sedimentary profiles, “spits”, sand bars or barrier islands. In contrast, significant tides associated with strong tidal currents generally produce normal sedimentary profiles on the coast including long sand banks, wide estuarine mouths, vigorous deltaic distributary channels, and wide intertidal flood plains. Hence, it is possible to distinguish between coasts dominated by waves (i.e., deltas dominated by waves, estuaries dominated by waves, sea entrances to the coastal plain, and coastal lagoons); and coasts dominated by tides (i.e., deltas dominated by tides, estuaries dominated by tides, and progradient tidal deltas; Fig. 14.3).

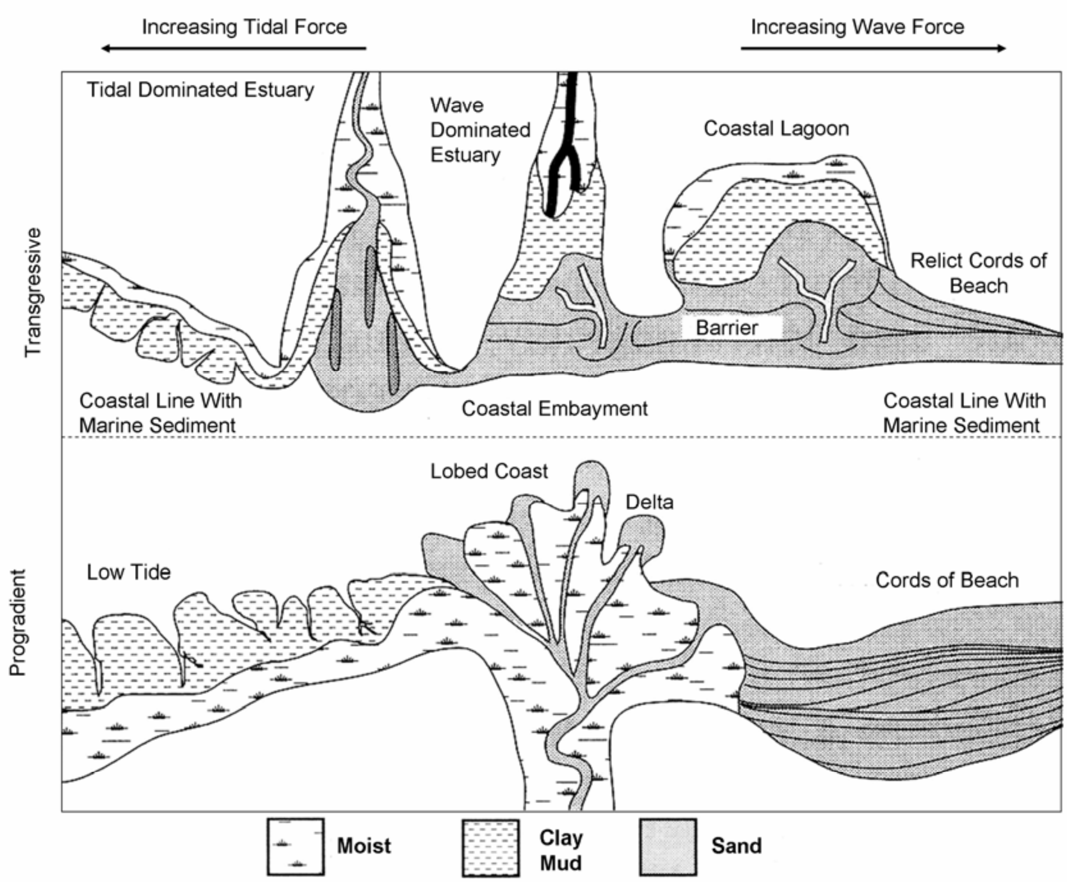


Fig. 14.3. Diagram of coastal depositional environments. Wave strength erodes strips of beach. The strength erodes areas at low tides. A lobe delta coast is the opposite image of a bay estuary dominated by waves. After Boyd *et al*. (1992).

DIAGNOSIS AND PROFILE OF REPRESENTATIVE ECOSYSTEMS

In the latitudinal gradient of the Mexican Atlantic coast, from Tamaulipas (on the U.S. border) to Quintana Roo (on the Belize border), geomorphologic and hydrodynamic contrasts can be observed represented by eight lagoon-estuary systems. From north to south these are: 1) the Laguna Madre de Tamaulipas system, Tamaulipas (LMT); 2) the Laguna Tamiahua system, Veracruz (LTV); 3) the Laguna Alvarado-Papaloapan Delta system, Veracruz (LAdP); 4) the Pantanos Centla -Grijalva-Usumacinta Delta system, Tabasco (PCdGU); 5) the Términos Lagoon-Usumacinta Delta system, Campeche (LTdU); 6) the Celestún Lagoon system, Yucatán (LCY); 7) the Puerto Morelos Reef Lagoon system, Quintana Roo (LAPQ); and 8) the Sian Ka'an Lagoon system, Quintana Roo (LSQ) (Table 14.2, Fig.14.4).

In four systems (LMT, LTV, LAPQ and LSQ), the factor with greatest environmental strength is coastal currents, which can be inferred from the shape of the coastline, the prograding direction of the barrier islands in the cases of LMT and LTV, and the parallel location of coastal bathymetric lines in the reef lagoons in LAPQ and LSQ, represented by a line of dots in the diagrams in the heading of Table 14.2. There are three systems clearly dominated by rivers (i.e., LAdP, PCdGU, and LtdU) and one system dominated by tides (i.e., LCY). The distribution of facies in the systems dominated by tides is organized in tidal sand banks, low, active dunes, and sandy intertidal plains colonized by halophytes. In the systems dominated by waves, at least three distinct facies can be identified: 1) barrier- tidal mouth - inflow-outflow tidal delta; 2) central basin-low energy zone; and 3) delta front bay to estuarine plume. Only LTdU comes close to this model during a few times of year (i.e., “Nortes”, according to Yáñez-Arancibia and Day 1982, 1988). The relative spatial extent of each of these facies varies among systems, depending on the relative strength of waves over tides and in relation to the relative contribution of marine vs. fluvial sediments, the shape and depth of the basin and the degree of drainage. None of the eight systems detailed in Table 14.2 is dominated by waves. On the contrary, long tidal channels often contain mobile sand banks and dunes, but are distinct to those truly dominated by tides by the absence of distributary channels.

LAGUNA MADRE DE TAMAULIPAS SYSTEM, TAMAULIPAS (LMT)

The LMT is characterized by an extensive sand barrier island with multiple connecting mouths and no or very localized and scarce river run off. The shape and bathymetry of the system is modified by tidal action, coastal currents are important environmental forces, and the evaporation rate is very high, and rainfall is low, therefore, it is predominantly hypersaline with low primary aquatic activity (Table 14.2, Fig. 14.4). The water deficit is over 500 mm/day, sediment trapping is low and water residence time is long, because ecological interaction with the ocean is very limited. Its geological origin (Lankford 1977; Tunnell and Judd 2002) is due to a barrier island on the shallow internal shelf modified by the coastal currents and winds (Table 14.2).

Table 14.2. Ecosystem profile in the coastal zone of the Gulf of Mexico and Caribbean Sea: dimensions, geomorphology, meteorology and climate, oceanography, hydrology, biology, ecology , functional structure. LMT Madre Lagoon System Tamaulipas; LMT – Laguna Madre de Tamaulipas; LTV – Laguna Tamiahua, Veracruz; LAdP – Laguna Alvarado-Papaloapan Delta, Veracruz, PCdGU – Pantanos Centla -Grijalva-Usumacinta Delta, Tabasco; LTdU – Términos Lagoon-Usumacinta Delta, Campeche; LCY – Laguna Celestún, Yucatán; LAPQ – Puerto Morelos Reef Lagoon, Quintana Roo; LSQ – Sian Ka'an Lagoon system, Quintana Roo. Climate and basins according to CNA México, Line of points on configurtions indicate tidal front and coastal circulation tendency. * – estimated by Bianchi *et al*. (1999). Residence times based on David and Kjerfve (1998). Sediment trapping efficiency based on Kjerfve *et al.* (1988). Aquatic primary productivity from J. W. Day, unpublished data. Climate, biodiversity, vegetation coverage, estuarine oceanography from A. Yáñez-Arancibia, unpublished data. Total area, water surface area and climate based on Deegan *et al*. (1986) and Bianchi *et al*. (1999). Trophic models from Abarca and Valero (1993), Arreguín *et al*. (1993) and Barba-Macías (2003). Data courtesy of Coastal Resource Program, Instituto de Ecología A.C. (CONACYT).

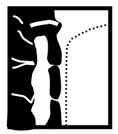
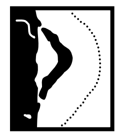
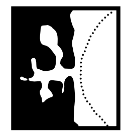
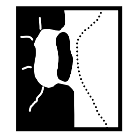
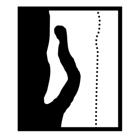
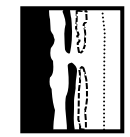
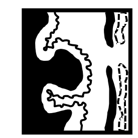
	LMT	LTV	LAdP	PCdGU	LRdU	LCY	LAPQ	LSQ
Configuration								
Area (km^2)	2,450	880	150	3,027	7,061	2,113	nd	nd
Water surface (km^2)	2,010	634	14	102	2,600	nd	nd	nd
Continental shelf/sediments	narrow; fine, mixed sands	narrow; fine, mixed sands	narrow; terrigenous	wide, terrigenous	wide; terrigenous/ calcareous	wide; calcareous	narrow, calcareous	narrow, calcareous
Climate	semi-arid	sub-humid	rainy, humid	rainy, humid	rainy, humid	arid, subhumid	dry, subhumid	dry, subhumid
Prevailing winds	SE, Mar-Sep NE, Oct-Feb	SE, Mar-Sep NE, Oct-Feb	SE, Mar-Sep NE, Oct-Feb	SE, Mar-Sep NE, Oct-Feb	SE, Mar-Sep NE, Oct-Feb	SE, Mar-Sep NE, Oct-Feb	SE, Mar-Sep NE, Oct-Feb	SE, Mar-Sep NE, Oct-Feb
Rainfall (mm/yr)	700	1,200	2,322	2,879	1,800	500	800	1,100
Important rivers/basins	Rio Grande, San Fernando, Soto la Marina	Tuxpan, Nautla	Papaloapan, Blanco, San Juan, Limonero, Jamada	Usumacinta, Grijalva	Usumacinta, Palizada, Candelaria, Chumpan	subterranean basin	coastal cenotes	coastal cenotes
Freshwater discharge (Gulf)			146 x 10^9 m^3/yr					
Freshwater discharge (Yucatan/Caribbean)							9.0 x 10^6 m^3/yr	
Potential evapotranspiration (mm)	1,283	1,327	1,392	1,401	1,586	1,444	1,502*	1,502*
Real evapotranspiration (mm)	761	1,209	1,269	1,356	1,471	466	898*	898*

Table 14.2. Continued.

	LMT	LTV	LAdP	PCdGU	LRdU	LCY	LAPQ	LSQ
Daily water deficit (mm)	522	118	123	45	115	978	604*	604*
Daily water gain (mm)	0	31	1,053	1,523	267	0	0	0
Salinity	hypersaline	mesohaline	oligohaline/ mesohaline	oligohaline	oligohaline/ mesohaline	marine/ mesohaline	marine	marine/ mesohaline
Microtides	diurnal	diurnal	diurnal/mixed	diurnal/mixed	diurnal/mixed	semidiurnal	semidiurnal	semidiurnal
Waves	intermediate	intermediate	low	low	low	low or intermediate	low or intermediate	low or intermediate
Environmental forcing factors	currents> winds> tides	currents> winds> tides	rivers> tides> currents	rivers> tides> currents	rivers> tides> winds	tides> currents	currents> tides	currents> tides
Residence time	long	long	medium	medium	medium	short	short	short
Circulation	well-mixed	partially mixed	salt wedge, partially mixed	salt wedge, partially mixed	salt wedge, partially mixed	salt wedge, partially mixed	well-mixed	well-mixed
Turbidity	low	moderate	high	high	high	low	low	moderate
Sediment trapping efficiency	low	moderate	high	high	high	low to moderate	low	moderate
Habitat alteration by sediments	high risk	high risk	low risk	low risk	low risk	low risk	low risk	moderate risk
Emergent vegetation (ha)	8,461	908	56,550	200,000	130,000	3,379	nd	nd
Fishes (species/yr)	65	80	90	62	214	125	60	73
Mollusks (species/yr)	76	67	49	nd	174	nd	nd	nd
Crustaceans (species/yr)	42	32	36	nd	60	nd	nd	nd
Aquatic primary productivity (mg $C/m^3/hr$)	78	150	200	220	333	80	70	90
Trophic model (ECOPATH-II; Figs. 14.7, 14.8, 14.9)	short chains; via macrobenthos	short chains; via macrobenthos	long chains; via detritus & macrobenthos	nd	long chains; via detritus & macrobenthos	short chains; via macrobenthos	short chains; via macrobenthos	moderate chains; via detritus &macrobenthos
Habitat profile (Fig. 14.5 a, b)	Transgressive Gulf delta; dry forests & scrublands	Transgressive Gulf delta; medium forest	Progradient Gulf delta; wetlands and forests	Progradient Gulf delta; wetlands and forests	Progradient Gulf delta; wetlands and forests	Caribean karst; dry forests, cenotes	Caribbean karst; corals, dry forests & scrublands; cenotes	Caribbean karst; medium forest, cenotes.

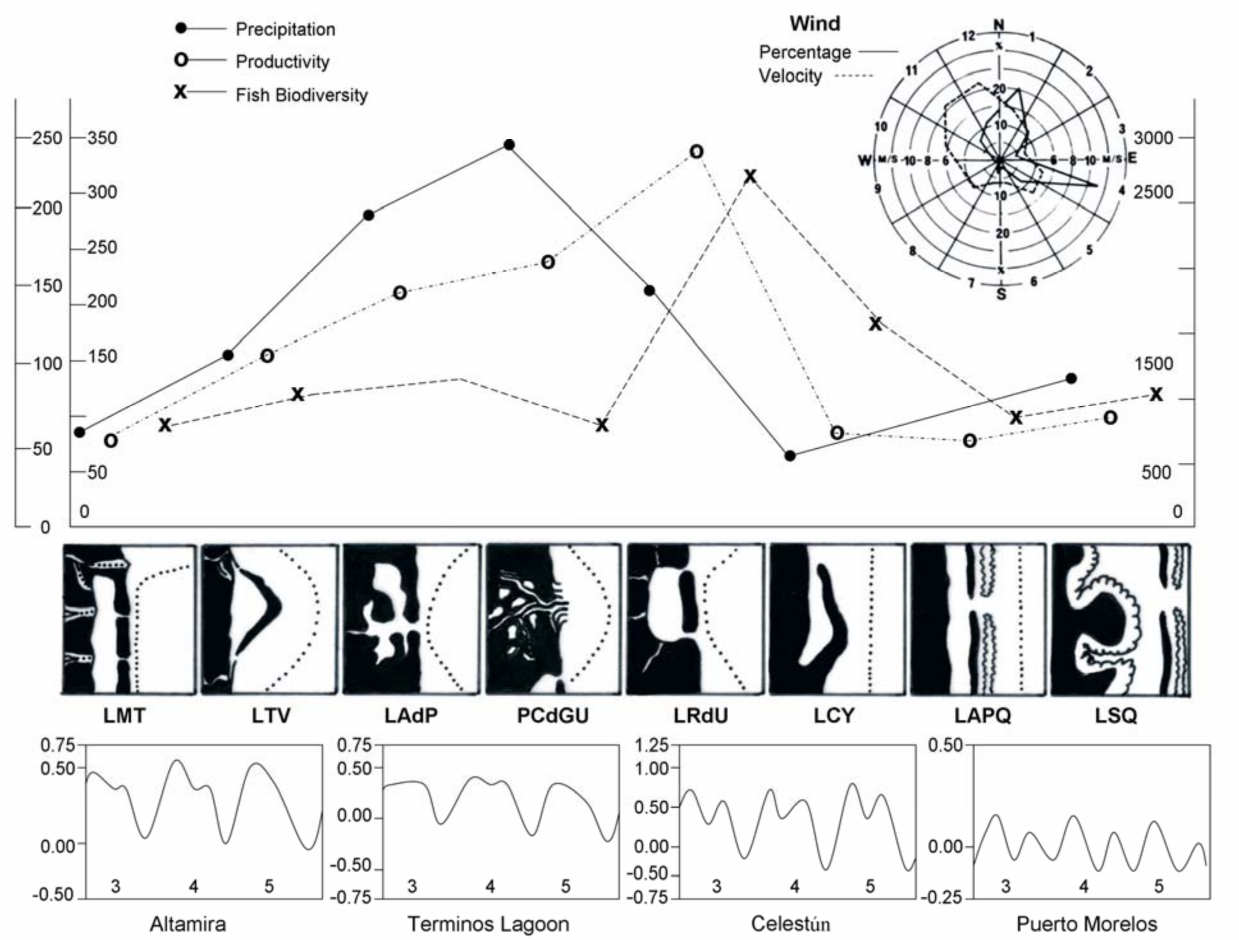


Fig. 14.4. Basic geomorphology of the systems studied: LMT – Laguna Madre de Tamaulipas; LTV – Laguna Tamiahua, Veracruz; LAdP – Laguna Alvarado-Papaloapan Delta, Veracruz, PCdGU – Pantanos Centla -Grijalva-Usumacinta Delta, Tabasco; LTdU – Términos Lagoon-Usumacinta Delta, Campeche; LCY – Laguna Celestún, Yucatán; LAPQ – Puerto Morelos Reef Lagoon, Quintana Roo; LSQ – Sian Ka'an Lagoon system, Quintana Roo. Latitudinal distribution of rainfall, primary productivity and biodiversity of fishes, correlate with maximum values in the delta region from LAdP to LTdU. Other parameters in Table 14.2 also show this tendency. Fish value of PCdGU is anomalous probably due to subsampling and tendency should be greater. South-southeasterly winds predominate from March to September, north-norwesterlies from October to February (see windrose for speed and frequency). Four tidal points are illustrated for the Gulf and Caribbean and other parameters in Table 14.2. From Coastal Resource Program Data Base, INECOL, A.C. (CONACYT).

LAGUNA TAMIAHUA SYSTEM, VERACRUZ (LTV)

The LTV is characterized by a peaked barrier island originating on the internal shelf and formed by sedimentation of its bars supported by relict coral reefs (Lankford 1977). It has two estuarine mouths, one to the north influenced by the low basin of the Río Panuco; and another tothe south by the low basin of the Río Tuxpan (Table 14.2, Fig. 14.4). The shape and bathymetry of the system are primarily modified by coastal currents synergistically interacting with winds and tides. Its daily water deficit and rainfall range place it closer to the conditions of the LMT than other systems, and is reflected in habitat profile and trophic model (Table 14.2, Fig.14.4). Low to moderate amounts of sediment are trapped in the system and water residence times are long, which is why ecological interaction with the ocean is limited.

LAGUNA ALVARADO – RÍO PAPALOAPAN DELTA SYSTEM, VERACRUZ (LAdP)

The appearance of the LAdP is characterized by differential terrigenous sedimentation in a tectonic marginal depression (Lankford 1977). The system is connected to the sea forming an estuarine mouth; the physical barrier and middle basin are modified in shape and bathymetry by delta lagoons and sublagoons, reflection of a progradient delta, modified by rivers as the main environmental force. Due to its isopluvial dynamics, freshwater discharge and evapotranspiration, it is very similar to the PCdGU and LTdU ecosystem profiles. This is clearly reflected in the habitat profile and trophic model (Table 14.2, Figure 14.4). Nutrient trapping is very efficient and water residence time is average, but because of fluvial discharge pulses, ecological interaction with the ocean is very high (Table 14.2).

PANTANOS DE CENTLA – GRIJALVA-USUMACINTA DELTA SYSTEM, TABASCO (PCdGU)

The PCdGU includes the primary deltaic and estuarine systems on the Mexican Gulf coast. This system forms the most extensive area of coastal plain and wetlands in Mesoamerica. It is connected to the sea by the estuarine mouth of the Río Usumacinta (joined by the Grijalva or vice-versa) and the mouth of the San Pedro. Its delta and flood plains are characteristics of active, differential terrigenous sedimentation in a wide coastal plain depression (Lankford 1977; Yánez-Arancibia *et al.* 2002). Rainfall exceeds evaporation and the habitat profile and trophic model of PCdGU is very similar to that of the LAdP and LTdU (Table 14.2, Fig. 14.4). Sediment trapping is very efficient and water residence time is average, so its interaction with the ocean is very high (Table 14.2).

LAGUNA DE TÉRMINOS – RÍO USUMACINTA DELTA SYSTEM, CAMPECHE (LTdU)

The geological origin of the LTdU has two components: differential terrigenous sedimentation and a sand barrier front (Lankford 1977). The explanation is very clear given that LTdU is located exactly opposite where terrigenous province modeled by the Usumacinta and the karstic carbonated province of the Yucatan Peninsula separate. The coastal current balances barrier erosion-deposit, but the main environmental force is river discharge and its synergistic effect with winds. The system communicates with the sea by two natural mouths (Puerto Real and El Carmen) and a smaller artificial one (Sabancuy). The LTdU forms an integral part of the PCdGU system wetlands and is typical because rainfall exceeds evaporation (Table 14.2, Fig. 14.4). Because of its environmental conditions, it is similar to the habitat profile and trophic model of both LAdP and PCdGU. Sediment trapping is very efficient and mixed water residence time is average due to the huge dynamics of its estuarine mouths (Yáñez-Arancibia and Day 1982, 1988; Yáñez- Arancibia *et al.* 1983, 1991; David and Kjerfve 1998). The LTdU system has the greatest estuarine-sea ecological interaction on the whole of the Mexican Gulf coast (Table 14.2), and its net primary production is mostly exported to the continental shelf (Day *et al.* 1982, 1987, 1988; Moore and Wetzel 1988).

LAGUNA CELESTÚN SYSTEM, YUCATÁN (LCY)

The Laguna Celstún system originates from a sand barrier on the internal shelf molded by coastline transport (Lankford 1977). It communicates with the sea through an estuarine mouth and peripheral relief is very low. Although there are no surface rivers in the Yucatán Peninsula, groundwater discharge through Pleistocene limestone caves is considerable (Table 14.2), therefore, the hydrological basin is internal in the subsoil due to the karstic topography. Evaporation greatly exceeds rainfall as in the LMT system (Table 14.2, Fig. 14.4), and due to the terrigenous sedimentary deficit, its trophic model is similar to LTV and LMT. Even though tides and waves are low, coastal circulation is the main environmental force. Sediment trapping is moderate to low due to low sediment supply, yet because of the short residence time of the mixed waters, its ecological interaction with the sea is very dynamic, and is modified by tides and currents, which is reflected in its daily water gain. Due to environmental conditions, its habitat profile is similar to LAPQ and LSQ, representative systems of the karstic Yucatán Peninsula (Table 14.2).

PUERTO MORELOS REEF LAGOON SYSTEM, QUINTANA ROO (LAPQ)

The Puerto Morelos Reef Lagoon system has been formed by differential erosion in a karstic depression, in a subtle submarine sand barrier modulated by waves and tides, combined with an organic barrier of coralline algae (Lankford 1977). The reef barrier and the sand threshold between the coralline algae barrier and the coastline (Table 14.2) are parallel to the coastline. This lagoon, which has marine grasses, communicates with ephemeral continental wetlands via groundwater discharge (Alvarez-Guillén *et al.* 1986). There is no typical mouth connection, but interaction with the sea occurs along its full length, modified mainly by tidal rhythm and coastal circulation (Table 14.2).

SIAN KA'AN LAGOON SYSTEM, QUINTANA ROO (LSQ)

The Sian Ka'an Lagoon system was formed as a result of differential erosion in a karstic depression, colonized by short but dense mangroves that act as an organic barrier between protected waters and the adjacent sea, as well as the reef barrier of coralline algae parallel to the coastline (Lankford 1977; López-Portillo *et al.* 1999). The lagoon is also colonized by marine grasses toward the sea and, as in LAPQ, contributes freshwater through the groundwater basin. The plain is limestone associated with cenotes (limestone sinkholes filled with freshwater). Communication with the sea, conditioned by coastal currents and tides, is wide. Nutrient trapping is moderate and is linked with metabolic activity of organic sediments from the mangroves. This is why the trophic model is more complex than LAPQ. In Fig. 14.4 pulsing is greater in the LSQ than in LCY and LAPQ for pluviometric and primary aquatic production, which distinguishes it from the Yucatán Peninsula coast and along the Caribbean coast of Mexico, even though habitat profile is similar for all peninsula systems. Without doubt, the ecological interactions of the mangroves/marine grasses/corals, is the hallmark of this system (Table 14.2).

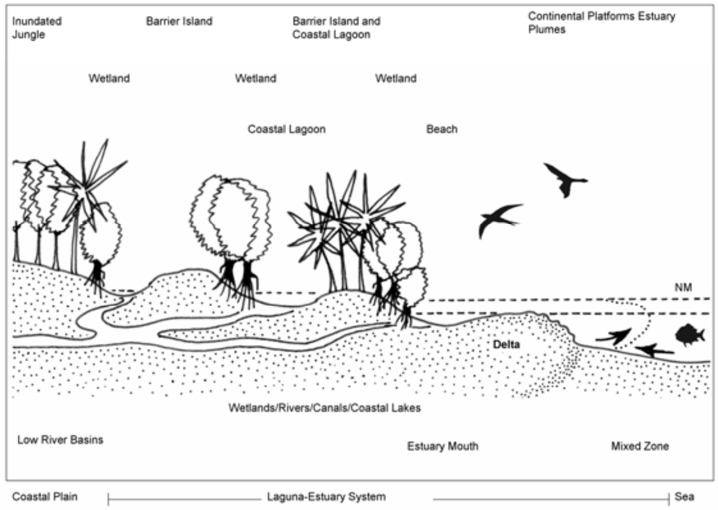
LATITUDINAL PATTERN, HABITAT PROFILE, COASTAL PROCESSES & AQUATIC FERTILITY HYPOTHESES

Figure 14.4, based on only some of the environmental parameters detailed in Table 14.2 shows the "ecological pulse" from Tamaulipas to Quintana Roo, with: a) analogies between Tamaulipas and Yucatán; b) the region of greatest estuary-sea ecological interaction from the Papaloapan delta to the Usumacinta delta, covering the coasts of Veracruz, Tabasco and Campeche; and c) the different profile from Yucatán to Quintana Roo, showing pulse elevation, which could increase even more off Laguna Chetumal (not detailed in this chapter). Figures 14.5a and 14.5b illustrate and describe habitat profiles for the Gulf and Caribbean based on the systems studied. All the Gulf systems respond to this scheme (Fig. 14.5a), with lesser or greater representation of the delta system. This contrasts notably from the northern Yucatán and coral reefs of the Caribbean coast. Table 14.2 shows estimated freshwater discharge values for the entire Mexican Atlantic coast. Subterranean basin discharge in the karstic Yucatán Peninsula is surprising (J.Herrera-Silveira, CINVESTAV, personal communication). On the other hand, river discharge on the Gulf coast is enormous. Yáñez-Arancibia *et al.* (2003) estimated total discharge at 7,000-10,000 m^3/sec, with contribution of important rivers estimated at: Rio Grande, 162 m^3/sec; Río Cazones, 43 m^3/sec, Río Candelaria, 45 m^3/sec, Río Nautla, 55 m^3/sec, Río Antigua, 60 m^3/sec, Río Tuxpan, 80 m^3/sec, Río Tecolutla, 200 m^3/sec, Río Coatzacoalcos, 440 m^3/sec, Río Pánuco, 630 m^3/sec, Río Papaloapan, 1360 m^3/sec, Río Usumacinta/Grijalva, 4,400 m^3/sec [rounded data]).

Figure 14.6 shows the seasonal pulses of river discharge to the Gulf of Mexico for each federal entity and the annual total. In September (the rainiest month) and October, the main pulse in the Gulf watershed occurs. This is of great ecological significance because in October the highest values of primary aquatic productivity are recorded in the southern coastal zone of the Gulf (J. W. Day, LSU, unpublished data). The pulses are: a) northerly winds that start in October; b) southeasterly winds in summer, during the rainy season; c) the lowest sea level in May, usually a period of extreme drought; d) the highest sea level in October at the beginning of northerlies; e) rains from June to September; and f) main river discharge in October. These pulses act as integrated ecological processes key in estuary-sea ecological interactions (Yáñez-Arancibia *et al.* 1991).

For example, in systems where a transgressive delta profile prevails (Table 14.2, Fig. 14.3), the organization of communities is modified by low organic detritus production, which in turn, causes the ichthyofaunal community to maintain itself via the macrobenthos. Food chains are normally short and third order consumers can be seasonally absent (Fig. 14.7). This figure by Abarca and Valero (1993) shows the estimated biomass (g/m^2) and flows ($g/m^2/y$) for the Tamiahua Lagoon system, but based on the integrated profile in Table 14.2 and the ecological pulse in Fig. 14.4, a structure analogous to the Laguna Madre de Tamaulipas, and the Celestún Lagoon systems can be expected. However, due to the dynamics of LTV, it exports less (11.4 $g/m^2/y$) than LCY (1483 $g/m^2/y$) through their respective estuarine mouths to the continental shelf. Barba-Macías (2003) corresponds in the analogy between LMT with LTV and LCY based on trophic interactions (Fig. 14.8), estimating an export of 250.8 g^2/y to the adjacent sea, an intermediate value between LTV and LCY.

In contrast, in more productive systems where a progradient delta profile prevails (Table 14.2, Fig. 14.3), community organization is modified by the large production of organic detritus, which in turn allows the ichthyofaunal community to maintain itself via detritus, but also



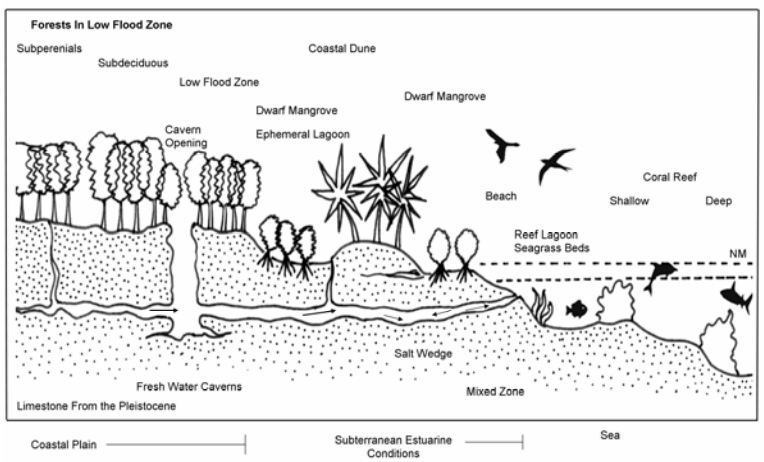


Fig. 14.5. Coastal ecosystem profile on the Atlantic coast of Mexico. Top: In the Gulf of Mexico characteristic habitats are associated with important fluvial discharges and the extensive coastal plain. From the continent to the sea, the characteristic habitats are: low jungle, coastal plain, low river basins, wetlands, coastal lagoons and medium to well developed mangroves, barrier islands, dunes/beaches, and significant deltas conditioning an estuarine plume front. The main ecological processes that condition productivity are coastal in nature: river discharge, mangrove metabolism, wind and terrigenous sediment contribution. Bottom: In the Caribbean Sea characteristic habitats are associated with karstic topography, Pleistocene limestone and a subterranean hydrological basin. From the continent to the sea, characteristic habitats are: low-dry jungle, cenotes, short mangroves, seasonal lagoons and aquifers, dunes/beaches, reef lagoon with seagrasses and deep reef. Clear freshwater caves discharge in the reef lagoon and a saline ridge can cause “subterranean estuarine conditions”. The main ecological processes that condition productivity are marine in nature: wind, coastal currents balanced with subterranean water discharge, and seagrass and coral metabolism. Nm=tidal level. See Table 14.2

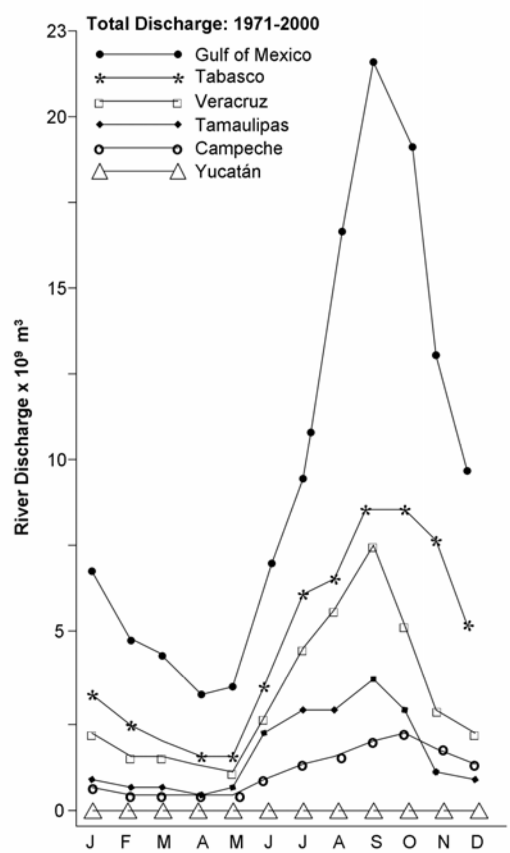


Fig. 14.6. Total discharge in the Mexican Gulf coast. September and October are the months of greatest discharge, after maximum precipitation from June to September. October is also the month of greatest primary aquatic production at estuarine plume front on the continental shelf. In the figure, Yucatán subterranean discharge is not considered (see Table 14.2). This contrasts with the greatest fluvial discharge of the USA coasts to the Gulf, which occurs between April and May; the entire Gulf exhibits a seasonal program of sequential pulses. Data courtesy of INEGI and Comisión Nacional de Agua.

consuming macrobenthos. The food chains are long and third order consumers are always present even though their seasonal abundance varies (Fig. 14.9). This figure by Arreguín *et al.* (1993) shows that the estimated data of biomass (g dry weight/m^2) and flows (g dry weight/m^2/y) is greater than 15% for the coastal zone of Veracruz, similar to LAdP, LTdU and Campeche Bay, where export in can be at least three time greater than in systems that import organic detritus (D. Pauly, UBC, personal communication).

The complexity of the models in Figs. 14.7-14.9 show an important relationship between river discharge, pluviometry, primary aquatic productivity and biodiversity (Table 14.2, Fig. 14.4). The region that includes LTdP, PCdGU and LTdU and their separation from other systems studied can be seen clearly (Table 14.2). The ecological effects of these deltas towards the continental shelf is important in these estuary-sea ecological interactions (Fig. 14.4).

The upwelling system on the continental shelf northeast of Yucatán has been mentioned many times in publications (Lohrenz *et al.* 1999), and in general terms its fertilizer effect on the rest of

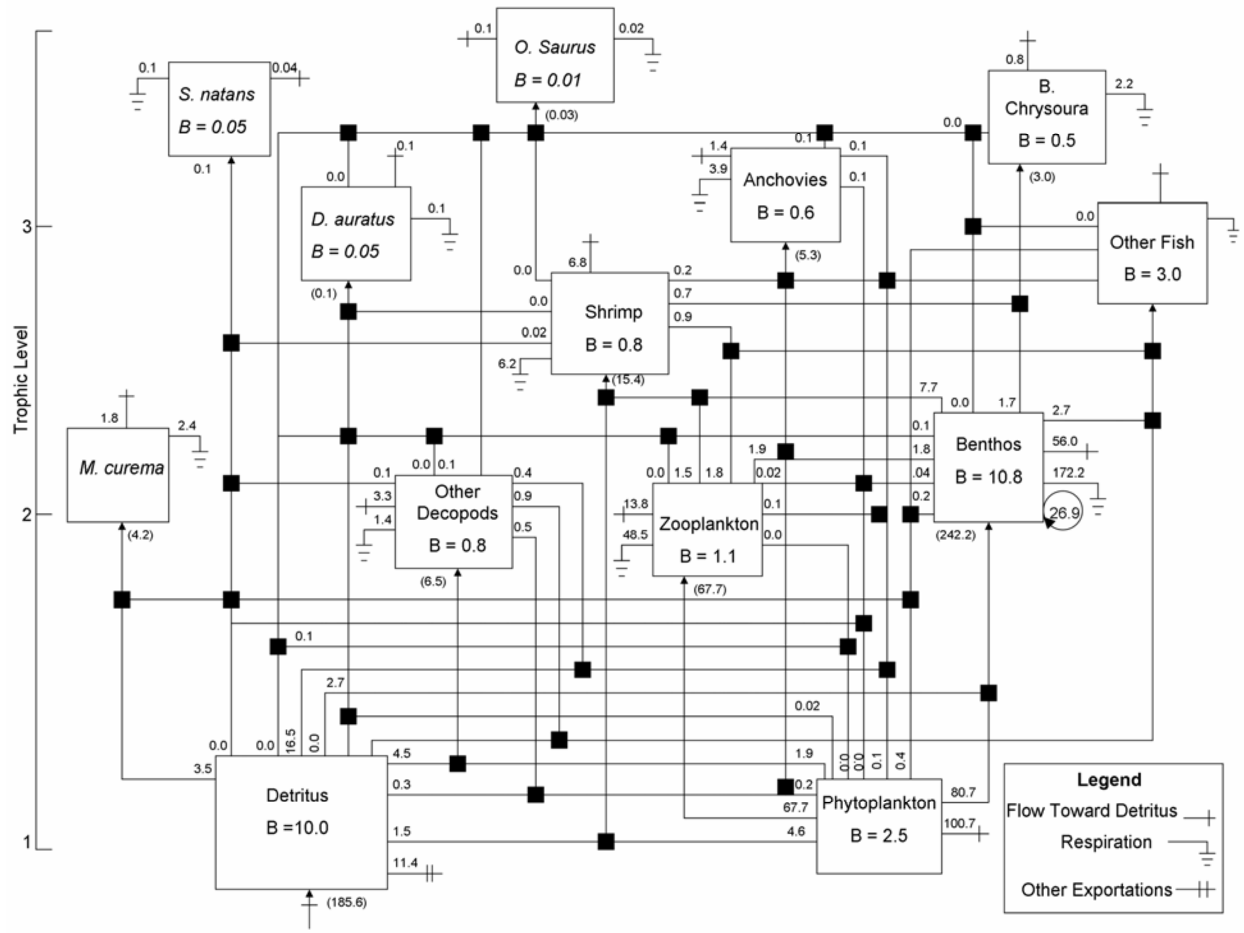


Fig. 14.7. Model of trophic structure (ECOPATH-II) in systems of lower productivity or that import organic detritus. The data corresponds to the LTV system (biomass g/m^2 and flows g/m^2/year), and its analogy is with the LMT and LCY systems. See Table 14.2, Fig. 14.4. From Abarca and Valero (1993).

the Gulf surface has been inferred. However, in reality, little or nothing is known about the ecological interaction of this upwelling with the neritic continental shelf and the Mexican coastal zone of the Gulf. Moreover, satellite images by Lohrenz *et al.* (1999) do not support the primary idea of the effect of these upwellings on the neritic coast, for example, in Campeche Bay.

On one hand, this chapter reinforces the idea that aquatic productivity of the neritic continental shelf from Yucatán to Quintana Roo *is* conditioned by marine processes (i.e., currents, tides, winds; Table 14.2, Fig. 14.5b), and this correlates with the karstic province. But, on the other hand, this article proposes the hypothesis that due to the direction of the Lazo Current crossing the Yucatán channel and entering the Gulf, its ecological link must be far greater with the central coasts, but above all with the northern coast of the Gulf of Mexico (satellite image in Lohrenz *et al.* 1999 and in Yáñez-Arancibia and Day 2003), and its link with neritic aquatic fertility in the southern Gulf is weak. This is reinforced by evidence of biological disconnectivity between the Caribbean coast of Mexico and the neritic shelf of the southern Gulf. There is sufficient information to understand that aquatic productivity of the continental shelf,

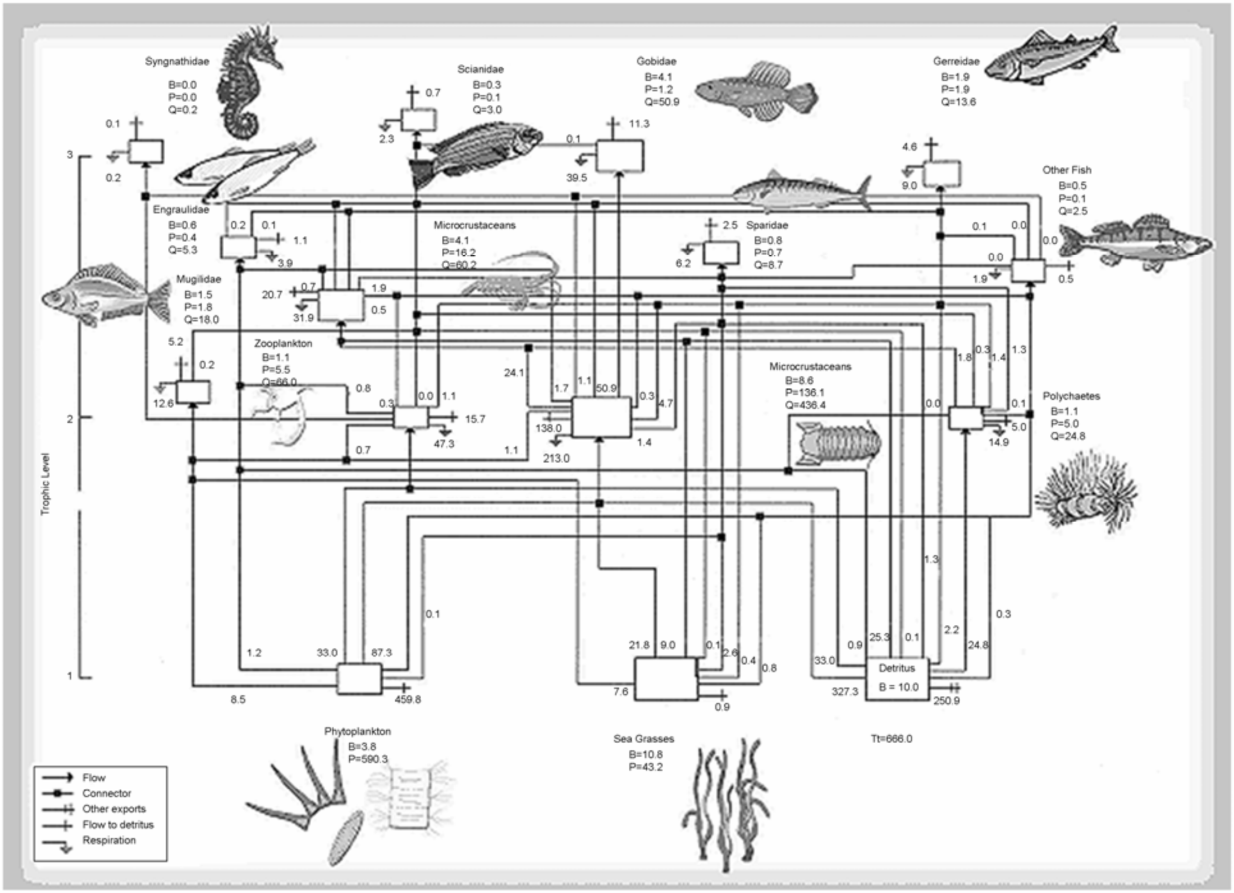


Fig. 14.8. Model of trophic structure (ECOPATH-II) in systems of less productivity or that import organic detritus. The data corresponds to LMT (biomass $g/m^2/year$, flows $g/m^2/year$) and is analogous to the LTV and LCY systems. See Table 14.2, Fig. 14.4. Model from Barba-Macias (2003) and courtesy of the author.

from the Mississippi Delta and to Campeche Bay is conditioned by coastal processes (i.e., river discharge, coastal circulation, tides, residual currents, winds, coastal vegetation cover), correlated with the terrigenous sedimentary province, all in an estuary-sea ecological interaction dynamic, as a reflection of important estuarine plume fronts (Table 14.2, Figs. 14.2 and 14.5a).

Several satellite images of the Coastal Studies Institute (Louisiana State University), of the Coastal Ocean Services (NOAA), and the analyses in Day *et al.* (1995, 1997) support our hypothesis that coastal processes control aquatic fertility and its seasonality in the Mexican coastal zone of the southern Gulf of Mexico.

PROJECTION OF THE RESULTS: ECOLOGICAL INTERACTIONS WITH IMPLICATIONS FOR ENVIRONMENTAL MANAGEMENT

In the framework of the environmental diagnosis of the Gulf of Mexico (Table 14.2, Fig. 14.4), at least four ecological indicators are important in supporting the hypothesis of greatest

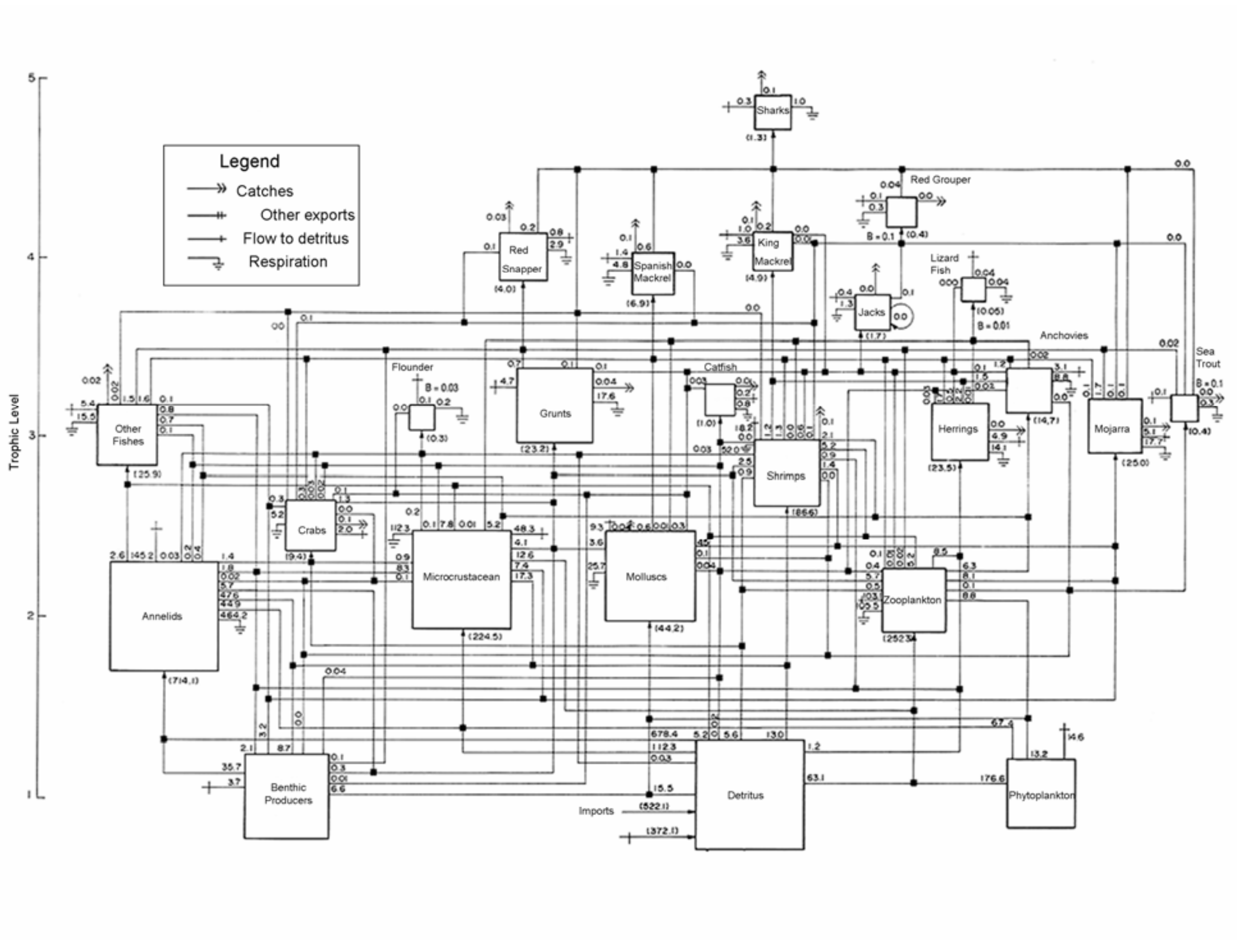


Fig. 14.9. Model of trophic structure (ECOPATH-II) in systems of greater productivity that export organic detritus. The data corresponds to southern Veracruz with affinity to the LAdP system (flows >15% g dry weight m^2/year, biomass g/m^2), and is analogous to the LAdP, LTdU and Campeche Bay systems. See Table 14.2, Fig. 14.4. From Arreguín *et al.* (1993).

aquatic productivity at the frontal boundary of the estuarine plume (Fig. 14.2), modulated by coastal processes (Fig. 14.5a) and estuary-sea ecological interactions. These are: a) sediment trapping efficiency; b) nutrient overload; c) hypoxia, and d) coastal processes and fishing resources. These aspects have direct implications for environmental management of the coastal zone.

SEDIMENT TRAPPING EFFICIENCY

Sediment trapping efficiency differs depending on the dominant sediment type in the study area and on whether the system is prograding or transgressive (Table 14.2, Fig. 14.3). The rate of retention or export of sediment in the coastal zone is linked to these two characteristics but also to the type of estuarine circulation (Schroeder and Wiseman 1999; Solis and Powell 1999). Therefore, the efficiency of sediment entrapment depends on: a) sediment type and the terrigenous/carbonated proportion; b) fluvial and marine sediment volume; c) flocculation of coacervates (spherical aggregations of lipid molecules held together by hydrophobic forces); and d) estuarine circulation type. Because diverse pollutants are associated with the fine grains of sediments, management implications of entrapment efficiency is immediately obvious (Table 14.2, Figs. 14.2, 14.3). Of course, there are also direct implications due to sedimentation for turbidity, circulation and habitat alteration (David and Kjerfve 1998). Progradient coasts, characterized by deltas of important rivers and low tides, export most of their sedimentary load to the sea and generally the sediment trapping efficiency at the estuary head is low; they contain a suite of habitats that are not significantly affected by excess sedimentation (Day *et al.* 1989, 1995, 1997). In contrast, transgressive coasts characterized by lagoons and estuaries are highly efficient sediment traps, and are therefore more susceptible to accumulation of particles associated to chemical pollutants and habitat change because they are more sensitive to disturbances that affect seasonal pulses of fluvial sediment load (Solis and Powell 1999; Table 14.2).

NUTRIENT OVERLOAD

Nutrient overload (enrichment) has often been linked to stimulation a bloom of a noxious algal species; but this is not absolutely clear and at times may only be an apparent linking factor (Anderson *et al.* 2002). Although they are important, nutrients are not the only explanation for blooms of toxic algae. Algal blooms, including toxic events, are sometimes due to natural phenomena and the bleaching or coloring of coastal waters has been mentioned for around 200 years (Anderson *et al.* 2002). With this vision, in order to understand the impact of nutrient availability and overload in estuary-sea ecological interactions, it is important to make the distinction between the effects on physiological or productivity processes opposed to biomass accumulation, and the answer to nutrient loading can be observed analogously to the response curve of saturation (Fig. 14.10).

The effect of nutrients can be in the region of minimum response, which is dominated by rapid physiological adjustments and low biomass accumulation or, alternatively, in the region of maximum response, in which physiological processes are saturated, but biomass accumulation continues (Moore and Wetzel 1988). The minimum response region also represents the beginning of the bloom period, whereas the maximum response region represents bloom support. Here there is a controversial aspect, given that if the beginning of the bloom is characterized by a minimum increase in biomass, then the role of nutrients in the beginning of the bloom is much less understood than the period in which a bloom is maintained. This process is extremely relevant in terms of environmental diagnosis with implications for management, linked to: a) circulation pattern; b) residence time; c) sediment trapping; d) river discharge; and e) primary aquatic production (Table 14.2, Fig. 14.4). Within this framework, it is important to acknowledge that impacts are few, difficult to detect and easy to reverse with mitigation measures in the minimum response region, whereas in the maximum response region, impacts are great and often easy to detect, but are substantially more difficult to reduce and control (Fig. 14.10).

Eutrophication is a global problem and gradually the Gulf of Mexico lagoon-estuarine systems have become a part of it. Even the Yucatán coastal zone is being affected (Herrera-Silveira *et al.* 2002). There is little doubt that nutrient loads are the fuel for algal blooms with high biomass, and chlorophyll increases with increased nutrient concentrations. But evidence that directly correlates eutrophication with noxious algal blooms is not clear. This is due to the

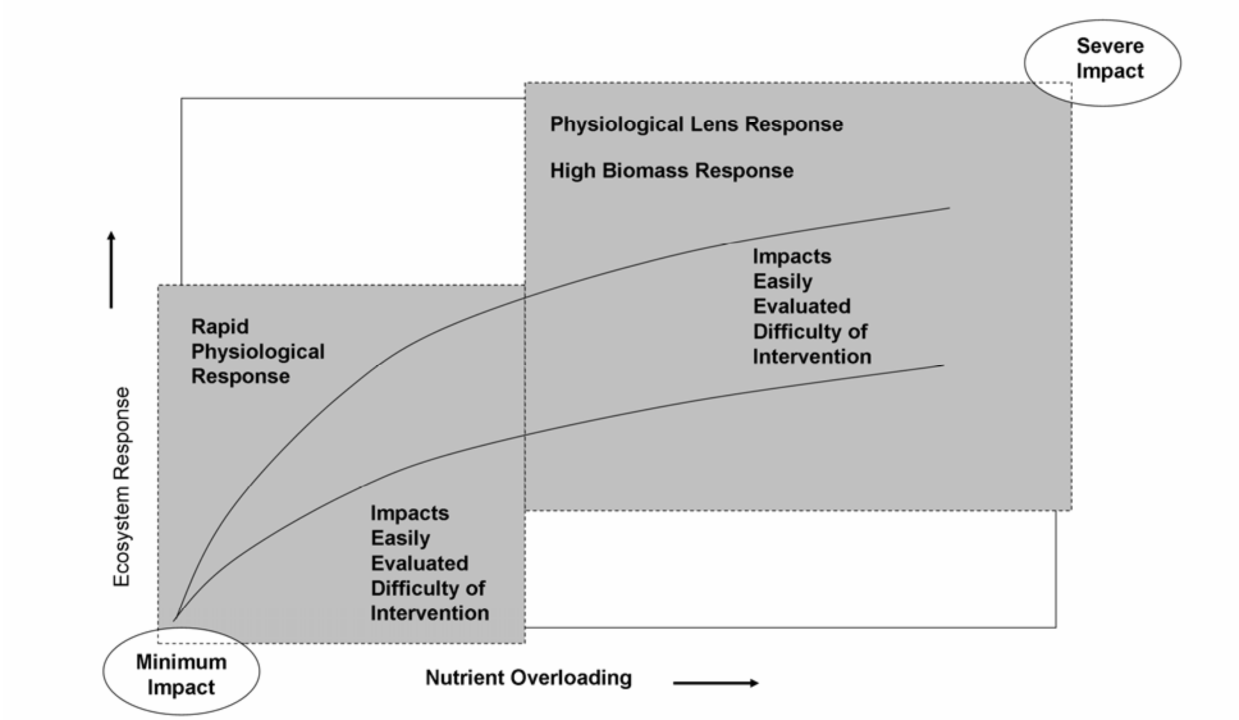


Fig. 14.10. Generalized response of the ecosystem to nutrient overload. At low overload level, organisms can respond rapidly, but changes in biomass may be small. At high overload level, physiological response of the organisms should be close to saturation rate and show little increase, but over a long period of time, biomass could increase. From Anderson *et al*. (2002).

impact of the nutrient load that depends on many factors (some of them in Table 14.2), such as a) bloom species composition; b) macrofaunal nutritional state; c) over-enrichment duration time; and d) environmental dynamics and physical factors of the system. High primary productivity of vascular plants, complex physical structure and characteristic habitats combine to create areas of great productivity and essential environments to support different biological cycles; but if success is desired in environmental management and restoration of these systems, a fundamental understanding of the mechanisms by which nekton can be affected by nutrient enrichment is needed.

For example, Deegan (2002) and Deegan *et al.* (1994, 2002) clearly establish that coastal systems with marine grasses and brackish wetlands have always been valued for their high productivity and importance to fish and crustaceans, but little is known about the link with nutrient enrichment. Figure 14.11 shows that nutrient load alters structural complexity within shallow areas with marine grasses, because the composition and abundance of vegetation cover is modified. Over-enrichment stimulates proliferation of some phytoplankton and rapid growth of epiphyte algae and macroalgae that compete with marine grasses for light and space. In deep systems such as LTdU, phytoplankton blooms can dominate (Day *et al.* 1982, 1988), whereas in very shallow and low energy systems macroalgae can replace marine grasses *(*i.e., LTV, LMT).

Declines in the structural complexity of marine grassbeds can alter predator-prey interactions resulting in an increase in nekton mortality, or a net decrease in nekton abundance biomass or diversity (Deegan *et al.* 1994, 2002; Deegan 2002; Table 14.3). This table shows the

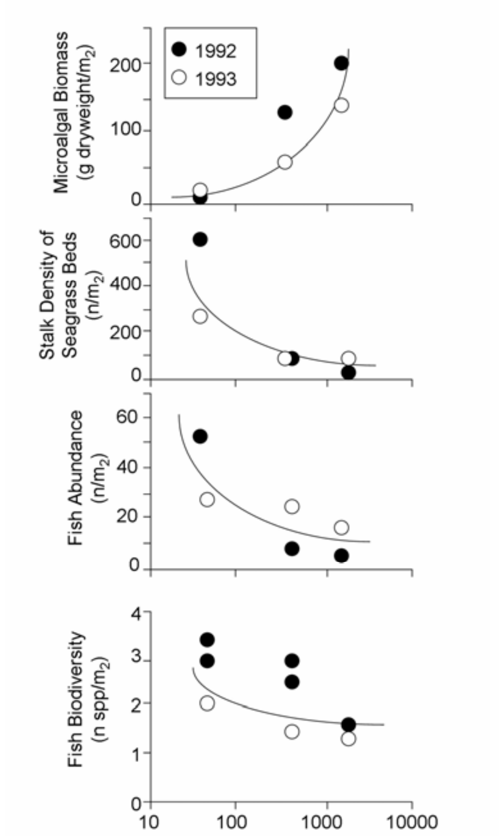


Fig. 14.11. Changes in plants and animals in a seagrass ecosystem in response to nutrient enrichment. From Deegan (2002).

different responses of marine grasses and brackish wetlands facing losses of ecosystem functions. Therefore, a better understanding of geographic variability in the functions of the ecosystems described in Table 14.2 is required to predict responses to nutrient enrichment and to protect ecosystem functioning, conserving estuary-sea ecological interactions.

There are still large gaps in the understanding of nutrient enrichment (Deegan 2002), but there has also been great progress (Rabalais and Nixon 2002). Previously, Deegan *et al.* (1994) considered that is this problem was to be dealt with comprehensively, it was practical to develop a conceptual model such as that shown in Fig. 14.12. At least 15 compartments were considered for the model of the lagoon-estuarine systems nitrogen cycle. The compartments and arrows describe four main patterns in the flow of organic matter and nutrients: a) a classic grazing food chain from inorganic nutrients to phytoplankton >20 mm, followed by macrozooplankton, planktivores and piscivores; b) a microbially-based food chain from organic material to bacteria, then microflagellated to microzooplankton, macrozooplankton, plantivores and piscivores; c) a hybrid chain incorporating elements of both the grazing chain and "microbial" pattern from inorganic nutrients; and d) the detrital chain from organic matter to sediments, bacteria and then benthic meio- and macrofauna, to benthivores and piscivores. The degree and rate at which organic material flows through one pathway or other probably depends on organic material quality (valued by the C:N proportion) and inorganic nutrient availability. How each of the four

Table 14.3. Similarities and differences in effects of nutrient enrichment on habitat structure, dissolved oxygen and food webs of seagrasses and brackish wetlands. “Initial” and “final” indicate whether the effect is expected to occur at the beginning or near the end of the eutrophication process.

Function	Seagrass	Brackish Wetland
Habitat Structure	Initial Overall decrease in area and size of patches; increased edge. Located in estuarine sheet near the mouth. Occurs rapidly; years	Final Potential subsidence relative to sea level. Increased edge and fragmentation. Wetlands near estuary head affected first. Occurs slowly; decades.
Chemical Sensitivity Low Dissolved Oxygen	Initial Results from accumulation of excess organic material, primarily due to algae	Final Results from of natural decomposition of *Spartina* and stimulation of algae and microbial community.
Food Web	Important increase in algae for primary consumers but not for nekton. Changes in the chemical and physical structure of the ecosystem limits nekton to algal production.	Some evidence that in the initial state algae can increase in importance in the food web. Not fully studied.

pathways in the functional structure of the system participates when exposed to nutrient overload is a very recently developed theme in the study of estuary-sea ecological interactions. Evidently, because of the environmental dynamics of LAdP, PCdGU and LTdU (Table 14.2), pathways 1 and 2 in Fig. 14.12, are viable for the continental shelf of the Gulf of Mexico. With nutrient overload, it is fundamental to integrate ecology of freshwater discharge with nutrient enrichment ecology in the management of estuarine resources (Montagna *et al.* 2002).

HYPOXIA

The reduction in dissolved oxygen due to excess nutrient enrichment in coastal waters is one of the most important direct effects on fish. This is why hypoxia can: a) cause mortality in certain species; b) reduce growth rate; c) alter fish distribution and behavior, d) change the relative importance of organisms; e) alter the pattern of carbon flow within the trophic structure; and f) lead to a large reduction in abundance, diversity and landings of fish in affected waters. However, nutrient over-enrichment generally increases catch in most well-oxygenated surface waters and beyond the border of the hypoxic zone, which determines a mosaic of interactions of high and low oxygen within a system and reordering of interspecific relations (Fig. 14.13). The negative effects of hypoxia on fishes, habitats and potential trophic structure, make the fish and the system in general much more susceptible when adding anthropogenic or natural stressors (Chestney and Baltz 2001). Figure 14.13 illustrates the last effect of oxygen reduction on fish

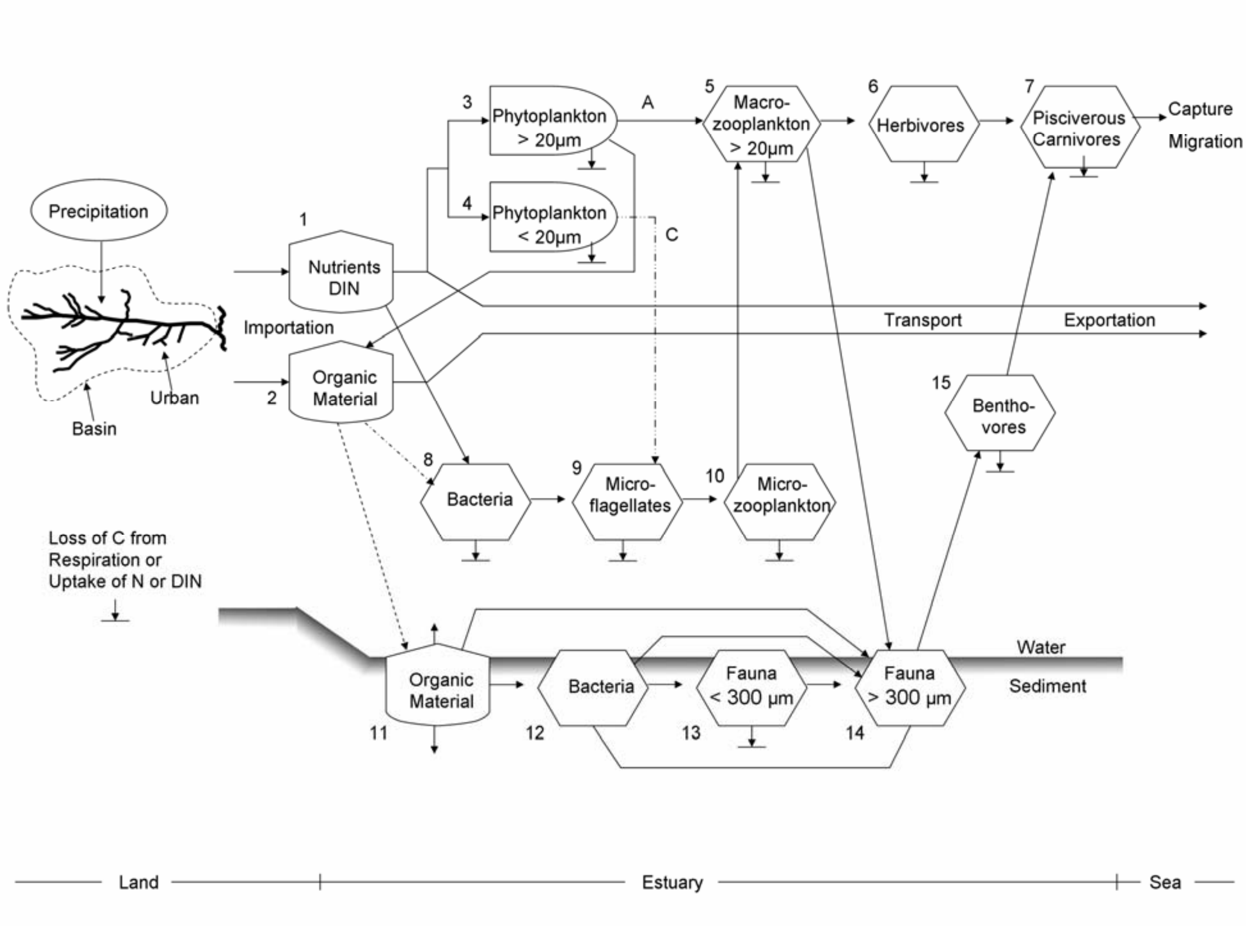


Fig. 14.12. Diagrammatic model of nitrogen flow in an estuary-lagoon system, emphasizing organic and inorganic nitrogen contributions from the hydrological basin to the coastal zone, and the four main pelagic and benthic trophic patterns that lead to production of high level carnivores. DIN = dissolved inorganic nitrogen, DON = dissolved organic nitrogen, DOC = dissolved organic carbon. How estuarine ecosystems can process N is illustrated and the figure has helped in hypothesis development on the final destination of nitrogen. From Deegan *et al.* (1994).

populations, but at the same time describes the mosaic of interactions between interspecific behavior and the reduction of dissolved oxygen with depth.

Important hypoxic zones in the USA are located on the Pawtuxet River, associated with Chesapeake Bay (temperate estuary), and in the Mississippi Sound (temperate subtropical), associated with the Mississippi River basin (Rabalais *et al.* 1999; Breitburg 2002). In the case of the Pawtuxet estuarine system (Fig. 14.13) the reduced dissolved oxygen in June and September (months that correspond to summer in the northern hemisphere) coincides with the large fluvial discharge in March and April (Fig. 14.14). In the case of the continental shelf off Louisiana and Texas, the hypoxic area has varied from 16,000 km^2 in 1993 to 18,000 km^2 in 1995 (Rabalais *et al.* 1999), and is a very significant problem, with the greatest severity in June, July and August, exactly analogous to the Pawtuxet River (Fig. 14.13). Rabalais *et al.* (1999) establish as main

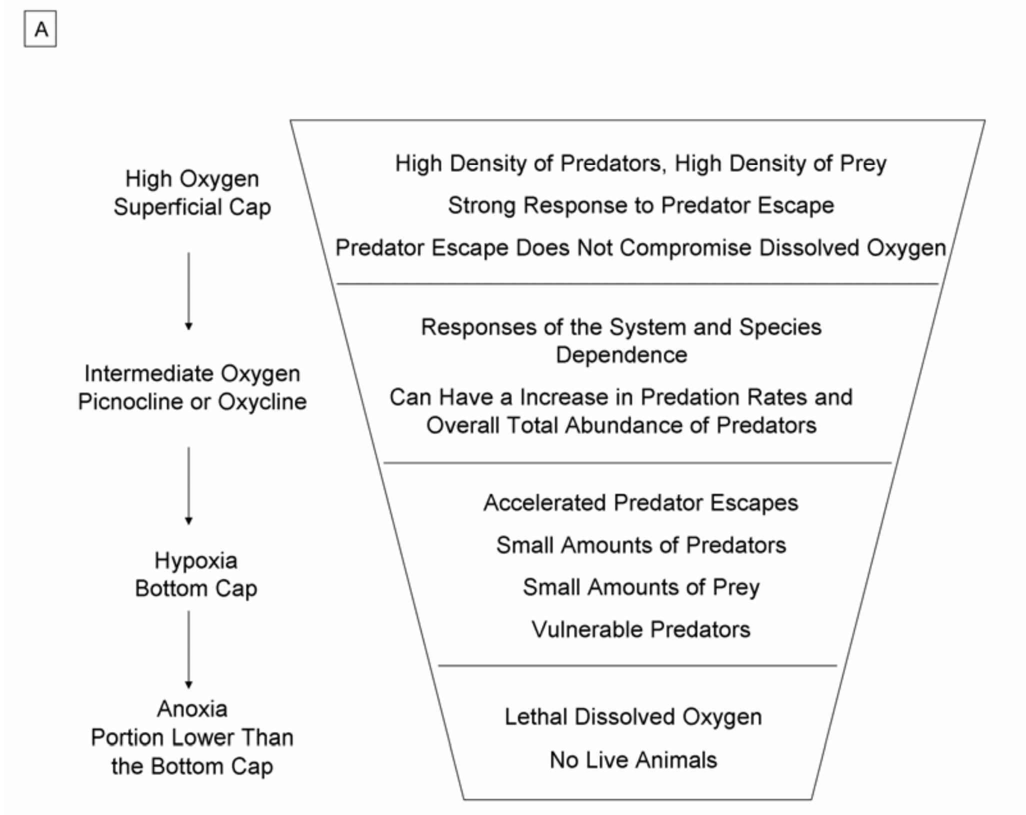
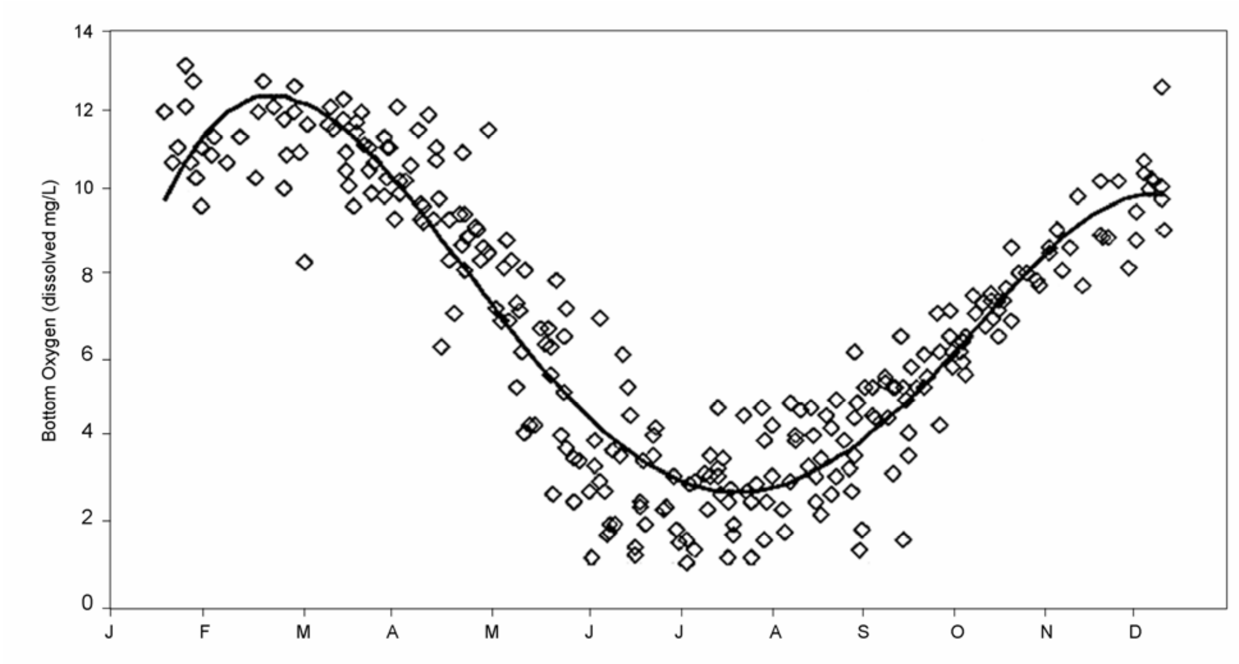


Fig. 14.13. Examples of spatial structure and temporal variability in a temperate estuarine system, resulting from declines in dissolved oxygen (A, B), and hypothetical proposal for the southern Gulf of Mexico (C). A). Spatial vertical structure and spatial variation resulting in direct and indirect effects from reduction in dissolved oxygen. The diagram shows the effect of the concentration of oxygen on various aspects of predator-prey interactions and abundance in different portions of a stratified water column with hypoxia at the bottom. B). Daytime variation of bottom dissolved oxygen, in a mesohaline zone of the Pawtuxet River estuary, USA. Data are dissolved oxygen concentrations near Bromees Island, Maryland. Variations regarding the continuous line (4^o polynomial, R^2=0.87) represent the intra- and inter-annual tendency for 15 years of data. Dissolved oxygen concentration on the bottom can change rapidly if stratification is broken down by turbulent mixing by shore winds. Modified from Breitburg (2002); d from Chesapeake Bay Program <www.chesapeake.net>. C) The analogy of pattern B) for the southern Gulf of Mexico, with maximum pulse of fluvial discharge, organic matter and nutrients of the LAdP, PCdGU and LTdU systems occurring in October; February to May is the dry season marked by greater light penetration and increased water temperature and, accumulation on the bottom in the estuarine plume frontal zone; and from June to September is the wet season with greater decomposition of organic matter on the bottom. It is reasonable to assume that potential hypoxia in Campeche Bay could appear on the continental shelf from LAdP to LTdU prevailing with greater severity from June to August. This hypothesis is explained in the text and should be studied in the immediate future.

B



C

> Bottom Accumulation | Increased Temperature and Light Bottom Decomposition | > River Discharge, Organic Material and Nutrients

Fig. 14.13. Continued.

causes the relatively large changes in freshwater discharge and nutrient flow from the Mississippi River to the coastal zone. This affects: a) water column stability; b) surface water productivity; c) carbon flow; and d) oxygen cycling in the northern Gulf of Mexico. Freshwater discharge from the Atchafalaya and Mississippi rivers rapidly forms the Louisiana coastal current, a highly stratified current that mainly flows to the west, along the Louisiana coast and to the sea along the Texas coast. At present, the hypoxic zone off Louisiana and Texas is 20,000 km^2 (Rozas *et al.* 1999).

POTENTIAL HYPOXIA IN MEXICO

From this perspective, the most susceptible area of potential hypoxia on the Mexican continental shelf of the Gulf of Mexico is Campeche Bay, especially the region that extends from LAdP to LTdU including PCdGU (Table 14.2, Fig. 14.4). The greatest severity of hypoxia would be from June to September, after the biggest fluvial discharges (September to November; Figs. 14.6, 14.13, 14.14) and after the water column has stabilized, following northerlies (October to February). In reality, decline of dissolved oxygen should start in March with a sustained decrease to September (Fig. 14.13c). This hypothesis has been corroborated by the Dirección de Oceanografía y Biología Marina de la Secretaría de Marina de México (Office of Oceanography and Marine Biology of the Marine Ministry of Mexico, with as yet unpublished data (Capt. De Fragata CG, Fernando A Angli Rodríguez, personal communication). Similarly to the U.S., hypoxic potential is probably greatest in the areas of main fishing importance, that are associated with the large deltaic systems with terrigenous bottoms, and influenced by river basins of that are extensively farmed. On the theme, Chestney *et al.* (2000) and Chestney and Baltz (2001) clearly discuss the features of habitats and fishing production, pointing out interesting controversial elements on the real impact of the hypoxia in the fishing resources of the Gulf. These authors conclude that since the fishing captures in Louisiana have not declined in the last 40 years harmful effects cannot be attributed to hypoxia alone. Some changes in structure are evident in the nektonic communities, but it is very complicated to attribute them solely to hypoxia. It is probable that the effects of hypoxia on nekton in the northern Gulf of Mexico are buffered by physiographic and geomorphologic characteristics of the basin (Caddy 1993), due to the type of fishing resource (Chestney and Baltz 2001) and the dynamics of ecosystem and its environmental pulses (Day *et al.* 1995, 1997).

When applied to the scenario of the southern Gulf of Mexico (Figs. 14.13c and 14.14), the approach of Chestney and Baltz (2001) is remarkably correct. The seasonality of fish landings has varied, but there is no information that indicates that this is due to harmful effects from hypoxia. In the southern Gulf of Mexico, fishing productivity is important, sustained, variable and closely linked to the dynamics of the ecosystem, with interaction between alternative functional ecological groups, physiography, biological cycle strategies, and physico-environmental pulses (Sánchez-Gil and Yáñez-Arancibia 1997). Therefore, should potential hypoxia exist, nothing is known about its relationship with or effects on current fishing resources in Campeche Bay. Perhaps it would be pertinent to place hypoxia and fishing resources against relationships that are already known and that are involved in the current debate on the issue. For example, it is known that fishing production and nutrient enrichment correlate positively in diverse marine coastal ecosystems (Nixon 1982; Nixon *et al.* 1986; Caddy 1993; Nixon and Thomas 2001; Nixon and Buckley 2002). Nutrient enrichment and hypoxia also correlate and are closely linked (Rabalais *et al.* 1999). However, as nutrient enrichment increases to the point of overload, instantaneous primary production increases leading to a great deal of secondary production, greater fishing catch and production, prior to abrupt decline associated with excessive eutrophication or collateral factors (Deegan *et al.* 1994; Deegan 2002). In addition, fish landings correlate with intertidal vegetation (Turner 1977), but also with river discharge and vegetation cover integrated to the lagoon-estuarine surface (Yáñez-Arancibia *et al.* 1985). The effects of the seasonality of environmental pulses conditioned by deltaic systems (Day *et al.* 1995, 1997) are an important factor in attenuation of, seasonality and/or disappearance of hypoxia. Recent literature continues to advance understanding of the controversial positive

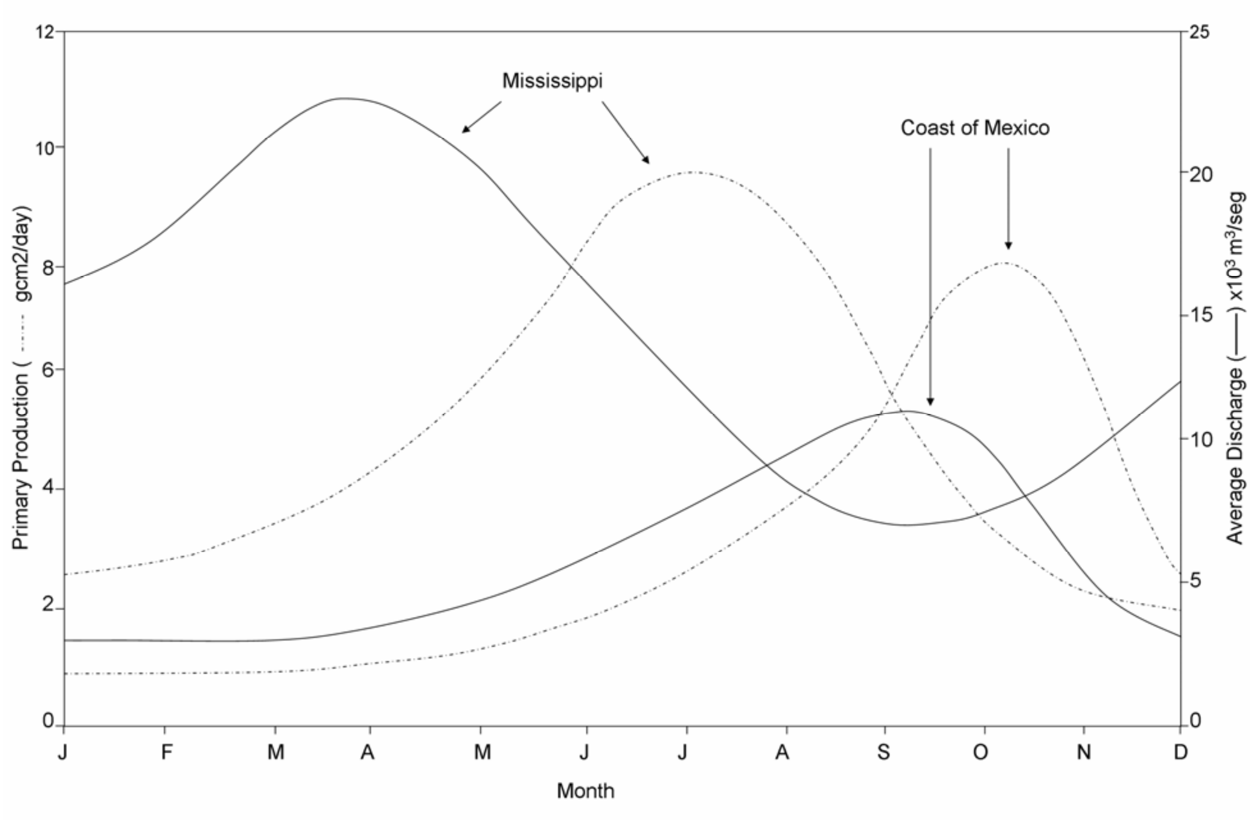


Fig. 14.14. Mississippi River discharge, showing primary production data integrated with the water column for each month, in relation to the average monthly discharge 1930-1994.

correlation between coastal vegetation and fishing catch, as well as the relationships between river discharge and fishing production, nutrients and fishing production, or nutrients and hypoxia. The debate of this decade is hypoxia and fishing production (Fig. 14.15).

Coastal Processes and Fishing Resources

Ecologically, the southern Gulf of Mexico is a large region where coastal and ecological processes are closely interconnected. The processes: a) climatic-meteorological; b) sedimentary; as well as c) river discharge, are the main physical variables that control the biological processes that impact fishing resources. The main habitats of the regional coastal zone (Figs 14.5a, b) are in close estuary-sea ecological interaction. This close relationships favors fishing resources (Yánez-Arancibia and Sánchez-Gil 1983; 1986, 1988; Yáñez-Arancibia *et al.* 1983) which are abundant and diverse even though the lagoon-estuarine systems are highly dynamic and physically variable (Table 14.2).

For example, Fig. 14.16 illustrates the gradient of climatic budget for the whole Gulf coast and clearly highlights greater evaporation than precipitation in the Texas/Tamaulipas area and in Yucatán as well as high rainfall in the Veracruz/Tabasco/Campeche area which correlates to the enormous discharge from the Mississippi and Usumacinta/Grijalva rivers. This climatic-meteorological scenario conditions to a great extent the parameters presented in Table 14.2. This characterization can sustain the hypothesis of high fish biodiversity described by Lara-Domínguez *et al.* (1993) for the coastal zone of the Gulf of Mexico, and furthermore, sustains

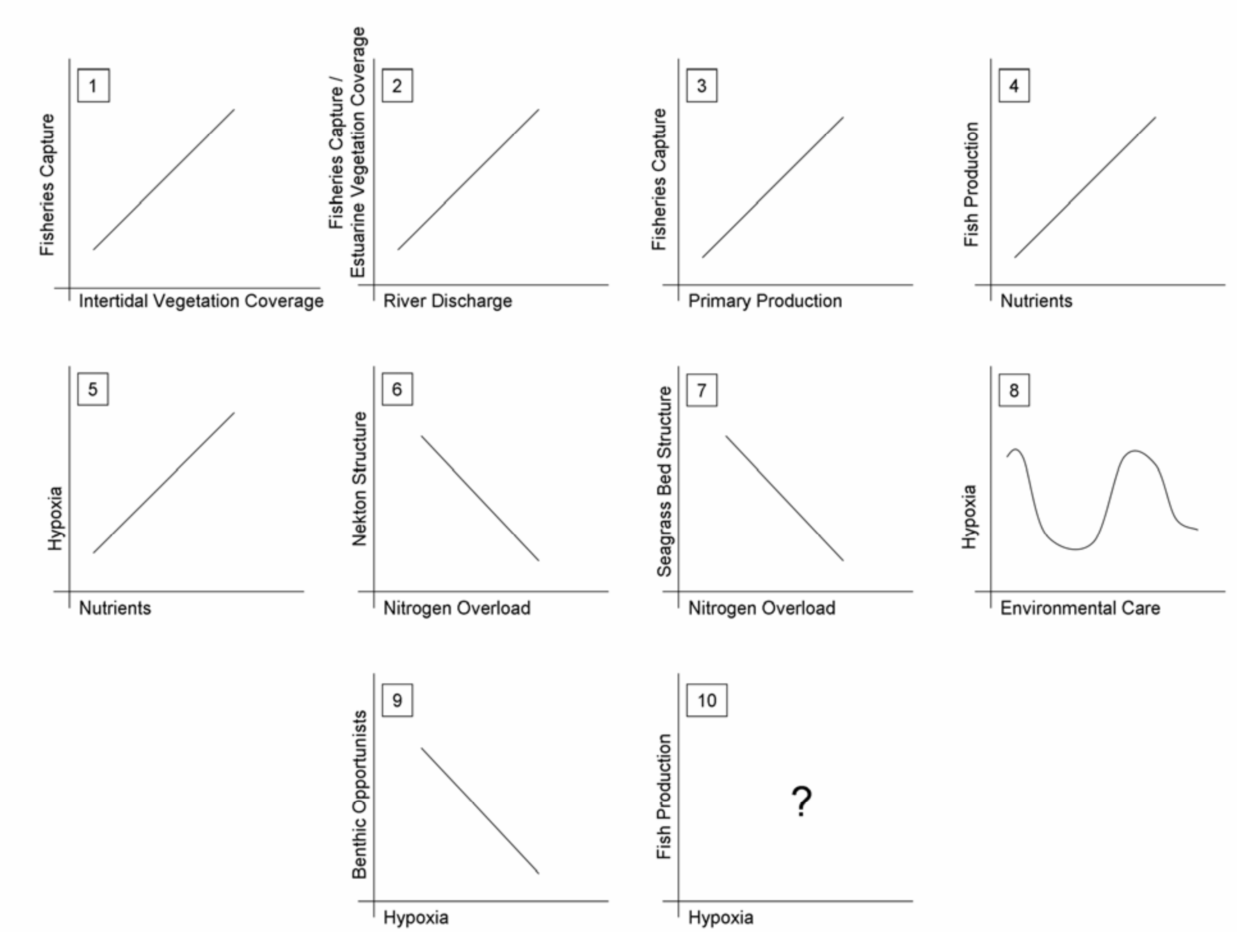


Fig. 14.15. Thirty-year synthesis of problems, questions and answers on characteristics of coastal ecosystem and fishing resources, showing the trend for 2000-2010. Data used to construct the conceptual figures: 1. Turner (1977); 2. Yáñez-Arancibia *et al.* (1985); 3. Nixon *et al.*(1986); 4. Deegan *et al.* (1994); 5. Rabalais *et al*. (1999); 6 and 7. Deegan (2002); 8. Day *et al*. (1997); 9. Chestney *et al.* (2000); 10. Chestney and Baltz (2001).

the Louisiana/Texas and Campeche Bay neritic shelf, as the two main centers of fishing abundance of the Gulf of Mexico. This is due to the great morpho-physiological adaptation of organisms to an extensive coastal ecosystem of enormous neritic habitat heterogeneity (Deegan *et al.* 1986; Pauly 1986; Sánchez-Gil and Yáñez-Arancibia 1997; Chestney *et al.* 2000; Chestney and Baltz 2001).

The use of habitats by coastal fish in estuary-sea ecological interactions is not by chance. Feeding and reproduction, as well as the condition of the young of many species (particularly the dominant ones) benefit significantly from exploiting high productivity in both time and space in the coastal system through important evolutionary adaptations (Yáñez-Arancibia *et al.* 1980, 1985, 1993; Day *et al.* 1989; Rojas-Galavíz *et al.* 1992;). When ecologically interpreting environmental system dynamics, the answers and explanations are found in behavior of biological resources, their productivity mechanisms and the interaction (physical and biological) of the continental shelf with the protected waters of the coast. For example, Yáñez-Arancibia and

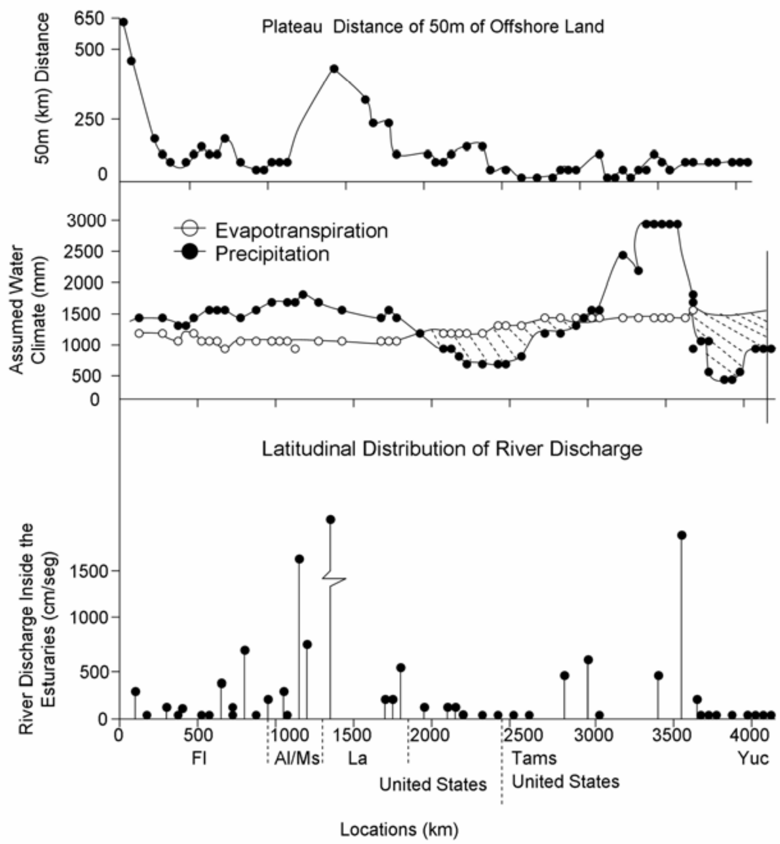
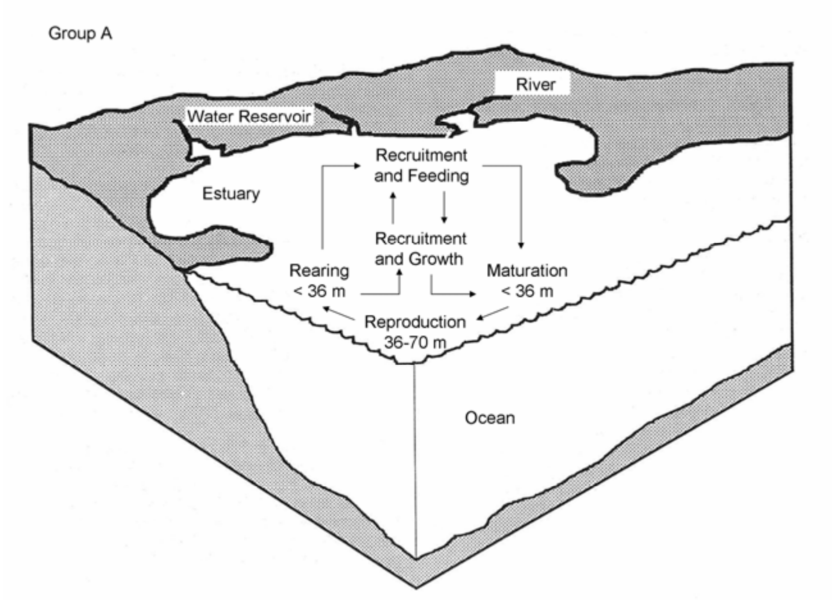


Fig. 14.16. Gradient from southern Florida to northern Yucatán in the Gulf of Mexico. A) distance of the coastline to the 50m point inland. Each point corresponds to an estuarine lagoon system (n=64) in Deegan *et al*. (1986). B) Water budget (shaded area represents evapotranspiration that exceeds precipitation). C) total annual fluvial discharge (m^3/ sec). The extensive coastal plain of the Mississippi/Louisiana area stands out. Far greater evaporation than rainfall occurs in the Texas/Tamaulipas area and in Yucatán, high rainfall occurs in the Veracruz/Tabasco/Campeche area and enormous fluvial discharge occurs in the Mississippi and Grijalva/Usumacinta delta. See Table 4.2 and Figs. 4.4 and 4.6.

Pauly (1986) summarize the results of a workshop of experts who give clear examples that in tropical coasts such as that of the Gulf of Mexico, coastal ecological processes modulate and condition, in first place, the success of biological recruitment, followed by that of fishing. In this sense, Figs. 14.17 and 14.18 by Sánchez-Gil and Yáñez-Arancibia (1997) show, for two functionally different ecological groups, the positive correlation between biological recruitment in estuarine-lagoon systems, and fluvial discharge and primary aquatic production described in Figs. 14.6 and 14.14. This is evident for Group A species (Fig. 14.17), but the correlation is maintained with the displacement of primary aquatic productivity toward the continental shelf via the estuarine plume, in Group D species (Fig. 14.18), whose recruitment to the continental shelf, both biological and fishing, is related not only to bathymetry and sedimentary



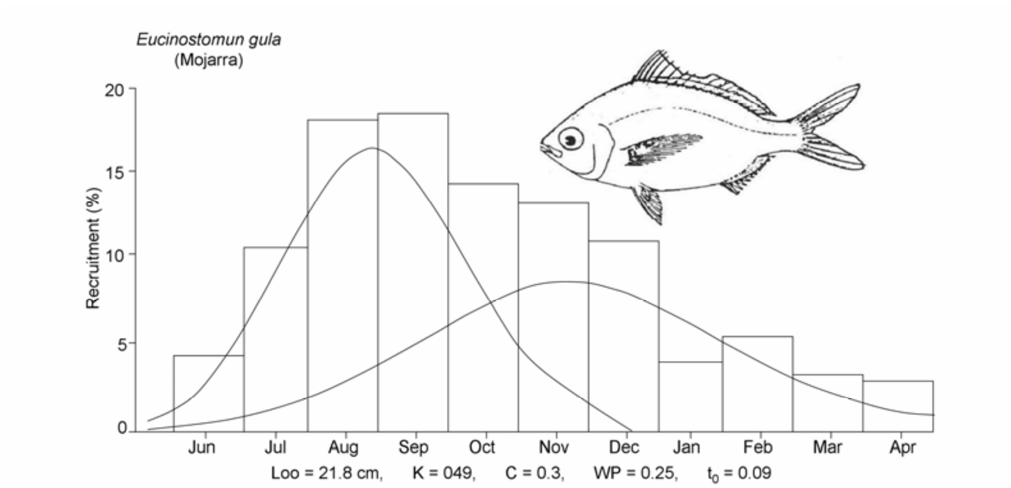
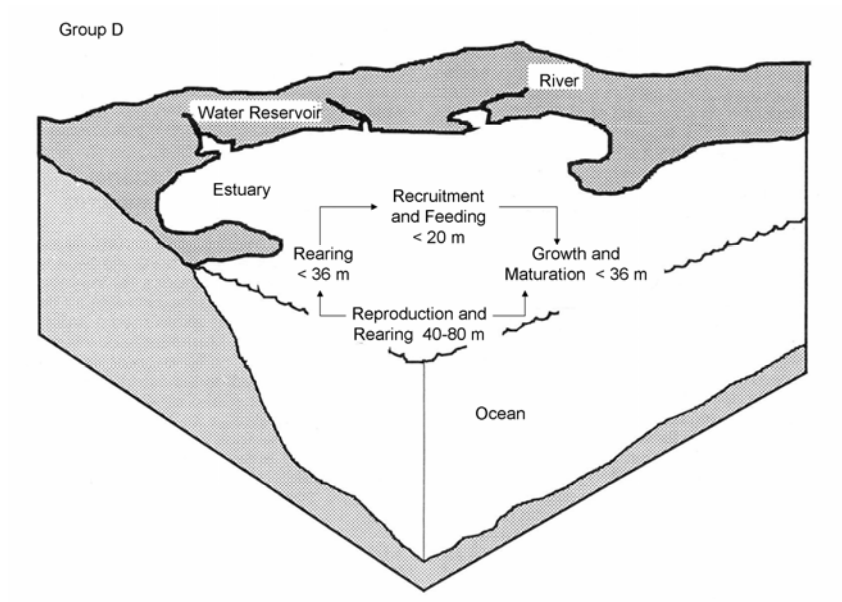


Fig. 14.17. Model of the life cycle of fish in “Functional Ecological Group A”, estuarine-dependent marine species. Seasonal pattern of recruitment (FAO ICLARM stock assessment package) and “example species” population structure parameters. Biological recruitment (4) and feeding occur within the associated lagoon-estuarine system in August and September (rain; higher mangrove and phytoplankton productivity inside the system), but fishing recruitment (3) and growth occur outside the system of protected waters from October to December (greatest river discharge toward the continental shelf, on the estuarine plume) with greatest primary aquatic production in the adjacent sea. From Sánchez-Gil and Yáñez-Arancibia (1997).



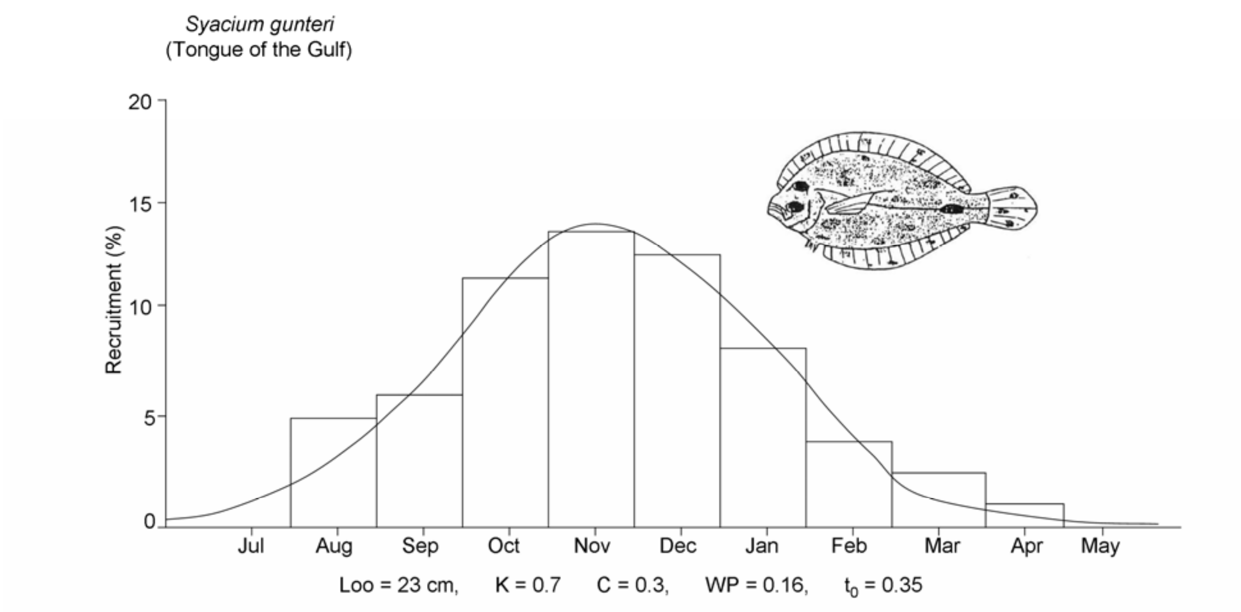


Fig. 14.18. Model of the life-cycle of fish in the "Functional Ecological Group D", marine species unrelated to estuaries but influenced by the estuarine plume. Seasonal pattern of recruitment (FAO ICLARM stock assessment package) and "example species" population structure parameters. The main recruitment pulse between October and December is marked (greatest river discharge toward the continental shelf, on the estuarine plume) and coincides with greatest primary aquatic production in the frontal zone. From Sánchez-Gil and Yáñez-Arancibia (1997).

environment, but also to seasonality of primary aquatic production and precipitation/freshwater discharge, described in Figs. 14.4, 14.6 and 14.14.

It is reasonable to assume that this proposal can also be valid, to a larger or smaller extent, for the coastal zone of the Laguna Madre in Tamaulipas, the Tamiahua and Alvarado lagoons in Veracruz, the coastal marshes in Tabasco, the Río Celestún in Yucatán and some systems such as Bahía Chetumal in the Mexican Caribbean, in relation to the latitudinal gradient described in Table 14.2.

The Gulf of Mexico is one of the most important systems in the world to scientifically understand tropical and subtropical fisheries in the context of coastal ecosystem (Pauly 1986, Yáñez-Arancibia and Pauly 1986, Longhurst and Pauly 1987). The continental shelf in the southern Gulf of Mexico is a region with great potential to expand fish landings, given the estimate that from Tamaulipas to Yucatán currently about 350,000 metric tones of incidental catch in shrimp fishing and trawl fishing is not used. However, the most remarkable thing is that multiple species use coastal zone resources intensely for feeding, refuge, growth or reproduction activities, with over 300 species fishes in the neritic shelf of the Gulf, of which ~75% use or depend on the coastal lagoons and estuaries to complete part of their life-cycle (Yáñez-Arancibia 1985, 1994; Yáñez-Arancibia and Sánchez-Gil 1986, 1988; Sánchez-Gil and Yáñez-Arancibia 1997).

Another notable ecological aspect that is known in the Gulf is the relation between the fish landings and the ecosystem. For example, important logarithmic correlations have been estimated between fish and crustacean catch and river discharge, coastal vegetation of protected waters and lagoon-estuarine system surface (Turner 1977; Yáñez-Arancibia *et al.* 1985, 1993; Deegan *et al.* 1986). Figure 14.19 analyzes not only lagoon-estuarine surface (including the body of water area and the associated area of vegetation cover), but also the average annual river discharge for the Gulf of Mexico.

Therefore, understanding Fig. 14.19 contextually and conceptually, but also reviewing the 30-year synthesis of problems, questions and answers about the linkages between fishing resources and characteristics of the coastal ecosystem (Fig. 14.15), leave few doubts regarding the dependence of fishing resources on the ecological processes of coastal ecosystems. These examples are fundamental to understanding fisheries in the region in the larger context of the coastal ecosystem of the Gulf of Mexico, and to visualize its limit of “uncertainty” in the face of environmental deterioration and declines in water quality and coastal habitats affected.

A retrospective look at Fig. 14.15 shows us that important efforts are still being made to link primary production provided by coastal processes, with secondary production, specifically with fishing resources (Yáñez-Arancibia *et al.* 1993, Nixon and Buckley 2002, Fig. 14.20). Even though recent efforts have concentrated on coastal ecosystems in intermediate or high latitudes, on tropical coasts this apparently has been well known for over two decades (Yáñez-Arancibia *et al.* 1980, 1988, 1993; Nixon 1982; Yáñez-Arancibia 1985, 1994; Yáñez-Arancibia and Pauly 1986; Yáñez-Arancibia and Sánchez-Gil 1988; Sánchez-Gil and Yáñez-Arancibia 1997). The point of uncertainty in common is that of “sustainability” of the model of Figs. 14.19-14.20. It is reasonable to assume that in none of the cases the decline could be maintained in the face of the deterioration of coastal processes that condition logarithmic regression, specially if the general model by Day *et al.* (1997) is applied to the Gulf of Mexico, confronting natural land areas and conversion of wetlands to open waters in relation to the abrupt fall in total net productivity of the coastal zone in the Gulf of Mexico (Fig. 14.21). This figure is, at the beginning of the 21st century, a permanently red light in the Gulf of Mexico.

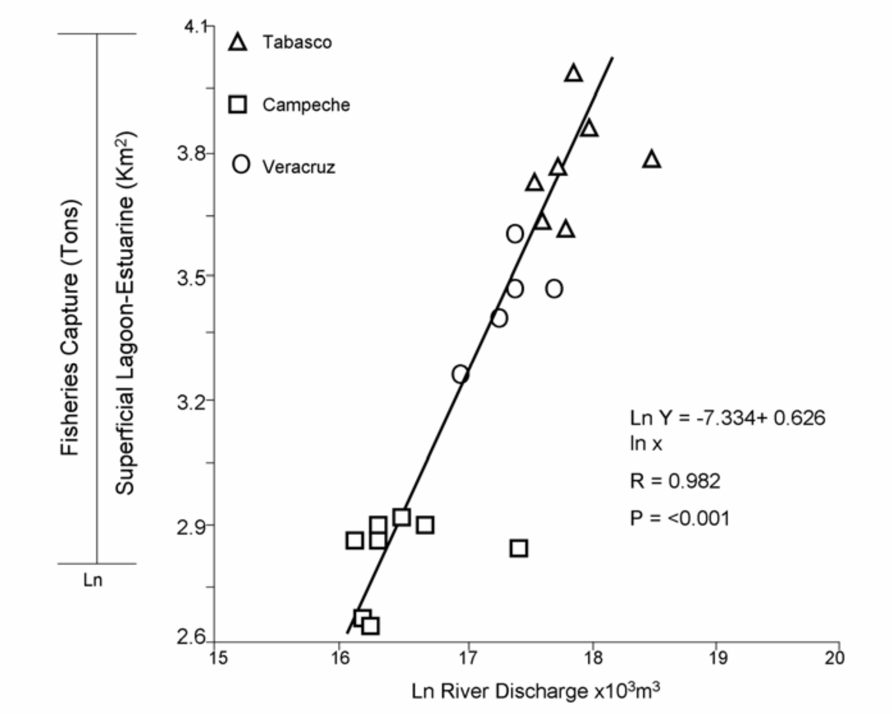


Figure 14.19. Linear logarithmic (ln) regression between fishing catch (metric tons/year) per lagoon-estuarine surface (including body of water area and associated vegetation cover) and annual average of river discharge for the Gulf of Mexico. Data for Veracruz, Tabasco and Campeche, 1973-1983 courtesy of INEGI, ex Secretaría de Pesca and ex Secretaría de Recursos Hidráulicos as detailed in Yáñez-Arancibia *et al*. (1985), and Deegan *et al*. (1986).

In the theoretical framework for coastal environment management of fishing resources, the uncertainty of sustainability is marked by urgent protection for the persistence of estuary-sea ecological interactions (Yáñez-Arancibia *et al.* 1991), conservation of the vegetation cover of coastal wetlands (Yáñez-Arancibia *et al.* 1988, 1993; Rojas-Galavíz *et al.* 1992), protection of sedimentary environments in the low river basins (Ortíz-Pérez and Benítez 1996), and maintenance of freshwater supply to the estuaries via river discharge (Powell *et al.* 2002; Yáñez-Arancibia *et al.* 2003), with the aim of ensuring the persistence of aquatic productivity on the neritic continental shelf (Day *et al.* 1995, 1997). Therefore, with the “coastal processes and fishing resources” approach, the main environmental problems that the greater Gulf basin faces are: a) loss of habitat; b) loss of biodiversity; c) water and sediment pollution; d) increased turbidity and nutrients; e) quality and reduction in freshwater supply to the coastal plain; f) alteration of estuarine dynamics and its connections; g) coastal erosion; and h) deterioration in public health.

SUMMARY AND CONCLUSIONS

1. Estuary-sea ecological interactions allow interpretation of linkages between coastal freshwater and adjacent marine environment, which in the Gulf of Mexico is understood by comparing contrasting lagoon-estuarine systems in a large latitudinal range.

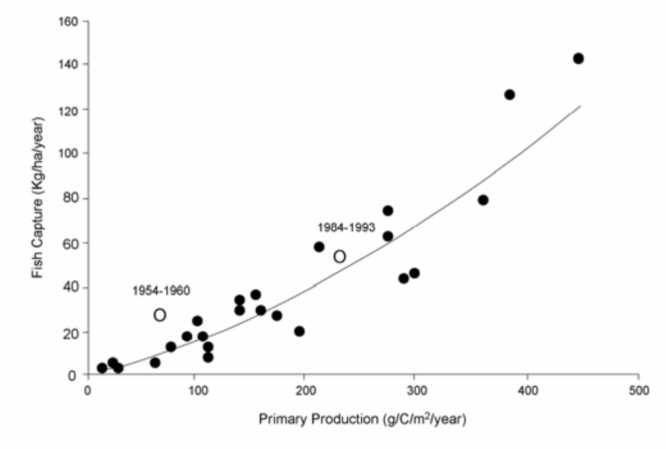


Fig. 14.20. Relationship between primary production (capture of particulate C^{14}) and commercial fisheries catch in some coastal-marine ecosystems with trophic structures based on phytoplankton. Data is not necessarily contemporary (Nixon and Thomas 2001). Open circles are data from the Kattegat during two different time periods. The increase in primary production is consistent with the increase in nitrogen contribution (Richardson and Heilmann 1995). Catch per area unit is calculated for the area of the Kattegat 22,177 km^2. From Nixon and Buckley (2002).

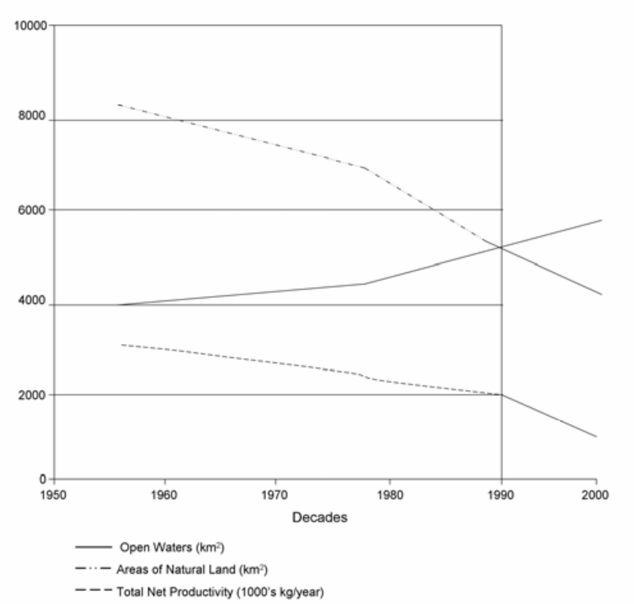


Fig. 14.21. The loss of original vegetation cover and reduction in wetlands increasing bodies of water by dredging and channeling is directly related to reduction in net productivity of the coastal zone (kg dry weight/year). The area of natural land includes forested wetlands, freshwater wetlands and brackish marshland, but excludes agriculturally developed areas. Agricultural productivity is incorporated into total net productivity which markedly decreases in the 1990s. The graph illustrates the coasts of Louisiana, according to the model by Day *et al*. (1997), but its analogical projection is as or more severe for the coasts of Mexico, given that the loss in Veracruz is 87%, Tabasco is 65%, and in Campeche 50%. Data from Coastal Resources Program database, INECOL A.C., CONACYT.

2. The purpose of an environmental diagnosis is to interpret ecosystems and offer integrated information for decision-making and management of natural resources. In this, definition of concepts is fundamental; coastal zone, estuary, coastal lagoon, lagoon-estuarine system, clastic depositional environment, facies, estuarine plume, and environmental pulses.
3. The dynamics of estuary-sea ecological interactions is conditioned by the geomorphological and hydrodynamic setting, which are themselves conditioned by physiography and climatic-meteorological pulses.
4. The results presented in the figures and in Table 14.2 clearly show that, due to the estuary-sea ecological interactions, a distinctive region can be observed from LMT to LTV, that could extend to the center north of the state of Veracruz. Furthermore, the region that runs from LAdP to LTdU, including PCdGU, is clearly different from the previously described region, and that it differs ecologically from the coast of the Yucatán Peninsula.
5. The systems described in this chapter provide examples of the lagoon-estuarine heterogeneity that exists in the Gulf of Mexico and the Caribbean Sea (Table 14.2). They can be divided into four categories. Semi-arid lagoon-estuarine systems (LMT and LCY), intermediate systems not dominated by rivers (LTV), systems dominated by rivers (LAdP, PCdGU and LTdU), and karstic systems on the Caribbean coast (LPMQ and LSQ).
6. The semi-arid systems LMT and LCY, despite being far apart latitudinally, are similar in that they are dominated by marine processes and have a limited contribution of freshwater. They differ in that LMT has a long residence time and high retention of nutrients, in comparison to LCY.
7. Water climate, river discharge, residence time in the mixing zone, nutrient and fertilizer concentration, and sediment trap efficiency, suggest that the systems studied in the coastal zone of the Gulf and Caribbean (except LPMQ and LSQ), are highly susceptible to eutrophication but this could be even greater in the LAdP, PCdGU and LTdU systems.
8. River-dominated systems are characterized by large progradient deltas and a wide estuarine plume on the continental shelf (i.e., LAdP, PCdGU, LTdU). They have a comparatively shorter residence time of mixed waters than the semi-arid systems, which is much less during the periods of greater river discharge, and which increases nutrient and sediment discharge to the ocean through the estuarine mouths.
9. The net result of these processes is that these river-dominated systems do not accumulate great quantities of dissolved inorganic substances during the season of northerlies, as occurs in systems with a long residence time. The synergistic effect with temperature and the good availability of light contribute to maintaining high rates of phytoplankton production at the leading edge of the estuarine plume almost all year round. Therefore, phytoplankton is an important regulator of nutrient dynamics in these systems, and values in the Gulf of Mexico can reach up to 350 gCm^2/year.
10. Given that nutrient load in these river-dominated systems in the Gulf of Mexico is primarily a result of a large discharge rather than high nutrient concentration, this suggests that these systems are placed below others in the relationship established between "phytoplankton production vs. chlorophyll concentration" and nutrient load. At the same time, seasonal environmental pulses in these shallow systems are very important in sustaining coastal-marine productivity on the neritic shelf of the Gulf of Mexico.
11. There is enough information to understand that aquatic productivity on the continental shelf from the Mississippi Sound to Campeche Bay is determined by coastal processes (i.e.,

river discharge, coastal circulation, tides, residual currents, winds, coastal vegetation cover), and is correlated with the terrigenous sedimentary province, in an estuary-sea ecological interaction dynamic, as a reflection of important estuarine plume fronts. Several satellite images reinforce the hypothesis that coastal processes modulate aquatic productivity and its seasonality in the Mexican coastal zone in the southern Gulf.

12. The susceptibility of the lagoon-estuarine systems to eutrophication and reduction in their pattern of sustainable fisheries on the neritic shelf is the main effect of the persistent reduction in natural vegetation cover of the hydrological basins and of the wetlands associated with the estuarine basin, as well as water quality in the mixing zone.
13. Eutrophication is directly linked to increased hypoxia and blooming of toxic algae, as well as an increase in bioaccumulation of noxious organic and inorganic compounds in the upper trophic levels of the estuarine-dependent coastal food web. Due to the magnitude of the estuary-sea ecological interactions, hypothetically, the region that runs from LAdP to PCdGU is the area of the neritic continental shelf with greatest potential for significant hypoxia in the short term.
14. With the analysis of the estuary-sea ecological interactions, the main problems faced by the greater Gulf basin are: a) loss of essential habitats; b) water and sediment pollution; c) increased turbidity and nutrients; d) reduction in freshwater discharge and its quality to the coastal plain; e) alteration of the estuarine dynamics and its connections; f) coastal erosion; g) loss of biodiversity; and h) deterioration in public health.
15. With a functional ecological approach, environmental management of the coastal zone of the Gulf of Mexico and the Caribbean Sea faces a great challenge to: a) guarantee the functioning of estuary-sea ecological interactions; b) conserve vegetation cover of the coastal wetlands; c) protect the sedimentary environments in the lower river basins; and d) maintain the supply of freshwater to the estuaries in order to guarantee the persistence of aquatic productivity on the neritic continental shelf.

LITERATURE CITED

Abarca L. G. and E. Valero. 1993. Toward a trophic model of Tamiahua a coastal lagoon in México. Pp. 181-185 in V. Christensen and D. Pauly (eds.), *Trophic Models of Aquatic Ecosystems.* ICLARM Conference Proceedings 26. Manilla, Phillipines: International Center for Living Aquatic Resources Management.

Alvarez-Guillén, H., M. C. García, M. Tapia, G. J. Villalobos and A. Yáñez-Arancibia. 1986. Prospección ictioecológica de la zona de pastos marinos de la laguna arrecifal en Puerto Morelos, Quintana Roo (Verano 1984). *Anales del Instituto de Ciencias del Mar y Limnología UNAM* 13(3):303-322.

Anderson, D. M., P. Gilbert and J. M. Burkholder. 2002. Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. *Estuaries* 25:704-726.

Barba-Macias, E. 2003. Energy fluxes in seagrass ecosystem from a hypersaline coastal lagoon, Laguna Madre Tamaulipas, México. ERF 2003 Conference Abstracts, Seattle, Washington.

Bianchi, T. S., J. R. Pennock and R. R. Twilley. 1999. Biogeochemistry of Gulf of Mexico estuaries: implications for management. Pp. 407-421 in T. S. Bianchi, J. R. Pennock, and R .R. Twilley (eds.), *Biogeochemistry of Gulf of Mexico Estuaries.* New York: John Wiley & Sons, Inc.

Bird, E.C.F. 1968. *An Introduction to Systematic Geomorphology: Coast, Vol. 4.* Cambridge, Massachusetts: MIT Press. 246 pp.

Boyd, R., R. Dalrymple and B.A. Zaitlin. 1992. Classification of clastic coastal depositional environments. *Sedimentary Geology* 80:139-150.

Breitburg, D. 2002. Effects of hypoxia, and balance between hypoxia and enrichment on coastal fisheries. *Estuaries* 25:767-781.

Caddy, J. E. 1993. Towards a comparative evaluation of human impacts on fishery ecosystems of enclosed and semi-enclosed seas. *Reviews in Fisheries Science* 1:57 95.

Cardoch, L., J. W. Day an C. Ibáñez. 2002. Net primary productivity as an indicator of sustainability in the Ebro and Mississippi deltas. *Ecological Applications* 12:10441055.

Chestney, E. J.,D. Baltz and R. G. Thomas. 2000.Louisiana estuarine coastal fisheries and habitats: perspectives from a fish´s eye view. *Ecological Applications* 10:350-366.

Chestney, E. J. and D. Baltz. 2001. The effects of hypoxia on the northern Gulf of Mexico coastal ecosystem: a fisheries perspective. Pp. 321-354 in N. N. Rabalais and R. E. Turner (eds.), *Coastal Hypoxia: Consequences for Living Resources and Ecosystems.* Coastal and Estuarine Studies Series Volume 58. Washington D.C.: American Geophysical Union.

Chua, T. E. and D. Pauly (eds.) 1989. *Coastal Area Management in Southeast Asia: Policies, Management, Strategies and Case Studies*. ICLARM Conference Proceedings19. Kuala Lumpur, Malaysia: Ministry of Science, Technology and the Environment. 254 p.

Chua, T. E. and L. F. Scura (eds.). 1992. *Integrative Framework and Methods for Coastal Area Management*. ICLARM Technical Reports 37. Manilla, Phillipines: International Center for Living Aquatic Resources Management. 169 p.

Cicin-Sain, B. and R. Knecht. 1998. *Integrated Coastal and Ocean Management: Concepts and Practices*. Washington D.C.: Island Press. 543 p.

Dalrymple, R. W., B. A. Zaitlin and R. Boyd. 1992. Estuarine facies models: conceptual basis and stratigraphic implications. *Journal of Sedimentary Petrology* 62:1130-1146.

Day, J. W. and A. Yáñez-Arancibia. 1982. Coastal lagoons and estuaries: ecosystem approach. *Ciencia Interamericana* 22(1-2):11-26.

Day, J.W., C.A.S. Hall, M. Kemp and A. Yáñez-Arancibia. 1989. *Estuarine Ecology*. New York: Wiley Interscience. 548 p.

Day, J. W., D. Pont, P. Hensel and C. Ibáñez. 1995. Impacts of sea level rise on deltas in the Gulf of Mexico and the Mediterranean: the importance of pulsing events to sustainability. *Estuaries* 18:636-647.

Day, J. W., J. F. Martin, L. Cardoch and P. H. Templet. 1997. System functioning as a basis for sustainable management of deltaic ecosystems. *Coastal Management* 25(2):115-153.

Day, J. W., R. H. Day, M. T. Barreiro, F. Ley and C. J. Madden. 1982. Primary production in Términos Lagoon, a tropical estuary in the southern Gulf of Mexico. *Oceanologica Acta* 5: 269-276.

Day, J. W., W. Conner, F. Ley, R. Day and A. Machado. 1987. The productivity and composition of mangrove forest, Laguna de Términos Mexico. *Aquatic Botany* 27:267-284.

Day, J. W., C. J. Madden, F. Ley, R. L. Wetzel and A. Machado. 1988. Aquatic primary productivity in the Términos Lagoon. Pp. 221-236 in A. Yáñez-Arancibia and J.W. Day (eds.), *Ecology of Coastal Ecosystems in the Southern Gulf of Mexico: The Terminos Lagoon Region.* Instituto de Ciencias del Mar y Limnología-UNAM México, Organization of American States, Washington D.C., Coastal Ecology Institute, Louisiana State University, Baton Rouge, Louisiana. México D.F.: Editorial Universitaria.

David, L. T. and B. Kjerfve. 1998. Tides and currents in a two-inlet coastal lagoon: Laguna de Términos México. *Continental Shelf Research* 18:1057-1079.

Deegan, L. 2002. Lessons learned: the effects of nutrient enrichment on the support of nekton by seagrass and salt marsh ecosystems. *Estuaries* 25 (4):727-742.

Deegan, L., J. Hughes, and R. Rountree. 2002. Salt marsh ecosystem support of marine transient species. Pp. 333-365 in M. P. Weinstein and D. A. Kreeger (eds.), *Concepts and Controversies in Tidal Marsh Ecology*. Amsterdam: Kluwer Academic Publishers.

Deegan, L., J. W. Day, J. G. Gosselink, A. Yáñez-Arancibia, G. Soberón-Chávez and P. Sánchez-Gil. 1986. Relationships among physical characteristics, vegetation distribution, and fisheries yield in Gulf of Mexico estuaries. Pp. 83-100 in D. A. Wolfe (ed.), *Estuarine Variability*. New York: Academic Press Inc.

Deegan, L., J. T. Finn, C. Hopkinson, A. Giblin, B. Peterson, B. Fry and J. Hobbie. 1994. Flow model analysis of the effects of organic matter-nutrient interactions on estuarine trophic dynamics. Pp. 273-281 in K. R. Dyer and R. J. Orth (eds.), *Changes in Fluxes in Estuaries: Implications from Science to Management*. ECSA/ERF Symposium, Institute of Marine Studies, University of Plymouth. Fredensborg, Denmark: Olsen & Olsen, International Symposium Series.

Dyer, K. R. and R.J. Orth (eds.). 1994. *Changes in Fluxes in Estuaries: Implications from Science to Management*. ECSA/ERF Symposium, Institute of Marine Studies, University of Plymouth. Fredensborg, Denmark: Olsen & Olsen, International Symposium Series. 485 p.

Harris, P. T. and A.D. Heap. 2003. Environmental management of clastic costal depositional environments: inferences from an Australian geomorphic data base. *Ocean & Coastal Management* 46:457-478.

Harris, P. T., A. D. Heap, S. M. Bryce, R. Porter-Smith, D. A. Ryan and D. T. Heggie. 2002. Classification of Australian clastic coastal depositional environments based upon a quantitative analysis of wave, tide and river power. *Journal o f Sedimentary Research* 72:858-870.

Herrera Silveira, J. A., I. Medina-Gómez, N. Aranda-Cicerol, J. A. Zaldivar, J. Ramírez and J. Trejo. 2002. Trophic status in coastal waters of the Yucatán Peninsula (SE México) using water quality indicators. Pp. 351-359 in C. A. Brebbia, (ed.), *Environment Problems in Coastal Regions IV*. Transactions of the Wessex Institute, Ecology and the Environment, Volume 58. Southampton, U.K: WIT Press.

Kjerfve, B. (ed.). 1978. *Estuarine Transport Processes, Volume 7*. Belle W. Baruch Institute for Marine Biology and Coastal Research. Columbia: University of South Carolina Press. 337 p.

Kjerfve, B. (ed.). 1994. *Coastal Lagoon Processes*. Elsevier Oceanography Series 60. Amsterdam: Elsevier Science B.V. 577 p.

Kumpf, H., K. Steidinger and K. Sherman (eds.). 1999. *The Gulf of Mexico Large Marine Ecosystem: Assessment, Sustainability, and Management*. Malden: Blackwell Science. 704 pp.

Lankford, R. R. 1977. Coastal lagoons of Mexico, their origin and classification. Pp. 192-216 in M. Wiley (ed.), *Estuarine Processes*. *Vol. II*. New York: Academic Press, Inc.

Lohrenz, S. E., D. A. Wiesenburg, R. A. Arnoney, and X. Chen. 1999. What controls primary product ion in the Gulf of Mexico? Pp. 151-170 in H. Kumpf, K. Steidinger y K. Sherman (eds.), *The Gulf of Mexico Large Marine Ecosystem: Assessment, Sustainability and Management*. Malden: Blackwell Science.

Lara-Domínguez, A. L., F. Arreguín-Sánchez and H. Alvarez-Guillén. 1993. Biodiversidad y el uso de los recursos naturales: las comunidades de peces en el sur del Golfo de México. *Revista de la Sociedad Mexicana de Historia Natural* 54:345-385.

Lasserre, P. and H. Postma (eds.). 1982. *Coastal Lagoons: Proceedings of the International Symposium on Coastal Lagoons (Bordeaux, France 8-14 September 1981).* Oceanologica Acta 5 (Supplement). Paris: Gauthier Villars. 461 p.

Lauff, G.H. (ed.) 1967. *Estuaries.* Publication No. 83. Washington D.C.: American Association for the Advancement of Science. 757 pp.

Longhurst, A. and D. Pauly. 1987. *Ecology o f Tropical Oceans*. ICLARM Contribution No. 389. San Diego: Academic Press Inc. 407 pp.

López-Portillo, J., D. Zárate Lomelí and J. L. Rojas. 1999. *Ordenamiento Ecológico de la Zona Costera Central de la Reserva de la Biosfera Sian Ka'an, Quintana Roo*. Xalapa, Veracruz: Instituto de Ecología A.C.

Moore, K.A. and R. L. Wetzel. 1988. The distribution and productivity of seagrass in the Términos Lagoon Mexico. Pp. 207-220 in A. Yáñez-Arancibia and J. W. Day (eds.), *Ecology of Coastal Ecosystems in the Southern Gulf of Mexico: The Terminos Lagoon Region.* Instituto de Ciencias del Mar y Limnología-UNAM, México, Organization of American States, Washington D.C., Coastal Ecology Institute, Louisiana State University, Baton Rouge, Louisiana. México D.F.: Editorial Universitaria.

Montagna,P. A., M. Alber and P. M. Doering. 2002. Freshwater inflow: science, policy, management. *Estuaries* 25:1243-1245.

Nixon, S. W.1982. Nutrient dynamics, primary production and fisheries yields of lagoons. *Oceanologica Acta* 5:231-242.

Nixon, S. W. and B. Buckley. 2002. A strikingly rich-zone:nutrient enrichment and secondary production in coastal marine ecosystems. *Estuaries* 25:782-796.

Nixon, S. W. and A. Thomas. 2001. On the size of the Peru up-welling ecosystem. *Deep Sea Research I* 48:2521-2528.

Nixon, S. W., C. A. Oviatt, J. Frithsen and B. Sullivan. 1986.Nutrients and the productivity of estuarine and marine coastal ecosystems. *Journal of Limnological Society of Southern Africa* 12:47-71.

Officer, C. B. 1976. *Physical Oceanography of Estuaries and (Associated Coastal Waters)*. New York: Wiley Interscience. 465 pp.

Ortíz-Pérez, M. A. and J. Benítez . 1996. Elementos teóricos para el entendimiento de los problemas de impacto ambiental en planicies deltáicas: la región de Tabasco y Campeche. Pp. X-X in A. V. Botello, J. L. Rojas, J. A. Benítez and D. Zarate (eds.), *Golfo de México Contaminación e Impacto Ambiental: Diagnóstico y Tendencias*. Universidad Autónoma de Campeche, EPOMEX Serie Científica. Xalapa, Veracruz: Instituto de Ecología A.C.

Pauly, D. 1986. Problems of tropical inshore fisheries: fishery research on tropical soft bottom communities and the evolution of its conceptual base. Pp. 29-37 in E. M. Borgese and N. Ginsburg (eds.), *Ocean Year Book*. Chicago: The University of Chicago Press.
Powell, G. L., J. Matsumoto and D.A. Brock. 2002. Methods for determining minimum freshwater inflow needs of Texas bays and estuaries. *Estuaries* 25:1262-1274.
Rabalais, N. N. and S.W. Nixon. 2002. Nutrient over-enrichment in coastal waters: global patterns of cause and effect. *Estuaries* 25:639.
Rabalais, N. N., R. E. Turner and W. J. Wiseman. 1999. Hypoxia in the northern Gulf of Mexico: linkage with the Mississippi River. Pp. 297-322 in H. Kumpf, K. Steidinger and K. Sherman (eds.), *The Gulf of Mexico Large Marine Ecosystem: Assessment, Sustainability and Management*. Malden: Blackwell Science.
Richardson, K. and J. P. Heilmann. 1995. Primary production in the Kattegat: past and present. *Ophelia* 41:317-328.
Rojas-Galaviz, J. L., A. Yáñez-Arancibia F. Vera-Herrera, and J. W. Day 1992. Estuarine primary producers: the Términos Lagoon a case study. Pp. 141-154 in U. Seeliger (ed.), *Coastal Plant Communities in Latin America*. New York: Academic Press Inc.
Rozas, L. P., J. A. Nyman, C. E. Proffit, N. N. Rabalais, D. J. Reed and R. E. Turner (eds.). 1999. *Recent Research in Coastal Louisiana: Natural Systems Function and Response to Human Influences*. Baton Rouge: Louisiana Sea Grant College Program. XX p.
Sánchez-Gil, P. and A. Yáñez-Arancibia. 1997. Grupos ecológicos funcionales y recursos pesqueros tropicales. Pp. 357-389 in D. Flores, P. Sánchez-Gil, J. C. Seijo, and F. Arreguín (eds.), *Análisis y Diagnóstico de los Recursos Pesqueros Críticos del Gulf of Mexico*. EPOMEX-UAC Campeche, Serie Científica 7, Campeche, México: Universidad Autónoma de Campeche.
Schroeder, W. W. and W. J.Wisemann. 1999. Geology and hydrodynamics of Gulf of Mexico estuaries. Pp. 1-28 in T. S. Bianchi, J. R. Pennock and R. R. Twilley (eds.), *Biogeochemistry of Gulf of Mexico Estuaries*. New York: John Wiley & Sons Inc.
Solis, R. S. and G. L. Powell. 1999. Hydrography, mixing characteristics and residence times of Gulf of Mexico estuaries. Pp. 29-58 in T. S. Bianchi, J. R. Pennock and R. R. Twilley (eds.), *Biogeochemistry of Gulf of Mexico Estuaries*. New York: John Wiley & Sons, Inc.
Turner, R. E. 1977. Intertidal vegetation and commercial yields of penaeid shrimp. *Transactions of the American Fisheries Society* 106:411-416.
Tunnell, J. W. and F. W. Judd (eds.). 2002. *The Laguna Madre of Texas and Tamaulipas.* College Station: Texas A & M University Press. 346 pp.
Yáñez-Arancibia, A. (ed.). 1985. *Fish Community Ecology in Estuaries and Coastal Lagoons. Towards an Ecosystem Integration*. México D.F.: Universidad Nacional Autónoma de México Editorial Universitaria. XX pp.
———. 1986. *Ecología de la Zona Costera: Análisis de Siete Tópicos, 1st Edition*. México D.F.: AGT Editorial. 189 p.
———. 1987. Lagunas costeras y estuarios: cronología, criterios y conceptos para una clasificación ecológica de sistemas costeros. *Revista Sociedad Mexicana de Historia Natural* 39(1):35-54
———. (ed.). 1994. *Recursos Faunísticos del Litoral de la Península de Yucatán*. Universidad Autónoma de Campeche, EPOMEX Serie Científica 2. Campeche: SEP FOMES. 136p

———. 1999. Terms of references towards coastal management and sustainable development in Latin America: introduction to special issue on progress and experiences. *Ocean & Coastal Management* 42:77-104.
———. 2003. Geomorphology and ecology of coastal zone in Middle America. Pp. 639-645 in M. Schwartz (ed.), *The Encyclopedia of Coastal Sciences.* London: Kluwer Academic Publisher.
Yáñez-Arancibia, A. and J. W. Day. 1982. Ecological characterization of Terminos Lagoon, a tropical lagoon-estuarine system in the southern Gulf of Mexico. *Oceanologica Acta* 5:431-440.
——— and ———. (eds.). 1988. *Ecology of Coastal Ecosystems in the Southern Gulf of Mexico: The Terminos Lagoon Region.* Instituto de Ciencias del Mar y Limnología-UNAM, México, Organization of American States, Washington D.C., Coastal Ecology Institute, Louisiana State University, Baton Rouge, Louisiana. México D.F.: Editorial Universitaria. 518 p.
——— and ———. 2003. Coastal management in the Gulf of Mexico: towards an integration of ICM with LME management. *Ocean & Coastal Management* 47: 727-757.
Yáñez-Arancibia, A. and D. Pauly (eds.). 1986. IOC/FAO Workshop on Recruitment in Tropical Coastal Demersal Communities. IOC Workshop Report No. 44. Paris: UNESCO. 46 p.
Yáñez-Arancibia, A. and P. Sánchez-Gil. 1983. Environmental behavior of Campeche Sound ecological system, off Términos Lagoon Mexico. *Anales del Instituto de Ciencias del Mar y Limnologia UNAM* 10(1): 117-136.
——— and ———. 1986. *Los Peces Demersales de la Plataforma Continental del sur del Golfo de México: Caracterización del Ecosistema y Ecología de las Especies, Poblaciones y Comunidades.* Instituto de Ciencias del Mar y Limnologia UNAM Publicación Especial No. 9. México, D.F.: Editorial Universitaria. 212 p.
——— and ———. 1988. *Ecología de los Recursos Demersales Marinos: Fundamentos en Costas Tropicales*. México, D.F.: AGT Editorial. 228 p.
Yáñez-Arancibia, A., F. Amezcua and J. W. Day. 1980. Fish community structure and function in Terminos Lagoon a tropical estuary in the southern Gulf of México. Pp. 465-484 in V. Kennedy (ed.), *Estuarine Perspectives*. New York: Academic Press Inc.
Yáñez-Arancibia, A., A. L. Lara-Domínguez and J. W. Day. 1993. Interactions between mangrove and seagrass habitat mediated by estuarine nekton assemblages: coupling of primary and secondary production. *Hydrobiologia* 264:1-12.
Yáñez-Arancibia, A., P. Sánchez-Gil and A. L. Lara-Domínguez. 1991. Interacciones ecológicas estuario-mar: estructura funcional de bocas estuarinas y su efecto en la productividad del ecosistema. *Academia de Ciencias Sao Paulo Brasil, ACIESP* 71(4):49-83.
Yáñez-Arancibia, A., G. Soberón-Chávez and P. Sánchez-Gil. 1985. Ecology of control mechanisms of natural fish production in the coastal zone. Pp. 571-594 in A. Yáñez-Arancibia (ed.), *Fish Community Ecology in Estuaries and Coastal Lagoons. Towards an Ecosystem Integration*. México, D.F.: Editorial Universitaria UNAM.
Yáñez-Arancibia, A., A. L. Lara-Domínguez, P. Chavance and D. Flores. 1983. Environmental behavior of Términos Lagoon ecological system, Campeche, Mexico. *Anales del Instituto de Ciencias del Mar y Limnología UNAM* 10:137-176.
Yáñez-Arancibia, A., A .L. Lara-Domínguez, J. L. Rojas, P. Sánchez-Gil, J. W. Day and C. J. Madden. 1988. Seasonal biomass and diversity of estuarine fishes coupled with tropical

habitat heterogeneity (southern Gulf of México). *Journal of Fish Biology* 33(Suppl. A):191-200.

Yánez-Arancibia, A., D. Zárate, P. Sánchez-Gil, A. L. Lara-Domínguez, E. Sainz-Hernández, L. Hernández, M. A. Ortíz, P. Méndez, J. W. Day, E. Reyes, A. Peralta and M. Hernández. 2002. Estrategia para la Gestión de la Reserva de la Biosfera Pantanos de Centla Tabasco. Cuarto Informe y Final. Proyecto PEMEX-PEP/SIPA/Inecol -PRC/ 001/2001. Xalapa, Veracruz: Instituto de Ecología, A.C.

Yáñez-Arancibia, A., A. L. Lara-Domínguez, D. Zárate, P. Sánchez-Gil, S. Jiménez, A. Sánchez, E. Rivera, A. Flores, M. A. Ortiz, C. Muñoz, M. Becerra, J. W. Day, G. L. Powell, C. J. Madden, E. Reyes, C. Barrientos. 2003. *Sub-Region 2 Gulf of Mexico; Scaling & Scoping & Detailed Assessment Report.* Global International Waters Assessment GIWA., Kalmar, Sweden: GEF-UNEP. 396 p.

Zárate Lomelí, D. and A.Yáñez-Arancibia. 2003. *Conclusiones: Segundo Panel Necesidades para la Gestión y el Manejo Integrado de la Zona Costera del Golfo de México y Mar Caribe.* Panel MIZC-Golfo/Caribe. Xalapa, Veracruz: Instituto de Ecología, A.C. and SEMARNAT. 33 p.