BETWEEN SCIENCE AND POLITICS: INCORPORATING THE MARINE, COASTAL AND CONTINENTAL COMPONENTS OF THE GULF OF MEXICO

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AN APPROACH BASED UPON THE ENVIRONMENTAL SERVICES OF THE SEA, COASTS AND RIVERS

The adventure of life on our planet began at sea. Until some 450 million years ago, all life was oceanic. However, millions of years before, marine ecosystems already provided a lengthy, complex and ample range of environmental functions. During the Middle Paleozoic, these functions made possible the emergence of life in terrestrial environments. There is geochemical evidence that, approximately 2.2 billion years ago, the amount of oxygen on Earth reached levels comparable to those found in the present atmosphere due to photosynthetic oxygenation by unicellular marine algae (phytoplankton). Since then, changes in primary oceanic production, along with changes in biochemical global cycles, have profoundly influenced the Earth's geochemical composition (Falkowski *et al.*1998; Field *et al.* 1998).

In today's ocean, the photosynthetic fixation of carbon produced by marine phytoplankton is a decisive factor in the annual formation of approximately 45 gigatons of organic carbon. This process affects levels of atmospheric carbon given the constant exchanges between atmosphere and sea. These atmosphere-sea interactions also influence and control mixing of deep waters, the currents of nutrients moving towards and inside the sea, the structure of the food chains and, ultimately, the location of crucial fishing grounds that serve to satisfy the human demand for food (Fasham *et al.* 2001).

Two mechanisms, working at different time scales, influence the concentration of CO_2 in its different reservoirs: the productivity of the marine biomass and patterns of oceanic circulation. These complex biological and physical mechanisms are the basis for the maintenance of oceanic life, as well as the global equilibrium that allows life on Earth. The earth, the ocean and the atmosphere are interconnected subsystems within one larger whole and affect each other reciprocally. Imbalances in one are quite likely to affect the others.

A number of physical processes such as geostrophic currents, cyclonic and anticyclonic gyres, upwellings, tides and fluvial currents control movement of nutrients and materials from surface waters down to the deeper layers and sediments in the oceanic floor. These mechanisms of transportation and distribution are known as the "physical bomb" (Vidal *et al.* 1990), and play a fundamental role in the cycles that affect both organic and inorganic forms. Not a drop of seawater escapes their influence.

The physical bomb is strongly related to the so-called "biological bomb". Through the latter, oceanic life controls the atmospheric concentration of carbon dioxide (CO_2). Today, we know that the CO_2 level in the atmosphere (700 billion metric tons) is sustained by the exchanges taking place between the great marine reservoirs (35 trillion metric tons). With 50 times more carbon than the atmosphere, the ocean contains the largest actively circulating reservoir of this element in the biosphere (Fasham *et al.* 2001; Fig 32.1).

The fact is that without these ecological functions and services, the level of atmospheric carbon released by the ocean could dramatically increase to twice to three times its present value; only these major physical and biological processes prevent that from happening (Norse 1993). Marine productivity is controlled by two factors the rate of nutrient regeneration and the amount

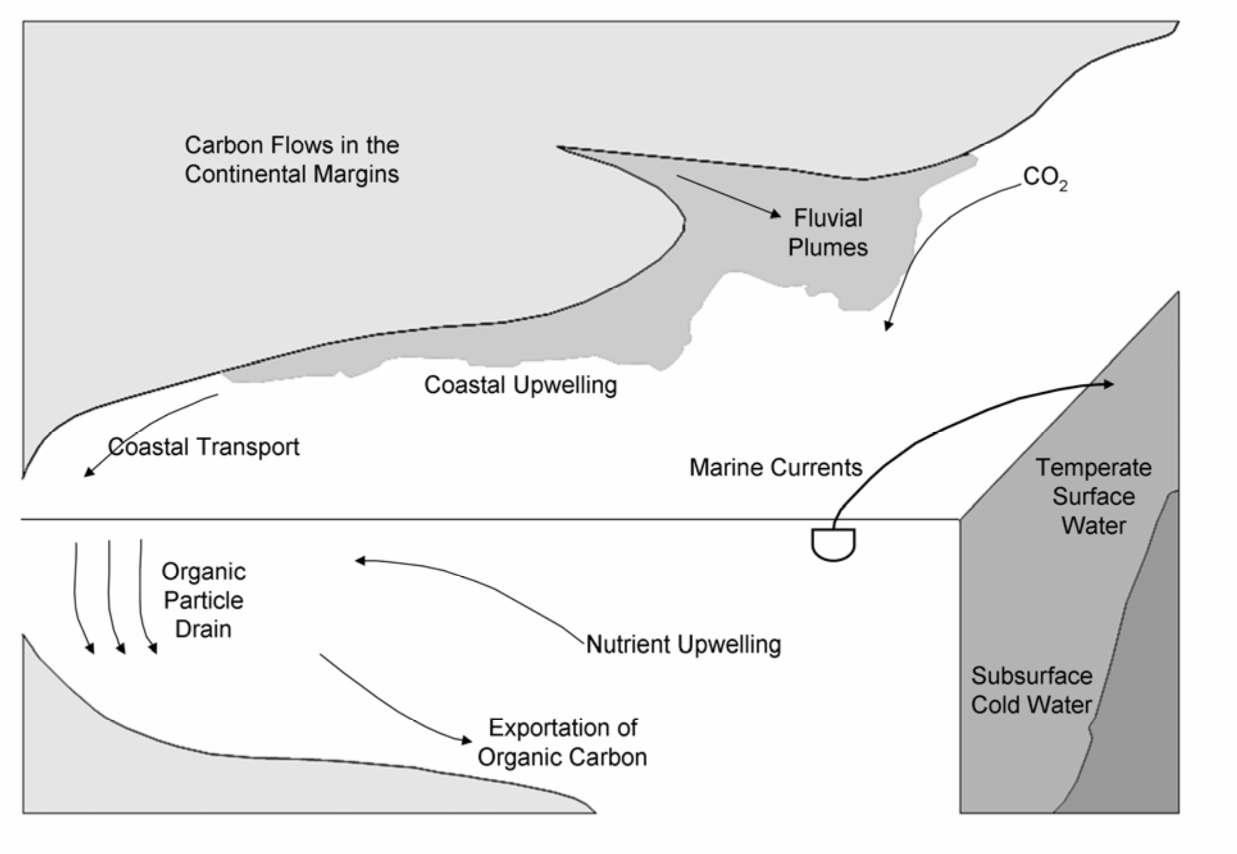

Fig. 32.1. Biophysical global processes and nutrient flow in coastal areas (redrawn from Fashan *et al.* 2001).

of available light. Since both vary greatly in space and time, the ocean's primary productivity is far from uniform. Well-lit waters at the center of oceanic basins usually have a low primary productivity. Materials rich in nutrients sink below the euphotic zone and their nutrients are not quickly replaced, which results in poor productivity. Nutrient concentrations are much higher on the continental shelves, which contain abundant nutrient sources and vigorous vertical mixing known as upwelling (see Fig. 32.1).

Upwelling is a powerful mechanism that brings nutrients to marine water. It generally occur when winds direct the surface waters toward the coasts. The cold subsurface waters, that are rich in nutrients, replace surface waters. Upwelling returns nutrients to the photic zone when, due to the decomposition of organic matter, these nutrients sink into deep waters. This results in a high primary productivity, five to ten times greater to that of the open sea. The short and efficient food chains found in these areas also affect fishing yield, which is much larger per unit of primary production. This is why many of the major fisheries are located in continental shelf or in upwelling zones. These areas are exceptionally important for oceanic productivity. Even though they only cover 0.1% of the ocean and constitute a mere fraction of the marine realm, they contribute one-third of the landings in the world and are disproportionately important for the human population and other animals that need dense concentrations of fish for food. Paradoxically, these enormous aggregations of fish in restricted areas make marine life particularly vulnerable to overexploitation and any other type of physical or chemical change (Norse 1993).

Periodical immersion and emersion tidal rhythms control life on the seacoast (Britton and Morton 1989). Tides provide the water and essential nutrients that enable rich and varied forms of life in estuaries, floodplains and wetlands, the most productive coastal zones. Along with winds, waves and tides are the physical mechanisms responsible for formation of multiple coastal habitats, and all the rhythms of coastal life are regulated by their environmental services. Most of the Gulf of Mexico has diurnal tides, except for areas in the continental shelf of Florida and Texas-Louisiana, where the tides are mixed; semi-diurnal tides have been reported in Campeche Bay. The Gulf is relatively peaceful when compared to other marine areas on the American continent, and its tidal oscillations are no bigger than 30 to 60 cm. Still, this relatively small range significantly influences vital seacoast environments. There are numerous bays, estuaries, wetlands and plains along the Gulf's coastline. These do not have a direct connection to the sea, but are linked by tide-generated channels. Tides allow a daily inflow and outflow of water masses, nutrients and materials, that move from the wetlands and mangroves bordering the seacoast to production zones such as seagrass meadows, reefs and other critical habitats on the coast and vice versa. Millions of organisms can then migrate to feeding, breeding or refuge sites, perpetuating life in the complex organism that is the Gulf of Mexico.

Even though they only represent 7% of the terrestrial surface, coasts are among the most valuable and vulnerable habitats on the planet (Jickells 1998). Their numerous environmental functions and services are necessary for human existence. Great concentrations of nutrients reach the transition zone between land and sea. They stream from the continental zones via the rivers. They travel from subterranean layers through particles that move into areas where salty and fresh waters meet. The processes of sedimentation, respiration and denitrification bring more nutrients from the continental shelf. In the case of oceanic waters, currents, tides and other meteorological phenomena help spread nutrients produced by respiration and photosynthetic processes taking place in adjacent seas (Fig. 32.2, Table 32.1).

The area between the oceanic continental shelf, the coast and the land has a large variety of gradients and ecotones regulated by four basic types of process: physical, biogenic, climactic and physiochemical. Physical processes (tides, waves and upwelling are among the most relevant) establish ecotones parallel to the coastal line. Biogenic processes produce gradients through the interaction of live organisms with physical structures, forming distinct marine, coastal and terrestrial habitats such as coral reefs, seagrass meadows, coastal wetlands, estuaries and floodplains. Climactic gradients are responsible for a diversity of organismal responses to physical changes in the terrestrial and marine environments within a hydrological region. Temporal scales may vary from minutes to centuries. Finally, physiochemical gradients establish oxygenation, salinity, and temperature conditions; these can regulate the spatial and temporal movements of organisms belonging to diverse habitats.

Gradients are expressed in complex ecosystem hierarchies, each with its own biotic associations: marine biomes, seacoast biomes, tidal biomes, coastal plain biomes and mountain biomes. Marine and coastal environments possess the largest diversity of life forms on the planet. They contain the widest array of vertebrates of all taxonomical levels: 3 classes, 50 orders, 4,445 families and approximately 22,000 species. A large proportion of these species live on the continental shelf, but some 8,500 species (40% of the total) live in fresh waters. Out of 13,200 marine species, almost 80% inhabit the coastal zone (Ray 1991).

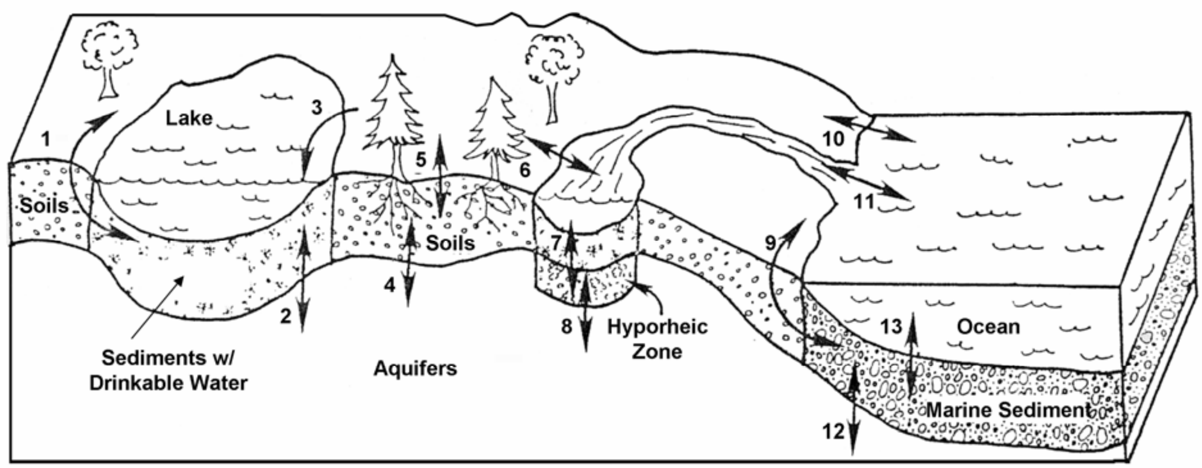

Fig. 32.2. Critical transition zones (redrawn from Fashan *et al.* 2001).

As we have seen, there are crucial and reciprocal interactions between the terrestrial, coastal and marine environments. Biomass and nutrients (nitrogen, phosphorous, carbon and micronutrients) derived from the sea are exported to fresh and continental waters, and vice versa. These supplies reinforce global productivity. They establish links between the ocean, the freshwaters of coastal plains and upstream river basins, and sustain complex and intricate food chains that horizontally intersect land and sea. Every year, and during different seasons, billions of fish migrate from marine areas to estuaries, floodplains and the upstream zones of rivers and estuaries to lay eggs, grow, feed and find refuge (Yáñez-Arancibia *et al.* 1985; Yáñez-Arancibia and Day 1988; Polis *et al.* 1995, 1997; Polis 1996; Wilson *et al*. 1998).

The interconnections between ocean, coast and continent extend beyond aquatic systems. They also encompass the scarcely known area of bottoms, soils and sediments in terrestrial as well as freshwater, coastal and marine locations. Recently, scientists collected data to prove that the sediments of lakes, rivers, wetlands, estuaries, coastal lagoons, seacoasts and the oceanic floor are part of a continuum of closely related ecosystems. Some studies suggest that the functions, services and links between these habitats are essential to the sustenance of life on Earth (Brussard 1997). Sediments play a vital and dynamic part in global ecosystem processes such as the recycling of nutrients and their release for plants and algae, the formation and decomposition of organic matter, nitrogen fixation, production and consumption of methane, formation and stabilization of bottoms, oxygenation of soils and sediments, production of organic acids, rock decomposition and transportation and degradation of pollutants. They also supply food to an enormous number of organisms and provide clean water. Oceanic soils and sediments are Earth's main repository for carbon as organic matter. Sediments of freshwater bodies, which contain low levels of carbon when compared to the seacoast and oceanic ecosystems to which they are connected, filter water and make it available for human beings. Aerobic continental soils contain twice as much organic matter as that found in terrestrial vegetation (Wall *et al.* 1997; Groffman and Bohlen 1999; Snelgrove 1999; Wall 1999).

All materials and minerals processed in the sea originate in the continents (Cifuentes *et al.* 1986). For billions of years, rivers have provided vital environmental services by transporting the products of erosion (sediments, minerals and nutrients that have been dislodged by floods

Table 32.1. Interfaces or transference control zones often determine the physical and biological state of adjacent terrestrial and aquatic systems. Biota living in these areas regulates movement and fate of materials. In Figure 32.2, the interfaces are identified with a number that corresponds to a number in this table with an example of the ecosystem process.

Interface	Examples of processes occurring in the interface
1. Soils-freshwater sediments-atmosphere	C, N, P cycling; nutrient and particle transfers; biogeochemical cycling
2. Freshwater sediments-lake waters-groundwater	Loss/recapture of sediment nutrients to/from lake waters, groundwater
3. Soils-freshwater	Gross primary productivity; nutrient leaching
4. Soils-groundwater	Loss/recapture of nutrients to/from groundwater
5. Soils-vegetation	Gross primary productivity; weathering; evapotranspiration
6. Freshwater-soils	Weathering and leaching; nutrient transfers
7. Freshwater sediments-hyporheic zone	Transfers of organic material, nutrients and particles
8. Hyporheic zone-groundwater	Loss/gain of nutrients to/from groundwater
9. Soils-marine sediments-atmosphere	C, N, P cycling; nutrient and particle transfers; biogeochemical cycling
10. Ocean-soils	Erosion and deposition of organic and inorganic particles; nutrient cycling
11. Freshwater-ocean	Transfers of nutrients, organisms and particles; transport/dilution of contaminants and excess nutrients
12: Marine sediments-groundwater	Recapture/loss of nutrients to/from groundwater
13. Marine sediments-ocean	Nutrient cycling through decomposition; gross primary productivity; secondary production; burial/metabolism of contaminants

and torrential rains throughout the geological ages) to the ocean (Jonson *et al.* 1995). Today it is estimated that rain and rivers provide the ocean with some 80 million metric tons of organic nitrogen in the form of ammonia and nitrate. However, only 10 million metric tons seem to make it to the ocean floor as organic nitrogen, and little is known about the routes and final destination of the remaining volume.

The close relationships between marine functions and services and life on Earth have increased with the passing of geological and biological time. During historical human time, they have reached an essential interdependency. It is quite clear that the human population has much need of marine products in order to satisfy its basic nutritional requirements. Sixteen percent of all animal proteins ingested by humans come from the sea. The overall value of fisheries in the world is estimated in 80 billion USD annually. They provide jobs for an estimated 15 to 20 million people, 90% of whom live on the shores. Some 180 million have jobs indirectly related to fishing activities (FAO 1997; NOAA 1998). Additionally, a considerable percentage of sea products are used in the production of agricultural fertilizers, cattle food and medicine, and these also represent employment and additional income sources for the human population.

What is less evident is the population's dependence on a complex net of environmental services provided by the oceanic, coastal and fluvial ecosystems. However, humankind increasingly needs these environmental services to survive. Only in recent years has attention been called to these indirect values while emphasizing their economic relevance, which is apparently the only way to get the attention of major players in a production/life system based on market valuations. Open-sea operations comprise 5.2 billion USD annually, while the services provided by coastal ecosystems are valued in 11.7 trillion USD (Costanza *et al.* 1997).

Despite an academic tradition still based on individual disciplines, we can no longer think of the environmental problems of the sea, the coasts and terrestrial river basins as if they were separate issues. Most, if not all, disturbances in marine ecosystems, even in the deepest parts of the sea, originate thousands of kilometers away, in the upstream basins. There, the destruction of forests and variations in the use of the soil develop in ways that influence the quality of the waters that flow into the sea (Swanson *et al* 1998). It is a grave mistake to design management plans for coastal or marine environments without taking into account the strategies being employed on land. This is why a strategy seeking the sustainable use of Mexico's seas must be based on the knowledge and protection of their environmental services. It must also take into account the role these services play in the preservation of the country's ecologic capital.

THE GULF OF MEXICO: A HIGHLY INTEGRATED, FRAGILE AND VULNERABLE ECOSYSTEM

The Gulf of Mexico is one of the richest and most diverse environmental ecosystems on Earth. Because of its dimensions and its semi-enclosed basin, it is the great interior sea of the tropical Atlantic. It is a highly interconnected system of marine, coastal and continental ecosystems housed in a basin of a mere 1.6 X 10^6 km^2 and nearly 2.3 X 10^6 km^3 of water. A series of physical, chemical and biological processes, as well as the nature of their interactions, turn the Gulf into a huge repository for the energy of the land-atmosphere-ocean system. This gigantic physical bomb is triggered by a complex mechanism driven by great marine currents and their cyclonic and anticyclonic rings, upwelling, tropical storms, tides and continental flows. These hydrodynamic processes foster a varied range of marine, coastal and fluvial ecosystems. Few places on Earth have such a diversity of temperate, subtropical and tropical ecosystems.

The great Lazo Current and its associated cyclonic and anticyclonic rings constitute the primary mechanisms that move and distribute water masses in the Gulf. These enormous flows, which are hundreds of times larger than continental fluvial discharges, play a decisive role in circulation and renewal of water masses as well as their thermal and saline balance, climate, the dynamics of their coastal processes and the balance of the marine and continental systems (de la Lanza 1991; Monreal and Salas 1997).

The Lazo Current carries waters, nutrients and organisms from the Caribbean to the eastern part of the Gulf through the straits of Yucatán and Florida at an estimated volume of 29-33 x $10^6 m^3 s^{-1}$. Meanwhile, the rings that detach from this enormous current move an estimated 8-10 x10^6 m^3 s^{-1} towards the interior of the basin (north, west and south). This huge physical bomb determines local productivity and influences the stock and diversity of species throughout the basin. The large diversity of species in the Gulf's deep marine sediments is closely related to these hydrodynamic processes (Arriaga *et al.* 1998).

The general biodiversity gradient is also strongly linked to river discharges (Lara-Domínguez *et al.* 2003*).* However, little is known about the mechanisms with which this biological bomb operates in regions of high productivity. It is known that at least parts of the Gulf of Mexico's oceanic waters are oligotrophic and biologically depauperate. The quantifications of chlorophyll, nitrates, phosphates and primary productivity in the centers of the Lazo Current and its rings (more than 50% of the Gulf's total area for more than 6 months a year) seem to confirm this situation. The surface waters at the centers of the rings, at depths of over 100 m, show low nitrate levels and chlorophyll stocks (20 mg m^{-1}). Primary productivity is registered at 0.4 mg C m^3 h^{-1}. At night, levels of zooplankton biomass in the layer above 200 m are 4 ml per 100 m^3, indicating low productivity (Biggs 1992).

In other regions, such as the plumes of the Mississippi and Grijalva-Usumacinta rivers, the Louisiana-Texas and Yucatán shelves, as well as on the borders of the Lazo Current and its rings, high concentrations of nutrients can be found, and the phytoplankton biomass is very high. In the coasts of Louisiana-Texas and southeast Mexico, primary productivity levels of 250-500 mg C m^3 d^{-1} have been reported. Upwelling and cascades characterize these areas (Bogdanov *et al*. 1968).

The larval distribution of some of the most important fisheries in the Gulf has been associated with the edges of the Lazo Current. These are very dynamic areas, with meanders and strong convergences and divergences capable of holding vast amounts of planktonic organisms, including eggs and larvae. Large volumes of plankton movement have been registered in these areas, with averages of 87 ml x 1,000 m^{-3}. High larval densities average 458 ml x 1,000 m^{-3} (Richards *et al.* 1989).

Geohydrologically speaking, the Gulf of Mexico is a distributive province consisting of a sedimentary area of some 5.4 x10^6 km^2, as well as 159,890 km of rivers, including two of North America's major hydrosystems: the Mississippi-Atchafalaya in the United States, and the Grijalva-Usumacinta in Mexico. Thirty-six percent of the Gulf's total area is water; the remaining 64% is composed by continental formations. Thirty-eight large rivers discharge a global annual freshwater volume of 1,110 x 10^9 m^3 into the Gulf, bring with it 775 million metric tons detritus and around 208 million metric tons of dissolved materials (Moody 1967).

Of the total amount of freshwaters poured into the Gulf by its rivers, 866 x 10^9 m^3 per year correspond to the basins in the United States (except the Rio Grande). Another 229 x 10^9 m^3 per year come from Mexican rivers, while some 12 x 10^9 m^3 per year come from the Rio Grande. The Mississippi and Atchafalaya rivers contribute 55% of the total, while the Grijalva-

Usumacinta makes up only 10%. The Rio Grande covers a 472,000 km^2 drainage basin, the Gulf's second largest. Despite the size of this drainage area, the Rio Grande has one of the lowest rates of flow discharge into the Gulf (approximately $0.03 \times 10^6 m^3 km^{-2} y^{-1}$) (Solís and Powell 1999).

The modification of natural river drainage patterns by human activities has dramatically altered the flow of freshwaters, sediments and nutrients that pour out into the Gulf, depriving this system of one its main ecological services. Variations in amount, water quality and discharge periods have been drastic in recent years. Dams in upstream basins, creation of artificial channels, changes in river courses, construction of highways and other communication systems, human settlement in wetland areas, and use of land for urban and agricultural purposes have profoundly altered water circulation patterns.

The re-damming of the main fluvial systems in the region has been a cataclysmic event (Ligon *et al.* 1995). For these dynamic environments, disruption of their natural flows has meant elimination of some of their most vital functions and services. The physical habitat is of crucial importance for these hydrosystems and can change more easily and quickly than in other ecosystems. When a reservoir is built, there is an immediate shift in the flow of water, sediments and nutrients. This favors changes in the physical, hydraulic and biological structures of the entire hydraulic region to which the river belongs. Whether visible or not, these changes are often dramatic and disastrous.

Practically all types of human activity in hydrological basins that flow into the sea (e.g. settlement and seaport development, construction of communication lines, occupation of forests for agricultural activity, particularly in slope areas) expose the ground to erosion, dramatically increasing sediment and pollutant transport from the land in fluvial currents and, finally, the ocean. Today's marine ecosystems are threatened by land use practices in areas that are sometimes thousands of kilometers away, in the upstream basins (Clark 1996; Escobar 2002).

Suspended sediments, especially fine particles, impede organism respiration, obstruct feeding organs of coastal and marine fauna, and reduce the amount of light available for photosynthesis. Often, these discharges cover areas where photosynthesis takes place, burying benthic organisms and making the rocky and coralline substrate impossible to colonize. Deforestation, inadequate agricultural practices and the resulting erosion have contaminated estuaries, seagrass beds and coral reefs in different areas of the Gulf of Mexico (Zárate-Lomelí *et al.* 1999*).* The cases of the Mississippi-Atchafalaya and Grijalva-Usumacinta systems are typical examples of this situation (Reyes *et al*. 2002).

The Mississippi River is among the ten largest in the world in terms of its water and continental sediment discharge capacity (Millman and Meade 1983). It is the main source of sediments, nutrients and pollutants in the Gulf of Mexico, discharging its waters to the neighboring coastal wetlands and into the ocean, where it forms an enormous, extended estuary and a plume that penetrates into the open sea. These flows contribute to the sustenance of the primary and most productive fisheries of the United States (Pennock *et al.* 1999).

The flow of the Mississippi-Atchafalaya system into the Gulf, estimated at 577 km^3 per year, has significantly changed its routes in the last century. Historically, it followed two paths: a complex system of bays and an ample coastal plain, and the principal channel of the Mississippi River. Today, due to leveeing and channel construction on the main channel and its adjacent floodplain, 65% of the flow moves directly to the continental shelf. This has drastically changed the way in which nutrients and sediments are incorporated into the diverse coastal and marine habitats (Rabalais *et al*. 1996; Turner and Rabalais 2003).

The nitrate-nitrogen concentration in the Mississippi River increased dramatically throughout the 20th century, particularly after the 1950s, when agricultural activity in the Mississippi watershed intensified and urban discharges into the river grew (Turner and Rabalais 1991, Bianchi *et al.* 1999). In the last century, nitrate concentrations released by the river into the Gulf have quadrupled. Higher nutrient discharges have degraded water quality and favored growth of phytoplankton and macroalgae, including some noxious and toxic species. This has produced an increase in the cloudiness of the waters, oxygen depletion in the coastal waters, loss of habitats, changes in the structure and performance of ecosystems on the adjacent continental shelf and a decrease in marine biodiversity. Changes in the nitrogen and phosphorous levels have exacerbated the eutrophication of the coastal waters, favoring the proliferation of toxic algae (red, green and brown tides), contributing to hypoxia and anoxia, and altering the structure of the marine food chains (Rabalais *et al.* 2002, Turner and Rabalais 2003).

Eutrophication of coastal waters is one of the main problems affecting large regions of the Gulf. The direct causes are intense agricultural use of watersheds and the increase of urban and seaport centers in crucial estuarine and coastal lagoon areas. Human activities have altered nitrogen and phosphorous cycles on a global level, and increased the availability of these two nutrients in marine ecosystems (Peierls *et al.* 1991; Mitsch *et al.* 2001, Rasbalais *et al.* 2002,).

Although less studied than the Mississippi, the Grijalva-Usumacinta River has also suffered severe alterations. Some of the causes are intense deforestation in the watersheds, dam systems built over the Grijalva River (the largest ones in Mexico), occupation of the river's floodplains by activities linked to commercial agriculture and cattle farming, explosive population growth on its plains, growth of human settlements on wetlands, estuaries and coastal lagoons, and intense seaport and industrial development linked to petroleum extraction and transport activities.

Due to its geomorphological and climactic characteristics, the Grijalva-Usumacinta hydrosystem is composed of fast-flowing and dynamic rivers. Its environmental services, which include its very high potential for transporting sediments and nutrients towards the low, coastal and marine zones, are of enormous ecological value. This powerful dynamic is originated by the proximity of mountainous systems that traverse eastern Mexican and join the mountain ranges of Central America. The amount of annual precipitation in these mountains is one of the highest amounts in the world, with an annual average of 2,143 mm, twice the national average (in the sierras of Chiapas and Lacandonia, rainfall surpasses the 4,000 mm average and reaches 5,000 mm in some areas), allows formation of alluvial plains. This capacity for plain formation is six times larger than that of the Mississippi and ten times larger that that of the Rio Grande (Moody 1967).

The continental aquatic, coastal and marine systems are joined by delicate and complex connections. In Campeche Bay, continental flows enrich the soil with sediments and nutrients. Thanks to the discharges from the Grijalva-Usumacinta, large coastal lagoons and adjacent wetlands, the area is an ideal habitat for demersal species and varied seacoast fauna. Long-term analyses of fisheries in the southern part of the Gulf and Campeche Bay (Soberón-Chávez and Yáñez-Arancibia 1985) quantify and demonstrate the high correlation between capture and fluvial discharges ($r = 0.758$ for Tabasco; $r = 0.932$ for Campeche, and $r = 0.922$, for Tabasco + Campeche). Correlations between captures and the extent of coastal lagoons and vegetation were equally strong.

Human activities undertaken in the last decades have affected the natural flow patterns of the Grijalva-Usumacinta system, along with its mechanisms for energy and material transfers.

Dams, which have been built with multiple purposes such as flood control in the downstream basins and energy generation in the upstream basins, interfere with the river's potential to transport sediments. This affects its bottom-formation capacity and obstructs nutrient and mineral transportation services to the floodplains, the coasts and Campeche Bay. Levels of suspended solids have decreased dramatically since 1974 (Casco 1979) and this has affected balances in the fluviomarine zone and the stability of the coastal front. The action of seacoast currents and tropical storms prevailed over the compensatory effect of fluvial discharges. Beaches and barrier islands have suffered intense erosion and are, frankly, in a state of regression. This affects seacoast activities like the oyster fisheries on the coastal lagoons of Tabasco, which once held the most important natural banks in the area (Ortiz-Pérez 1988).

The Gulf's coastal wetlands are some of the richest, largest and most productive ecosystems on Earth. Even today and after significant losses of irreplaceable ecological wealth, more than 14,000 km^2 border the estuaries and coastal lagoons. Out of this total, approximately 476,841 ha are mangrove forests and 974,500 ha are herbaceous marshes. The Florida Peninsula has some 219,610 ha of mangrove swamp. The entire Mexican seacoast is more or less occupied by wetlands. The Laguna de Términos region alone holds a mangrove forest area that is larger than the entirety of mangroves on the United States' Gulf coasts (some 250,000 ha) (Bianchi *et al.* 1999).

The Gulf is also one of the most important estuarine zones on Earth. Estuaries make up more than 50% of its seacoasts and host a highly complex net of marine and fluvial interconnections, along with a wide-ranging climate that goes from tropical to temperate, from humid to arid (Deegan *et al*. 1986; Contreras 1988). Marine currents, continental hydrological forces, winds and tides are responsible for the properties that make estuaries the most biologically productive areas, the most important support systems for fisheries and the largest refuge zones for wild seacoast fauna. Thirty-nine large estuarine zones border the Gulf's seacoast, from Florida to Yucatán.

A diversity of environmental factors, habitats, and connections and interactions with adjacent environments such as rivers, floodplains and continental shelves, provide these ecosystems with ample biotic wealth. The total primary productivity of these lagoon and estuary ecosystems is estimated between 500 to 4,000 g dry weight m^{-2} y^{-1} (Yañez-Arancibia and Day 1988).

The icthyofauna that inhabits the Mexican estuaries is estimated at 300 species. More than 50% of these are euryhaline, some 25% are marine stenohaline and the remainder are temporary and permanent estuarine inhabitants (Reséndez-Medina and Kobelkowski-Díaz 1991).

The functions, processes and environmental services provided by these ecosystems have been profoundly affected by human activities. On the eastern part of the Gulf, urban developments and the use of wetlands for residential and recreational purposes have altered the quantity and quality of water being discharged into the estuaries, particularly on the western coast of Florida. In northern areas, erosion and chemical pollution of estuaries has grown. Because of this, increasingly large open sea zones, especially those influenced by the Mississippi River suffer from anoxia and hypoxia, which cause widespread mortality among highly nutritive fish species. Rivers have been regulated on the northwestern part of the Gulf, towards southern Texas. This has resulted in diminished freshwater discharges into the Gulf, which has altered food chains and fishing production. The southeastern part of the Gulf, especially the large and rich ecosystems (marine, coastal and continental) of the Grijalva-Usumacinta region, have suffered the effects of hydroelectric and agricultural development in the watersheds, occupation of wetlands, and oil production in the watersheds and off the coast.

The four major fluvial systems that discharge into the Gulf of Mexico (Pánuco, Papaloapan, Coatzacoalcos and Grijalva-Usumacinta rivers) show severe deterioration in their functions and environmental services. The seaport and industrial developments in the lower basin of the Río Pánuco have produced serious pollution problems, affecting soil and surface and subterranean waters, as well as sediments in coastal plains, estuaries and lagoons. The lower watershed of the Río Papaloapan contains large concentrations of pesticides such as DDT: sediments contain up to 60.7 ppb, while fish (*Oreochromis niloticus*) tissues contain 2,477.6 ppm and crustaceans (*Penaeus* sp.) 1,383 ppm. Hydrocarbon levels of 680 ppm have been registered in the basin of the Río Coatzacoalcos. These are ten times higher than the levels established by UNESCO for non-polluted waters (70 ppm). High hydrocarbon levels have also been detected in the sediments of the Mecoacán lagoon in Tabasco, with measurements of 88 ppm and in the Laguna de Términos lagoon in Campeche, concentrations are 85 ppm. Hydrocarbon levels detected in the surface waters of Campeche Bay (48 ppb) are the highest in the Gulf of Mexico (Botello *et al.* 1996).

THE NEED FOR A SCIENTIFIC POLICY THAT PROMOTES THE SUSTAINABLE USE OF THE ENVIRONMENTAL SERVICES OF THE GULF OF MEXICO

Today, human activities can simultaneously cause global, regional and local changes. The environmental sustainability of the Gulf of Mexico is seriously threatened by these changes. Global, regional and local environmental problems affect crucial functions and environmental services in the Gulf of Mexico, endangering its contributions to the sustainability of the biosphere and the human population that directly depend on those resources. New strategies that combine several marine, coastal and terrestrial scientific disciplines are needed. These strategies should be intimately linked to the global services of the Gulf, the maintenance of its biodiversity and the sustainable management of its environmental services. This requires inter- and trans-disciplinary studies that comprise the local, regional and global scales.

A new vision of the Gulf as a great organism with highly interconnected marine, coastal and terrestrial ecosystems must develop from the scientific community’s ability to integrate and synthesize information. Reports on global processes should also be made available, particularly those concerning the interfaces of land, coast and sea. Synthesized information is crucial for the understanding of the relationships between these large and vital environmental unities. Interaction between the disciplines will make ecological knowledge more accessible to the general population, the designers of scientific policy and decision makers.

A strategy based on the knowledge of the interrelations between hydrological basins, the coast and sea in the Gulf of Mexico must take into account two fundamental issues. First, its large contribution to the basic knowledge of the processes that determine the Gulf’s productivity, which makes possible its environmental services, second its importance for the sustainable management of one of the richest regions of the biosphere.

In order to combine our knowledge of land, coast and sea and emphasize their functions, processes, environmental services and interconnections, we must change our present scientific structures, which are currently oriented towards partial disciplines and knowledge. We must become increasingly able to answer crucial questions such as what processes govern the environmental services of the Gulf, their nature and how they respond to the stress derived from anthropogenic activity. Inter- and trans-disciplinary research must generate new methods capable of integrating ecology, economics, and other social sciences. We should come up with techniques that enable conservation with minimal intervention, restore ecosystems that provide essential services to the biosphere, and promote self-sufficient ecological systems whose multiple services are used in a sustainable manner. These goals can only be achieved if they are organized in a coherent fashion and obey a scientific and technological policy with clear objectives for the short, medium and long terms. A policy of this kind will allow us to find the answers to some essential questions:

1. What is the relationship between patterns of land use and the quality of the water in the basin of the Gulf of Mexico (locally, regionally and globally)?
2. What are the effects of fragmentation of the Gulf's landscapes (marine, coastal and terrestrial) on local, regional and global biological diversity?
3. How do changes in the size and location of human populations affect, now and in the future, the Gulf's environmental services?
4. What are the long-term consequences of the intensive use of terrestrial, coastal and marine natural resources? How do these affect the Gulf's environmental services?
5. What type of scientific and technological policies can supply, within a relatively short time, a basic set of indicators depicting the state of the Gulf's environmental services and their response to anthropogenic stress?

Answers to these questions would provide some of the clarity and coherence needed for the management and sustainable use of marine, coastal and terrestrial ecosystems in the Gulf of Mexico.

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