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Review

Can Continental Shelf River Plumes in the Northern and Southern Gulf of Mexico Promote Ecological Resilience in a Time of Climate Change?

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Abstract: Deltas and estuaries built by the Mississippi/Atchafalaya River (MAR) in the United States and the Usumacinta/Grijalva River (UGR) in Mexico account for 80 percent of all Gulf of Mexico (GoM) coastal wetlands outside of Cuba. They rank first and second in freshwater discharge to the GoM and owe their natural resilience to a modular geomorphology that spreads risk across the coast-scape while providing ecosystem connectivity through shelf plumes that connect estuaries. Both river systems generate large plumes that strongly influence fisheries production over large areas of the northern and southern GoM continental shelves. Recent watershed process simulations (DLEM, MAPSS) driven by CMIP3 General Circulation Model (GCM) output indicate that the two systems face diverging futures, with the mean annual discharge of the MAR predicted to increase 11 to 63 percent, and that of the UGR to decline as much as 80 percent in the 21st century. MAR delta subsidence rates are the highest in North America, making it particularly susceptible to channel training interventions that have curtailed a natural propensity to shift course and deliver sediment to new areas, or to refurbish zones of high wetland loss. Undoing these restrictions in a controlled way has become the focus of a multi-billion-dollar effort to restore the MAR delta internally, while releasing fine-grained sediments trapped behind dams in the Great Plains has become an external goal. The UGR is, from an internal vulnerability standpoint, most threatened by land use changes that interfere with a deltaic architecture that is naturally resilient to sea level rise. This recognition has led to successful efforts in Mexico to protect still intact coastal systems against further anthropogenic impacts, as evidenced by establishment of the Centla Wetland Biosphere Preserve and the Terminos Lagoon Protected Area. The greatest threat to the UGR system, however, is an external one that will be imposed by the severe drying predicted for the entire Mesoamerican "climate change hot-spot", a change that will necessitate much greater international involvement to protect threatened communities and lifeways as well as rare habitats and species.

Keywords: Mississippi River; Usumacinta/Grijalva Rivers; Gulf of Mexico; continental shelf productivity; plume dynamics; ecosystem resilience; delta vulnerability; climate change; Mesoamerica; DLEM; MAPSS

1. Introduction

The Mississippi/Atchafalaya (MAR) and Usumacinta/Grijalva Rivers (UGR) rank first (18,000 $m^3 \cdot s^{-1}$, 650 $km^3 \cdot year^{-1}$) and second (4500 $m^3 \cdot s^{-1}$, 140 $km^3 \cdot year^{-1}$) in freshwater discharge to the Gulf of Mexico [1,2]. The UGR flows into the Gulf of Mexico (GoM) through the Mexican states of Tabasco and Campeche (Figure 1). When combined with the nearby Papaloapan and Coatzacoalcos Rivers that discharge to the southern Veracruz coast (UGCPR), fluvial input to the Veracruz to Campeche "fertile crescent" rises to 200 km^3· year^{-1}.

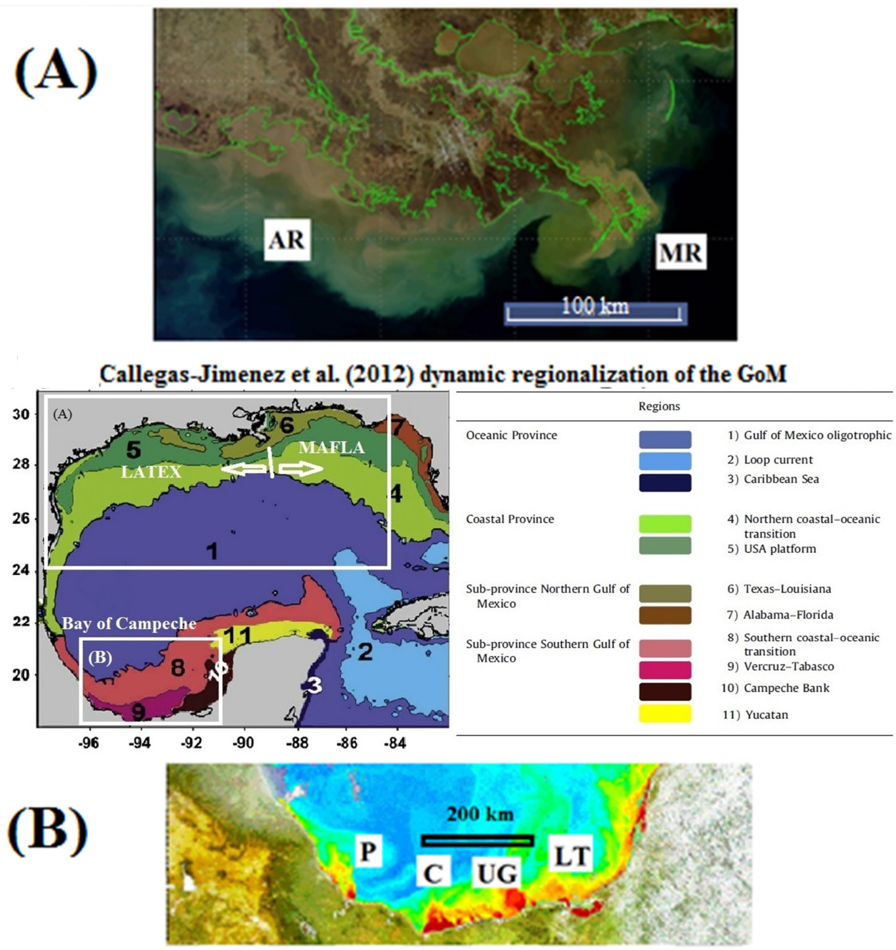


Figure 1. Characteristic surface water types of the GoM as classified by Callejas-Jimenez *et al.* [3] from MODIS-Aqua satellite images, used by permission. High discharge images of (**A**) the MAR on 2 March 2003, showing Atchafalaya and Mississippi birdsfoot outlets and sediment plume from MODIS-Aqua sensor, and (**B**) Papaloapan (P), Coatzacoalcos (C), Usamacinta-Grijalva (UG) and Laguna de Terminos plumes on 25 October 1997, flood from SeaWifs Chl-a sensor.

The MAR drains a 3.2 million km^2 watershed that covers 16% of continental North America including all or parts of 31 US states and 2 provinces of Canada [4], with a mean annual precipitation of 800 mm· year^{-1} distributed relatively evenly through the year [5]. The UGCPR delta complex receives runoff from less than 134 thousand km^2, just 4.2% of MAR Basin area, but annual precipitation in the UGCPR watershed ranges from 1000 to more than 5000 mm· year^{-1}, with the highest rates in the tropical highlands of Mexico and Guatemala. A pronounced dry season occurs from February to late June, while it rains frequently from July through January with a pronounced runoff peak in October. From July through October, precipitation is governed by dynamics of the intertropical convergence zone, while from November through January precipitation is associated with passage of cold front systems, locally called *nortes* [6].

The MAR and UGCPR both generate large coastal plumes [7,8] of low-salinity (<34 psu), sediment and nutrient-enriched water that extend hundreds of kilometers alongshore (Figure 1). Peak river discharges on the northern (28° to 29° N) and southern (18° to 19° N) GoM coasts are temporally offset, occurring on the MAR from March to May coincident with snow melt and spring rains, while this is the dry season in the Bay of Campeche. Both systems are affected by hurricanes, most frequently in August and September, though the potential for large storm surges is far greater on the northern GoM coast. The Yucatan land mass shelters the southern GoM coast from the strongest hurricane winds generated by cyclones on the most common northerly or westerly tracks. Both coasts experience strong north winds associated with passage of cold air frontal systems. Except during *nortes*, coasts surrounding the Bay of Campeche are dominated by relatively steady easterly trade winds, while the northern GoM experiences greater variation in wind speed and direction.

Deforestation and dam-building upriver, as well as subsidence, oil and gas impacts and construction of river levees have caused wetland loss in both systems [9–12]. But the severity of these impacts has been much greater in the MAR delta, where more than 4800 km^2 of deltaic wetlands have converted to open water since 1930 [11,12]. These perturbations, along with hypoxia (bottom DO < 2 ppm) on the inner shelf in the summer, are common to both systems, though again with much greater impacts on the Louisiana-Texas (LATEX) shelf [7,8,13–15]. Hypoxia may cover up to 20,000 km^2 on the LATEX shelf in some years while low DO offshore of the UGCPR is more ephemeral.

Oil spills are common on both coasts due to extensive onshore and offshore energy development. The Ixtoc I blowout released 3 million barrels into the Bay of Campeche about 100 km offshore of the Usamacinta River mouth over 10 months in 1979 and 1980, while the Deepwater Horizon well gushed 5 million barrels about 60 km offshore of the Mississippi River birdsfoot over 3 months in 2010 [16,17]. Long-term influences of climate change on weather systems and sea-level rise can be expected to synergistically interact with these anthropogenic stressors to collectively challenge resiliency of GoM deltas.

Ecological Resilience and Climate Change

In a review of the "vulnerability" of coastal river deltas, Wolters and Kuenzler [18] define resilience as the "degree to which a system and its components are able to anticipate, absorb, accommodate, or recover from perturbations or stress". They divide processes that affect deltas into "internal" and "external" types.

Internal processes that can contribute to resilience include channel shifting and crevassing that confer geomorphic or architectural redundancy, giving rise to multiple outlets, estuaries and depocenters [18]. Anthropogenic management, in contrast, has aimed to reduce this self-organized redundancy by confining flow to fewer channels to enhance navigation, flood control and economic development [11,19–26]. For the MAR delta, this has compromised the capacity for the Mississippi River to supply sediment to wetlands experiencing high rates of subsidence [10].

External processes originate outside the delta but can significantly affect it. For the most part, these take place within the upstream watershed, but with the acceleration of sea level rise, as well as oil spills of regional extent, they also increasingly affect the seaward margins of the delta. A great number of inland anthropogenic activities can affect the timing and volume of sediment, nutrient and water delivery to a delta [10,20,26]. Climate change is, however, emerging as a systemic influence that, in some places, will overwhelm all others in the 21st century because of the profound effect it will have on river discharge dynamics and sea-level rise [22,23].

Bernhardt and Leslie [27] have reviewed coastal ecosystem attributes that contribute to resilience in a time of rapid climate change, and have identified a tension between "modularity" and "connectivity", which are not mutually exclusive. Modularity or compartmentalization "may contribute to an ecosystem's resistance to disturbance and its ability to regenerate following disturbance", as risk is not spread uniformly across redundant modules. Furthermore, they regard ecosystem connectivity that contributes to the "movement of organisms and organic materials between ecosystems" as an "often essential component of community persistance".

One barometer of ecosystem resilience with important socio-economic consequences, for example, is the health and sustainability of estuarine-dependent penaid shrimp fisheries (*Farfantepenaeus aztecus*, *Litopenaeus setiferus*, *Farfantepenaeus duorarum*) around the GoM. These fisheries have greater economic value than any other on both north and south GoM coasts [28–30].

Shrimp landings in the Bay of Campeche are positively correlated with river discharge into specific estuaries (Figure 2A), and the relationship is improved when normalized by estuary size (Figure 2B). Recruitment of shrimp, as with many estuarine-dependent species targeted in the northern GoM, maybe as strongly influenced by the dynamics of shelf river plumes as on conditions inside the estuaries [28,29].

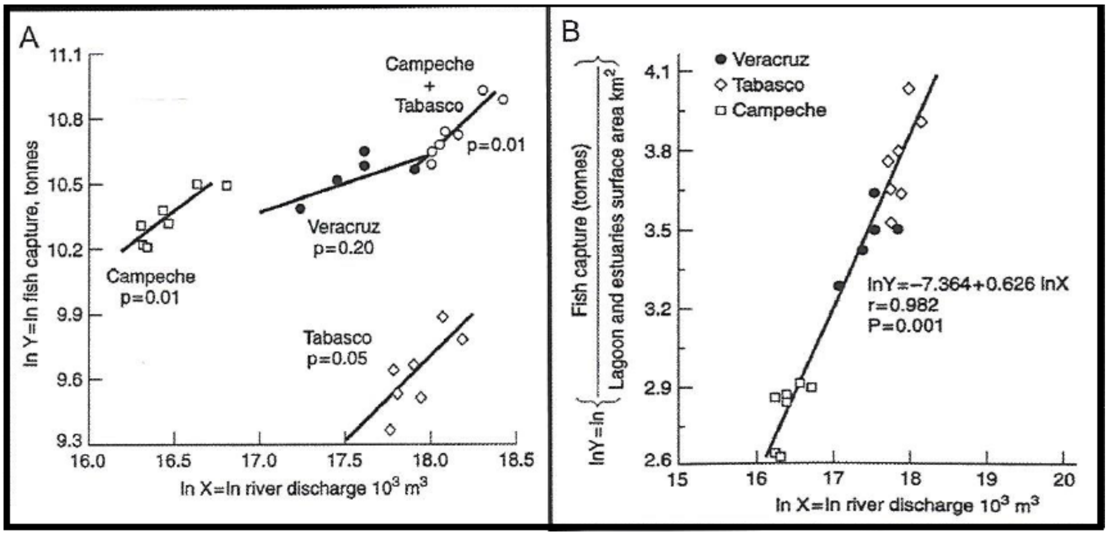


Figure 2. Relationships between river discharge and (**A**) annual fish landings in the Mexican states of Veracruz, Tabasco and Campeche and river discharge; and (**B**) normalized to the surface area of estuaries, as shown in Baltz and Yáñez-Arancibia [31].

No fishery-independent data on shrimp populations exist for the Bay of Campeche [29], but such information from the northern GoM [32] indicates that penaid stocks are more affected by short-term changes in fishing effort (Figure 3) than by a 3800 km^2 (20%) loss of MAR delta wetlands since 1956 [12], the expansion of hypoxia on the LATEX shelf since the 1980s [13–15], the 2010 Deepwater Horizon oil spill [17] or climate change. The 75% reduction in fishing pressure since the late 1990s in areas influenced by the MAR plume reflects competition with low-cost farmed shrimp imported mainly from Asian countries [33]. This decrease in effort has been accompanied by an 80% rebound of northern GoM shrimp populations [32], but little drop in the combined landings of white and brown shrimp (Figure 3). Such rapid rebuilding of shrimp stocks despite ongoing estuarine habitat loss and other system shocks is evidence of ecosystem resilience. While not definitive, some of this resilience is attributed to connectivity provided by highly productive river plumes [34–39].

The influence of climate change on river discharge for these GoM systems is being assessed using a new generation of process-based terrestrial ecosystem models driven by downscaled atmosphere-ocean General Circulation Model (GCM) output. These data are available from the Coupled Model Intercomparison Project (CMIP3 and CMIP5) and Regional Climate Models (RCMs) with boundary conditions supplied by GCMs [40].

Tao *et al.* [41] used the Dynamic Land Ecosystem Model (DLEM) to simulate climate change effects on runoff from the continental scale MAR watershed. The Southern Mexico and Central America region (SMECAM), of which the UGCPR watershed forms the northwestern portion, was first identified by Georgi [42] from GCM forecasts as a "climate change hot-spot in the tropics". This designation has been reinforced by Taylor *et al.* [43], and most recently by Fuentes-Franco *et al.* [44] based on a CMIP5 based RCM (RegCM4 CORDEX). Future discharge regimes for the UGCPR are inferred from runoff forecasts through the 2090s by Imbach *et al.* [45] using the Mapped Atmosphere Plant Soil System

(MAPSS) model. The DLEM and MAPSS models have been calibrated against historic MAR and UGCPR watershed runoff for the 1901–2008 and 1950–2000 intervals, respectively [4,6].

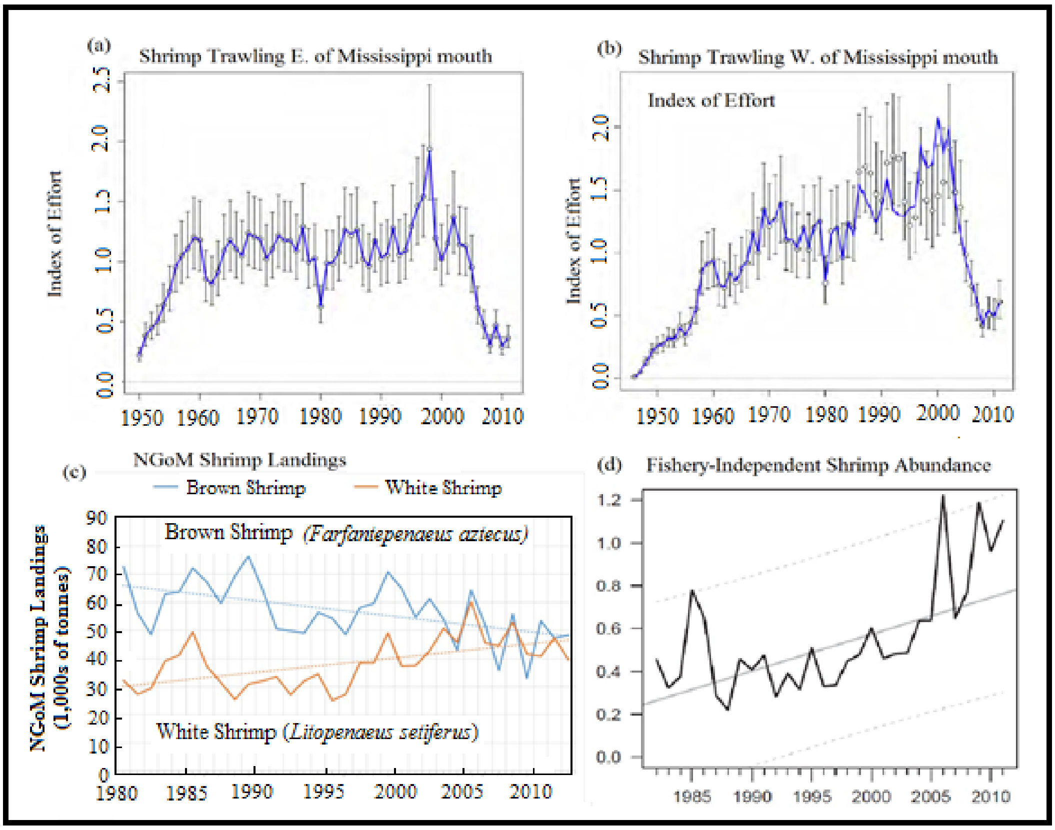


Figure 3. Observed and estimated indices of shrimp trawling effort 1950–2011 (**A**) east and (**B**) west of the Mississippi birdsfoot delta; (**C**) 1981–2013 landings data for white and brown shrimp and (**D**) 1981–2011 fishery-independent abundance index since 1982 from Karnauskas *et al.* [32].

Here, we compare these two deltaic systems and assess how geomorphic modularity and oceanographic connectivity will affect ecosystem resilience as climate change influences river discharge. Finally, we discuss how the differences between these systems have led to divergent, but site-appropriate, ecosystem management strategies; specifically, engineered wetland restoration in the MAR delta [11,46] and preservation of intact systems in the UGCPR [47,48].

2. Study Sites

The MAR and UGCPR river systems both meet the GoM in large, micro-tidal (<0.5 m) deltaic estuarine systems, each covering about 20,000 km^2, that together contain more than 80 percent of all GoM emergent coastal wetlands outside of Cuba [11,49–51]. Please check. The MAR dominated shelf is characterized by terriginous sediments of fluvial origin. It is bounded on the east by coastal systems of the Florida panhandle (Figure 1), a zone of lower freshwater input and smaller estuaries. West of the MAR influenced shelf, beyond Galveston Bay, arid watersheds in south Texas and northern Mexico contribute little freshwater to the GoM coast.

River input increases in the southern GoM from north of Veracruz around the Bay of Campeche past the UGCPR dominated shelf to the Yucatan Peninsula (Figure 1). Shelf sedimentation transitions from terriginous to biogenic at the western margin of Mexico's largest estuary, the Laguna de Terminos (Figure 4). Northeast of Laguna de Terminos the Yucatan platform is a karst region with high freshwater input to the coast via groundwater outflow rather than rivers. The Campeche Bank west of the Yucatan Peninsula is wide, with carbonate sediments and extensive seagrass meadows but few estuaries [47].

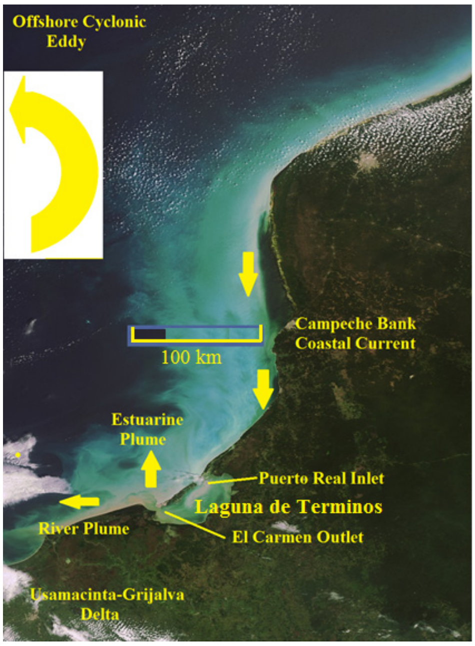
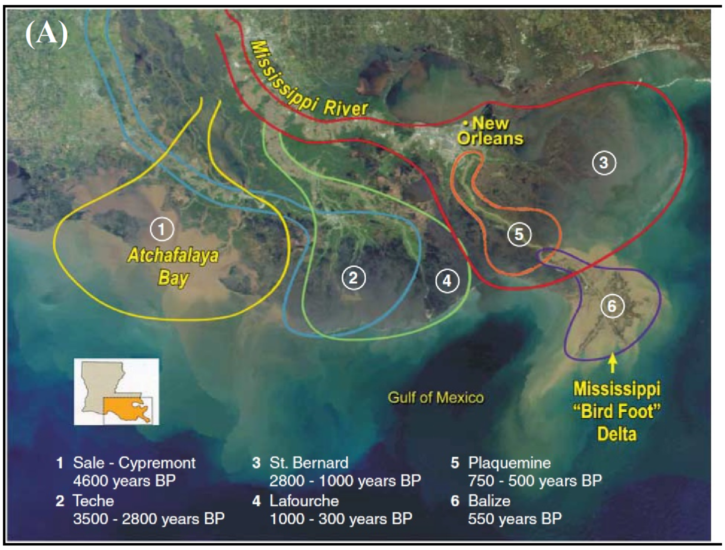


Figure 4. Laguna de Terminos estuary showing river and estuarine plumes in the southeastern Bay of Campeche in a Landsat image acquired on 26 January 2010.

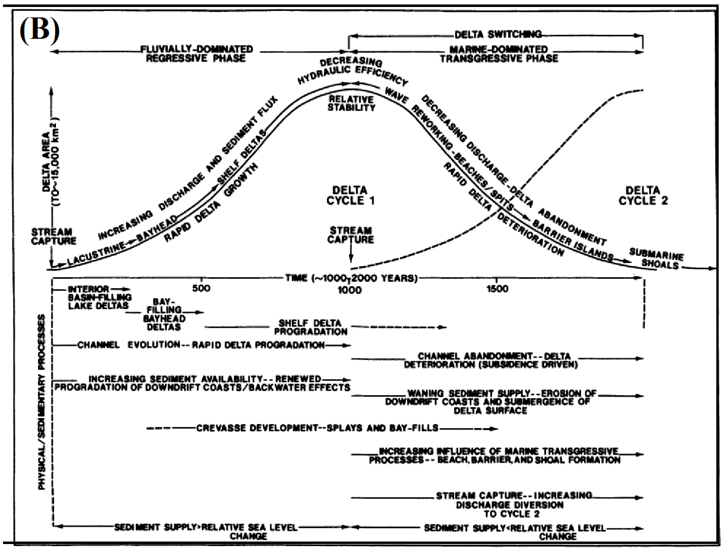
2.1. Deltaic Architecture

The Holocene architecture of the MAR and UGCPR deltaic tracts are quite different, but are both modularly built of self-organized geomorphic units that repeat over time and space. The Mississippi River has built a composite Holocene delta (Figure 5) through upstream avulsion and sequential creation and abandonment of onlapping and offlapping lobes [10,25,49,52–54]. Under natural conditions, crevasses and distributaries formed along the supply channels of major lobes remained important to sediment distribution even in the lobe abandonment phase [19,25,49,52,54]. As long as sediment provenance from the basin was high, this land building system was resilient to high rates of Holocene sea level rise even though the MAR delta is subsiding faster than any other coast in North America (5–20 mm· year^{-1}) as recent deposits dewater and compact [55–57].



(**A**)

Figure 5. *Cont.*



(**B**)

Figure 5. The Holocene Mississippi River delta cycle showing (**A**) spatial and temporal distribution of deltaic lobes [11]; and (**B**) overlapping temporal sequence of lobe building and abandonment [54], used by permission.

By 500 years BP, the MAR birdsfoot delta had built a peninsula that extends about 200 km seaward from the Pleistocene contact to the shelf edge. This peninsula divides the northern GoM continental shelf into eastern and western portions, the MAFLA (Mississippi-Alabama-Florida) and LATEX (Louisiana-Texas) zones, respectively (Figure 1). In the past 100 years, however, the MAR has both lost more than 50 percent of its fine-grained sediment supply [10,24,26], and most sand and mud that gets to the delta has been prevented by levees and artificial closure of distributaries from reaching deltaic wetlands [20].

The UGCPR deltaic landscape is a mosaic replicated along 500 km of the southern coast of the Bay of Campeche. Several rivers have joined and separated over time to deliver coarse sediment to the coast at multiple locations (Figure 6), where incident waves have built numerous modular beach ridge complexes that vary from a few hundred meters wide (shore normal) to more than 40 km near major river outlets [58]. Longshore drift and plume direction is to the west. The rivers also supply fine-grained sediment to lagoons sheltered behind the ridges, many of which have completely filled with wetlands. Because subsidence is low compared to the MAR delta, little sediment is needed each year to allow these wetlands to keep up with sea level rise. The inland deltas of the UGCPR have created and sustained as large a wetland expanse as in the MAR delta, but with a more efficient use of sediment than the MAR across a broad coastal plain in the Veracruz, Tabasco and Campeche lowlands extending up to 125 km inland behind the shore-parallel beach ridge complexes.

Laguna de Terminos is a unique coastal feature along the southern GoM shoreline, and is Mexico's largest estuary (Figure 4). It is a large bar-built lagoon with more than 1500 km^2 of open water, fringed by about 1000 km^2 of wetlands [59,60] (Figure 4). The brackish *Spartina* (sp.) marshes and freshwater wetlands found in coastal Louisiana are replaced by mangrove forests in the deltas of the UGCPR (mainly *Rhizophora mangle*, *Laguncularia racemosa*, and *Avicenia germinans*).

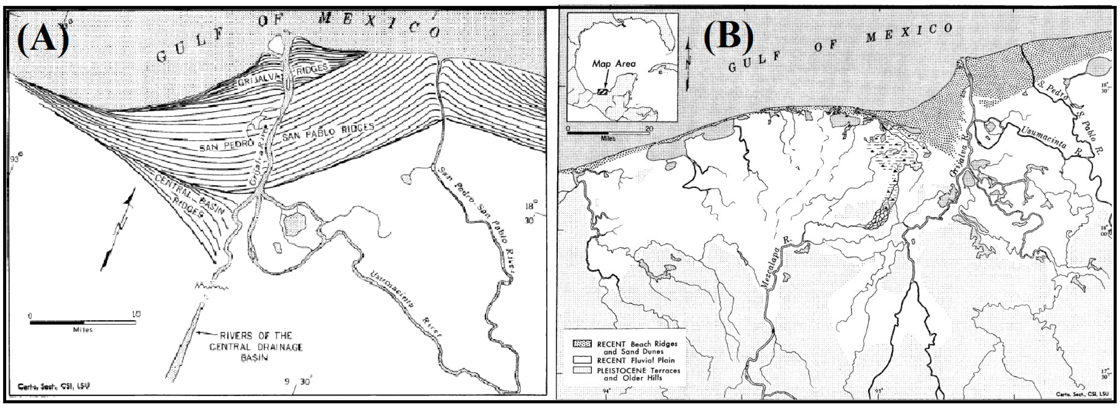


Figure 6. Beach ridges of Tabasco from Psuty [58] showing (**A**) the sequence of ridge construction and (**B**) anastomosing river systems that cause interior lagoon filling and delta building, used by permission.

Terminos Lagoon directly receives discharge from the UGR through the Rio Palizado distributary outlet at its western end, but most water that discharges from ebb dominated western inlet (El Carmen) enters the estuary through the flood-dominated eastern inlet (Puerto Real) from the south flowing coastal current that follows the western Yucatan coast (Figure 4). The El Carmen inlet marks the boundary between a terriginous siliciclastic coast and shelf province to the west and the carbonate shelf of the Campeche Bank [61]. From Terminos lagoon to the northern portion of the Yucatan Peninsula, rivers are absent from the landscape. Freshwater flow to the GoM occurs underground through a porous limestone matrix. Shallows of the Campeche Bank east of Laguna de Terminos support extensive beds of submerged seagrasses (*Thallassia testudinum*, *Halodule wrightii*, *Syringodium filiforme*) while substantial coral reefs occur 100 km offshore.

2.2. Climate Change Effects on River Discharge

If the volume and seasonality of river discharge are primary factors affecting deltaic resiliency and shelf plume dynamics, then projecting how these parameters will be affected by climate change is critical to assessing future delta vulnerability. River discharge has a complex relationship not only with climate but also with often conflicting terrestrial biospheric processes in the watershed, which include natural as well as anthropogenic influences on land cover and plant succession [62].

The DLEM model of Tao *et al.* [41] predicts increases in annual Mississippi River discharge through the 21st century relative to a 1992–2010 baseline. When Liu *et al.* [4] compared historical discharge in different MAR basins from 1901 to 1978 with the 1979 to 2008 period, as part of DLEM calibration, they noted a reduction in runoff from the Great Plains region of the Missouri River basin that was offset by increased discharge from the wetter Upper Mississippi and Ohio River basins. As climate change effects were modeled into the 2090s, however, the DLEM predicts that any drying in the Great Plains will be more than offset by increases in discharge from other MAR basins [41]. Mean annual MAR discharge volume rises 11 to 26 percent for the low-emission IPCC scenario (CMIP3 SRES B1), and from 27 to 63 percent for the high-emission future (CMIP3 SRES A1).

Tao *et al.* [41] used the DLEM to parse the causes of increased MAR discharge in the 21st century, finding that while climate change accounted for 75 percent of the predicted increase under the low-emission scenario, it was responsible for only 50 percent of increased Mississippi River flux under the high-emission simulation. The remainder was attributed to effects of elevated CO_2 on reducing transpiration (stomatal conductance) along with a smaller contribution from continued anthropogenic land use changes.

In contrast, climate modeling for the Mesoamerican SMECOM zone predicts a significant drying trend for all IPCC scenarios with an increase in the frequency and duration of very dry seasons [43–45]. Fuentes-Franco *et al.* [44] report that the drying trend is forced by greater warming of sea surface temperature (SST) on the Pacific side of the SMECOM isthmus relative to SST in the GoM. The resulting

SST gradient intensifies the easterly Caribbean Low-Level Jet. This weakens the land-sea breeze system that contributes to convection-induced rainfall, both at the coast and in the Guatemalan highland headwaters. The MAPSS model applied by Imbach *et al.* [45] to the SMECOM predicts an overall reduction in runoff for the central Yucatan Peninsula and Guatemalan highlands of up to 80 percent for both the low- and high-emissions IPCC scenarios, and 20 percent reductions for the Veracruz, Tabascan and Campeche lowlands that include the UGCPR deltas.

General trends predicted for annual runoff and river discharge to the GoM from the MAR and UGCPR watersheds in the 21st century are clearly divergent. An increase in inter-annual variability is, however, expected to increase for both river systems [41,45]. This means that the frequencies of large flood events and extended low flow periods can be expected to rise in both systems. This can result from a lowering of base flow that is more effectively and frequently offset by periods of high flow in the Mississippi Valley than in the UGCPR basins.

It is interesting that even without an increase in mean annual discharge for the Mississippi River duringthe 20th century [4], large floods became more common over the last 50 years. The Bonnet Carre Spillway, an emergency overbank flood outlet constructed just upstream of New Orleans in 1931 to limit flow past the city to 35,000 $m^3 \cdot s^{-1}$ has been operated 11 times in its 85-year history, but has been opened twice as often in the last 4 decades than in the previous 43 years, including 3 times since 2000. Because fluvial sediment transport is biased toward the highest discharge events, the modeling does not yet allow predictions of whether sediment delivery to the northern and southern GoM coasts will increase or decrease. On the other hand, it is expected that the persistence, spatial extent and ecological significance of the MAR shelf plume will increase over time, while that associated with the UGCPR system is likely to shrink.

3. Synthesis

Dynamics of the MAR and UGCPR shelf plumes are influenced not only by fluvial discharge but also by circulation within the receiving GoM. To the extent that river plumes spread along the inner shelf, they provide estuarine corridors that connect estuaries. On the other hand, large eddies impinging on the shelf edge may entrain and carry plume water and organisms offshore [63]. Callegas-Jimenez *et al.* [8] have classified GoM waters into 11 types based on analysis of water-leaving radiance values from 12,500 MODIS-Aqua satellite images acquired from 2002 to 2007 (Figure 1). The first 3 Callegas-Jimenez (C-J) types define waters in the deep Gulf, while C-J 4 through 7 are found in the northern GoM associated with continental slope, shelf and nearshore settings in the MAR study area. C-J types 8 through 10 occur in the southern GoM UGCPR study area.

To better understand the characteristics of the C-J water types, GoM 1/25° nowcast output of the Data Assimilative US Navy HYbrid Coordinate Ocean Model (HYCOM) for sea surface elevation (SSH), surface velocity (SSV) and salinity (SSS) were acquired for 10 October 2015 [64], a recent date selected for no particular reason, from the U.S. Navy HYCOM server (Figure 7A–C)). A 10-day composite of chlorophyll-a (Chl a) concentrations from the MODIS sensor on the Aqua satellite centered around this date [65], was also composited from the NOAA ERDAP site (Figure 7D). Radiance properties that distinguish C-J water types arise in part from mesoscale circulation (Figure 7A) associated with eddies (Figure 7B). River inputs of sediment and nutrients are indicated by low-salinity zones (Figure 7C), and by the spatial variation in Chl-a concentration (Figure 7D), a proxy for phytoplankton productivity.

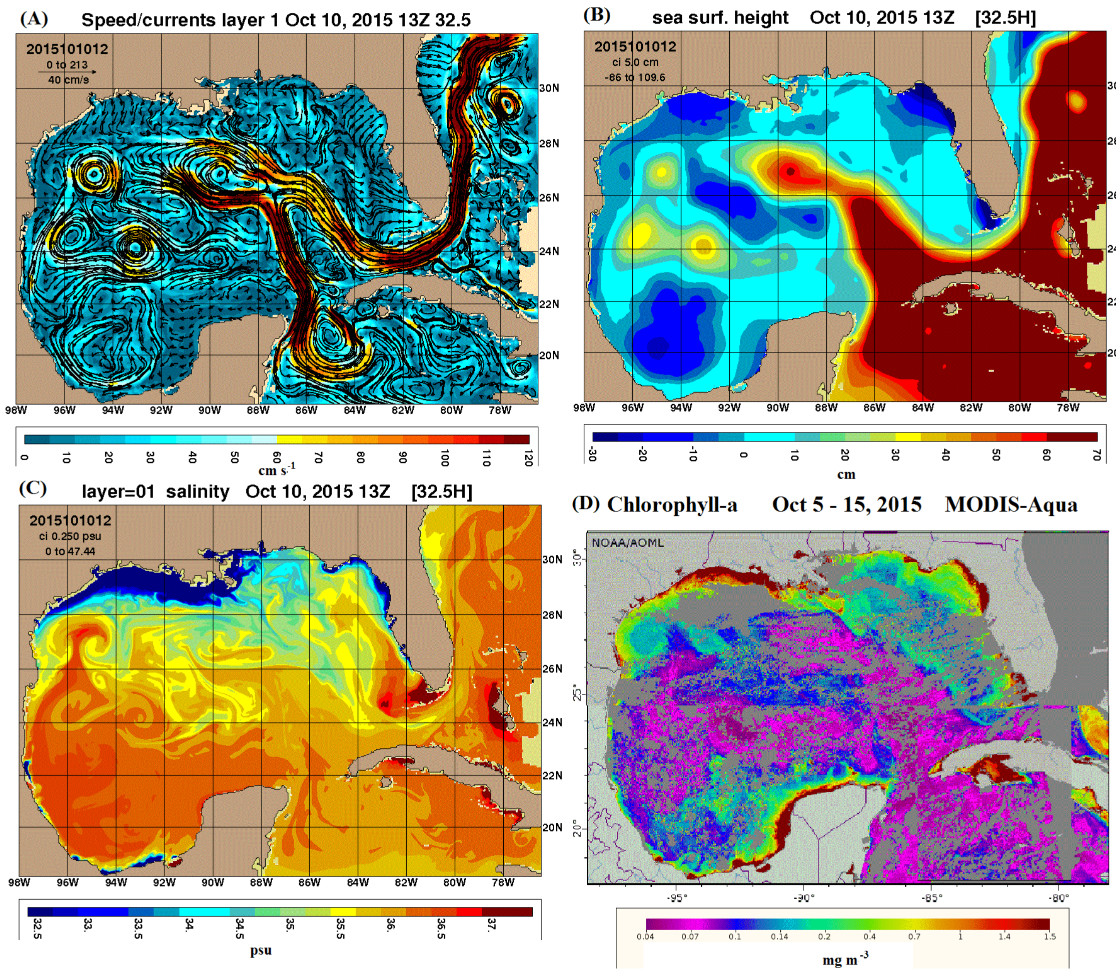


Figure 7. Synoptic views of the 10 October 2015 GoM surface layer (**A**) current velocity; (**B**) sea surface height; (**C**) salinity; and (**D**) Chl a concentration. Images (**A**–**C**) are daily model output from U.S. Navy HYCOM [64], while (**D**) is a composite of Chl-a concentration acquired by the MODIS sensor of the NOAA Aqua satellite between 5 and 15 October 2015 [65].

3.1. Mesoscale Circulation in the Gulf of Mexico

The LOOP current, a massive (23 to 27 Sv) surface flow up to 500 m deep, enters the eastern Gulf as the Yucatan Current and leaves through the Florida Strait to form the Atlantic Gulf Stream (C-J 2, Figure 1). It follows a cycle of northward GoM elongation followed by truncation and retreat [66]. Southward retreat begins when the distal bend pinches off to form an anticyclonic gyre, which then detaches to form a peripatetic LOOP Current Eddy (LCE) that begins a slow westward journey as it loses energy. The GoM situation on October 10 has the LOOP current in an extended condition close to the northern Gulf shelf break west of the MAR birdsfoot outlet, with a pinch-off event in progress at 27° N latitude (Figure 7A,B). Three already shed warm-core anticyclonic LCEs are visible in the western Gulf. A number of small, cold-core cyclonic vortices are apparent on the edges of the LOOP (Figure 7A).

Lower salinity water originating from the MAR birdsfoot is being dragged offshore along the eastern boundary of the LOOP current while discharge from the Atchafalaya outlet has pooled on the LATEX shelf (C-Y 5, 6, Figure 1) where a weak coastal boundary current is slowly carrying plume water to the west (Figure 7C). Chl-a concentrations are high all across the inner portion of the northern Gulf shelf, but particularly from west of the Atchafalaya outlet almost to the Rio Grande/Bravo deltaic bulge at 25° N latitude (Figure 7D).

Discharges of the UGCPR (C-Y 9, Figure 1) are at their annual peak in October and support high nearshore Chl-a levels from southern Veracruz (19° N) east into Laguna de Terminos (Figure 7D). Low-salinity river water forms a much smaller band adjacent to the UGCPR coast where the shelf is much narrower than in the LATEX zone influenced by the MAR. It is confined to the immediate vicinity of the outlets, suggesting that little alongshore plume transport is occurring at this time (Figure 7C).

High Chl-a concentrations northeast of Terminos Lagoon, adjacent to the Yucatan Peninsula (Figure 7D), are attributed to nutrient-rich groundwater discharges and the convergence of clear water stripped from the Yucatan Current with a weak anticyclonic circulation [47] on the Campeche Bank (C-J 10, Figure 1). Together, the UGCPR deltas and the ground water dominated karst platform to the north produce a 1200 km long nearshore zone of high coastal productivity from southern Veracruz around the Yucatan Peninsula to the Caribbean (Figure 7D).

A large cyclonic eddy centered at 20° N latitude and 94° W longitude that covers much of the Bay of Campeche is clearly visible in the GoM velocity field (Figure 7A), and as a circular region of depressed sea surface elevation (Figure 7B), where deeper, saltier water is upwelling (Figure 7C). Though not consistently cyclonic [8], an eddy typically develops in this area in the spring (April) and often persists for the remainder of the year [61]. It is seen in the October 2015 image to be entraining and transporting coastal water with a high Chl-a concentration offshore from the Campeche Bank (Figures 4 and 7D). Perez-Brunius *et al.* [66] described how the eddy is trapped in this location by the topography of the shelf edge, with a deep basin, steep continental slope and narrow shelf to the west, and a gently sloping submarine fan to the east.

3.2. Plume Dynamics and Coastal Currents

The discussion above sets the stage for considering river plume dynamics on the northern and southern GoM shelves. Horner-Devine *et al.* [67] describe the primary parameters that govern the behavior of river plumes as "freshwater discharge, tidal amplitude, coastline bathymetry/geometry, ambient ocean currents, wind stress and the Earth's rotation". The volume of freshwater discharge, wind stress and the strength of the Coriolis effect (arising from the Earth's rotation) differ most between the two systems. Tidal amplitude is similar (0.5 m) as is the east-west orientation of the coasts, though with a 180° rotation.

Mean MAR discharge is an order of magnitude greater than that of the UGCPR and wind direction is more variable on the northern GoM coast than along the Bay of Campeche with its steady, northeasterly trades. Because the Campeche coast is about 10° closer to the equator, however, the Coriolis parameter is diminished for the UGCPR plume relative to that affecting MAR discharge reaching the shelf. Signoret *et al.* [8] calculated a Kelvin number (K), the ratio between the width of the offshore jet (effectively that of the river mouth) and the internal Rossby radius of deformation for the buoyant Usumacinta River plume. They arrived at a value $K = 0.2$, well below that ($K > 1$) at which the Coriolis force could be expected to turn the plume to the right/east in the northern hemisphere. Accordingly, UGCPR flows tend to deflect to the west under the influence of easterly trade winds [63]. More symmetric river plumes might be expected to issue from the UGCPR compared to the higher latitude MAR outflow, as Saramul and Ezer [68] found for rivers discharging at 13° N into the Upper Gulf of Thailand. Some imagery of the southern Gulf of Campeche appears to show this symmetry (Figure 1).

Salas-de-Leon [61], however, observed that a cloudy plume issuing from the western, strongly ebb-dominant, 6 km wide El Carmen "inlet" of the Laguna de Terminos often does turn to the right (east) where it influences circulation on the Campeche Bank (Figure 4). With a discharge that can reach 12,000 $m^3 \cdot s^{-1}$, largely contributed by the 36 psu Yucatan coastal current that enters the estuary through the eastern Puerto Real inlet, this jet outflow has a greater magnitude than that of all of the UGCPR rivers combined, though with a mean salinity of 22 psu it is less buoyant than the river plumes to the west [56]. The Palizado distributary of the Usamacinta River, which discharges into the western portion of the Terminos Lagoon near the El Carmen inlet with a flow of 300 to 500 $m^3 \cdot s^{-1}$, is responsible for most of the freshwater entrained in the El Carmen outflow. Salas-de-Leon *et al.* [61] concluded that the strength of the El Carmen estuarine jet explains the sharp divide on the adjacent shelf between calcareous muds of the Campeche Bank and the siliciclastic sedimentary province to the west (Figure 4).

The buoyant MR plume either turns west (downcoast) to form a coastal boundary current inshore of the 20 m isobath along the LATEX shelf [69–71], or, alternatively, northeast (upcoast) to follow shelf-edge bathymetry of the MAFLA coast. There, plume waters can be exposed to cyclonic eddies that form on the edge of the LOOP current (Figure 7C). A turn to the right (west) is the normal result of the geostrophic balance between the Coriolis force and the buoyancy-influenced cross-shelf pressure gradient, in the absence of opposing winds [71]. The MR plume turns east out of the birdsfoot most commonly during the summer when discharge is low and westerly winds prevail. Then, flow is governed by the balance between along-shelf acceleration and the along-shelf pressure gradient, and is more likely to result in offshore conveyance [71].

The northern GoM coast is affected for 6–7 months each year by passage of cold air frontal systems as often as weekly between October and April, while the season of *nortes* on the southern Campeche coast is shorter, lasting for about 3 months between November and January [72]. Strong southerly winds prior to front passage set up water levels against the MAR coast while the northerly winds that follow flush water out of estuaries onto the shelf. On, the southern GoM coast, in contrast, only the northerly winds that follow front passage set up water levels, which relax when the trade winds resume. Year-round persistence of easterly trade winds, and influx from the Yucatan Current to the Campeche Bank, drive a coast following, westward setting boundary current that typically deflects UGCPR turbid plumes to the west (Figure 4).

A shift to summer westerlies on the northern Gulf coast reduces westward transport in the LATEX coastal boundary current as buoyancy- and wind-driven flows compete for dominance [64,66]. The outcome of this competition during the summer affects the expanse and duration of the near-bottom hypoxic zone that forms in a lagged response to nutrient inputs from the MAR as plume water stably overlies higher salinity shelf water [13–15]. Stratification of the LATEX water column and bottom water hypoxia is interrupted in the fall by energetic wind-driven mixing that accompanies onset of cold front passages and hurricanes [15].

4. Conclusions and Management Implications

The MAR and UGCPR deltas owe their natural resilience to a modular construction that spreads risk across the shoreline while providing ecosystem connectivity through shelf plumes that extend estuarine conditions outside of the estuary. The MAR delta has proven vulnerable to anthropogenic interventions reducing fluvial sediment supply to sinking deltaic wetlands, so that the displacement of the land surface relative to sea level yields the highest relative sea level rise rates in North America [56,57,73]. Where previously the river shifted course to deliver sediment to interior wetlands, by forming large and small deltaic splays, crevasses and distributaries throughout the landscape, this natural mobility has been artificially curtailed now for more than a century.

It has long been recognized that the most effective internal management approach to saving the MAR delta will be to recreate the fluvial distributive capacity so that the aggradation potential of tidal delta marshes is increased sufficiently to avoid vegetative death through submergence [68]. That is why efforts to save the Mississippi River delta are focused on reconnecting the MAR with wetland basins by constructing artificial, controllable river diversions that will mimic the natural channels that have been lost [20,46,74].

More recently, attention has turned toward an "external" measure to increase resilience and reduce vulnerability in the sense that this term is used by Wolters and Kuenzler [18], that of releasing fine-grained sediment now collecting behind tributary dams of the Platte and Kansas Rivers [10,20,24,75], Great Plains drainages were once the primary source of such material to the Mississippi via the Lower Missouri River [10]. With increased runoff predicted for the MAR basin as climate change accelerates, further expansion of the shelf plume should continue to enhance ecosystem resiliency over a larger portion of the northern GoM coast. Accelerating plans to take advantage of this additional flux to deliver more sediment to the coast will be critical to at least partially offset the negative impacts of global sea level rise.

Subsidence and relative sea level rise are low in the UGCPR deltas compared to that of the MAR. The UGCPR deltas are currently most threatened by impoundment, especially by road building to support logging, oil and gas activities and other development that disrupts natural hydrology [48]. Because most of the system is still relatively unaltered, however, a high priority is to put protective measures in place now that will keep the UGCPR deltas from being damaged in the future as development pressures increase.

On the other hand, a climate future of rapidly decreasing precipitation and runoff throughout the Mesoamerican "climate hot-spot" raises concern not only for rapidly changing habitats, but also for the estuarine-dependent fisheries that appear to be reliant on shelf plumes for their productivity. The seemingly inevitable drying of Mesoamerica will have greater effects on human populations and developing economies, as well as on all dimensions of natural biodiversity than is anticipated in the MAR basin.

Mexican scientists working with political decision-makers and local communities have been remarkably successful in protecting large tracts of the most ecologically important deltaic lagoons and wetlands from human impacts by establishing refuges like the 3027 km^2 Centla Wetlands Biosphere Reserve that covers much of the Usumacinta-Grijalva delta [48] and the Special Area for Protection of Aquatic Flora and Fauna that takes in the entire Laguna de Terminos system [76,77]. But less protection has been afforded the mountainous headwater areas that cross international borders.

Coastal restoration in the MAR delta was initiated in the mid-1980s largely through the efforts of coastal citizens who mobilized with the strong support of the scientific community to form local non-profit charitable organizations like the Coalition to Restore Coastal Louisiana (www.crcl.org) and the Lake Pontchartrain Basin Foundation (www.saveourlake.org). These groups have worked over more than two decades with churches and communities across the coast to build awareness of the catastrophic wetland loss currently in progress, and to propose scientifically supported measures to address the causes of that damage.

Input from citizen leaders and the scientific community inspired political leaders at the state level and in the US Congress in 1989 and 1990, respectively, to put complementary legislation and funding in place to begin the restoration process through passage of the Coastal Wetlands Planning Protection and Restoration Act (CWPPRA). This initiative received attention from national environmental nongovernmental organizations (NGOs) after two catastrophic hurricanes (Katrina and Rita) struck the Louisiana coast in 2005, causing 1500 fatalities during the flooding of New Orleans and smaller coastal towns [11,78]. The hurricanes brought understanding at all levels of government that restoring deltaic wetlands was critical to a "multiple lines of defense" approach to enhancing the resilience of coastal communities to survive future storms as well as other foreseeable impacts of climate change [46].

New impacts from oil and gas and port facilities have been greatly reduced in the MAR delta by a strong regulatory program created at the state level with funding from the federal Coastal Zone Management Act. Wetland loss from permitted activities has slowed significantly since the 1980s. Even so, the MAR delta restoration initiative has succeeded in constructing only three relatively small river diversions and nourishing limited segments of disappearing barrier islands with dredged sand. Loss of interior deltaic wetlands, however, continues largely unabated. Slow progress is often attributed to lack of funding, but disagreement among user groups about inevitable changes to fishing grounds and navigation infrastructure is also delaying construction of the large sediment diversions that are clearly necessary to turn the tide [20].

The political processes that have led to a multi-billion-dollar restoration initiative in the MAR delta and to formation of large estuarine reserves in Mexico have followed different trajectories. In Mexico, as has been noted, numerous protective reserves have been established by national decree, but with little funding. The Centla Wetland Biosphere Preserve established in 1992 includes much of the UGR delta, while the Terminos Lagoon Protected Area covers the lagoon, surrounding shoreline and adjacent coastal waters out to the 20 m contour [48,76,77]. The objective of the Centla Preserve and Lagoon Protected Area is to preserve "the genetic diversity of the flora and fauna" while at the same time allowing for sustainable development.

Achieving the desired objectives has been difficult because of the growth of oil and gas extraction [48]. Currently, activities of PEMEX, the national oil company, in the Preserve are poorly regulated because management plans were developed before such development was envisioned. Established communities have been allowed to remain and the practice cattle ranching within the UGCPR deltas has been allowed to continue, but new settlements are prohibited. While the scientific community has been involved from the beginning, effective efforts to engage a broader public in planning and management is still in the early stages, with assistance from international NGOs like the Nature Conservancy [79]. The citizen engagement that preceded restoration efforts and continues in Louisiana is only now beginning to come together in the UGCPR deltas [77], while the focused international effort that will be necessary to address the great "drying" of Mesoamerica remains over the horizon.

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