The Response of Deltas to Sea-Level Rise under Natural and Human-Impacted Conditions

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Objectives and hypothesis

The main goals of this presentation are:

a) to review the scientific literature concerning the effects of sea level rise (SLR) on deltas both under natural and human-impacted scenarios, and

b) to discuss a common framework to understand past and future changes of deltas due to SLR.

Relevant questions:

- Did deltas survive high rates of SLR during the early Holocene ?
- Can deltas survive accelerated rates of SLR due to global warming ?
- Can we manage deltas to be more resilient against relative sea level rise (RSLR) ?

We hypothesize that deltas can withstand high rates of SLR (> 1 cm/yr) under certain natural and human-managed scenarios, existing some specific mechanisms that make them more resilient to SLR than other non-deltaic (low-lying) coastal systems.

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Understanding the past, predicting the future

- The **response of deltas to SLR** has been either studied from a perspective of **human impacts** like global warming and impoundment, or from a perspective of **natural changes** associated to glacial cycles.

- The **time scales, methods and disciplines of both approaches have been different**, and up to date there is not a comprehensive framework to analyze and compare the changes that deltas undergo due to SLR with natural and human-impacted conditions.

- Analyzing the response of deltas to a **natural SLR scenario** usually means looking at the **past** (i.e. last deglaciation), at a **longer time scale** (1000's yr) and using **geological methods** (i.e. stratigraphy);

- Whereas analyzing the response to **human-impacted scenarios** means looking at the present and **future**, at a **shorter time scale** (10's yr) and using a more diverse set of methods from **different disciplines**.

- The **current paradigm** in both scenarios is that relatively **high rates of SLR** (i.e. deglaciation rates > 1 cm/yr) **lead to a destructive phase of deltas**.

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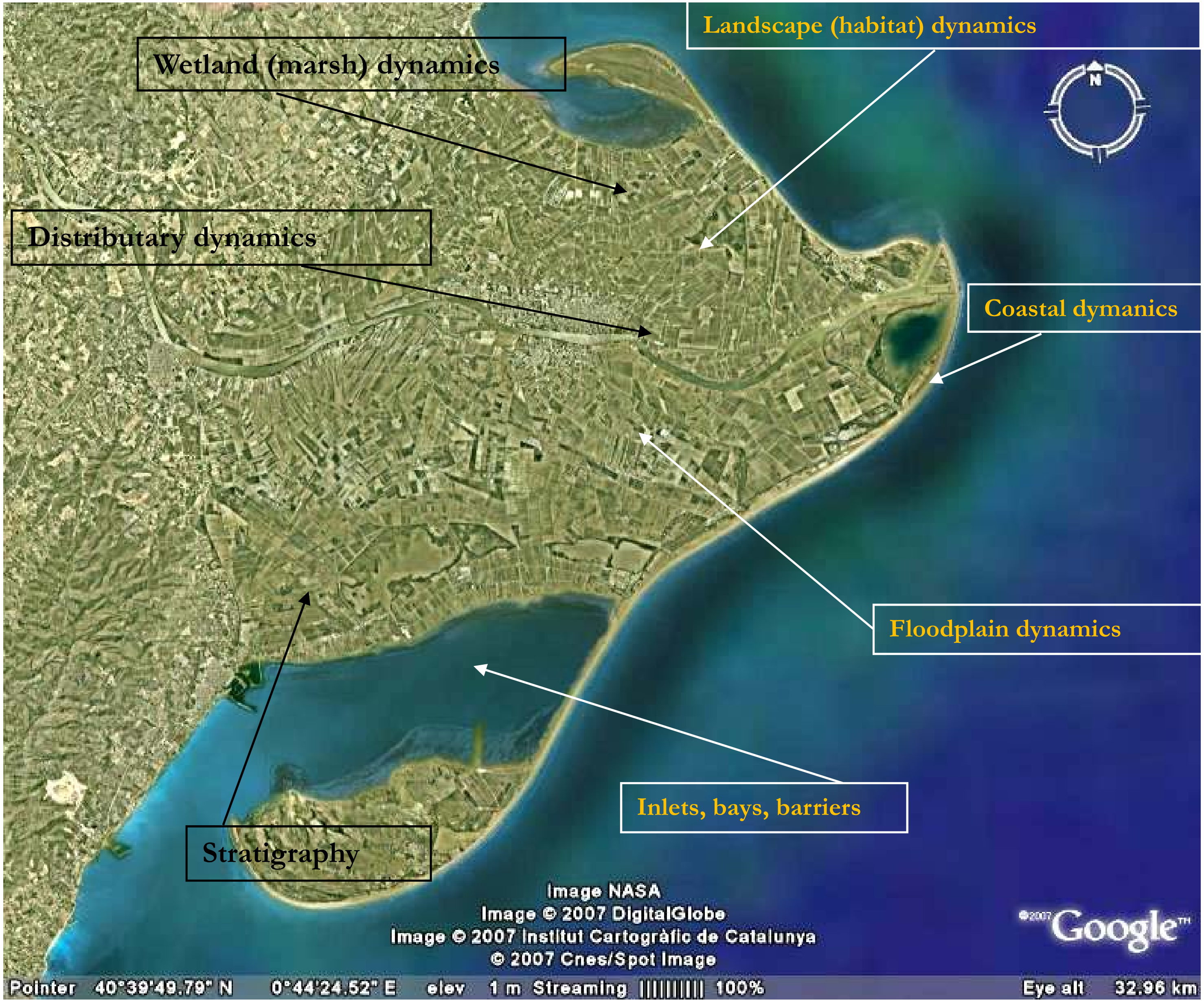
Different disciplines, different models



Different approaches, different views

• Existing **modeling and field approaches do not look at deltas as a unique systems** with different spatial and temporal scales.

•There is a **need to integrate different approaches** coming from the sedimentology, geomorphology, stratigraphy, coastal engineering and ecology.

• Models dealing with **delta construction and evolution** do not incorporate long-term sea level changes, whereas models dealing with **long-term sea level changes** do not consider the details of delta construction.

• There is not a synthesis on the response of deltas to sea level rise:

  - Often there are **contradictions between data and conclusions derived from each particular discipline**.
  - There is a **disconnect between research looking at future and past responses of deltas to SLR**.

"**Although we have come a long way in our understanding of delta patterns and their response to changes in sea level, our models are still rudimentary and fairly untested**."
(**Jerolmack 2009**, *Quaternary Science Reviews* 28: 1786-1800).

"**Coastal scientists, engineers, managers, and planners face a great challenge in interpreting the impact of SLR on beaches and barriers because synergistic processes produce responses over a various temporal and spatial scales**."
(**FitzGerald et al. 2008***, Annual Review of Earth and Planetary Sciences* 36: 601-647).

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The response of deltas to SLR: mechanisms

Deltas can withstand high rates of RSLR provided that:

a) there is enough sediment supply from the river,
b) the slope of the continental shelf through which the deltas migrate is smooth,
c) the human intervention do not tend to isolate the delta plain from the riverine and marine dynamics.

There are two main (autogenic) mechanisms for deltas to cope with RSLR that are self-enforced as the rates increase:

a) the river avulsion and formation of new lobes in shallow areas,
b) the increased overflowing from the river, that increases the sediment inputs and the trapping efficiency of the delta plain.

These mechanisms can be enhanced through management measures based on natural system functioning and ecological engineering methods.

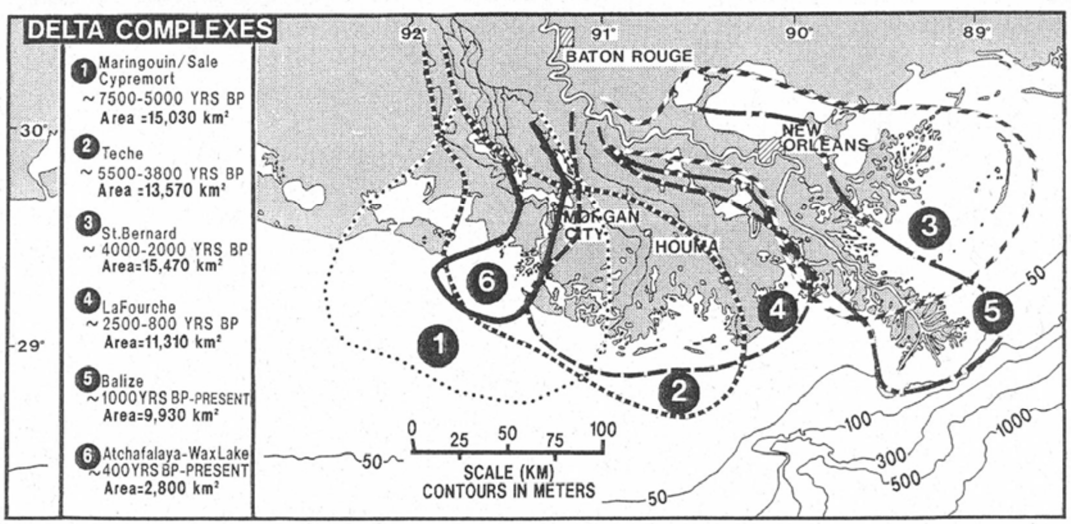

Figure 1. The Mississippi River deltaic plain, illustrating the locations of major delta complexes, including their approximate ages and sizes.

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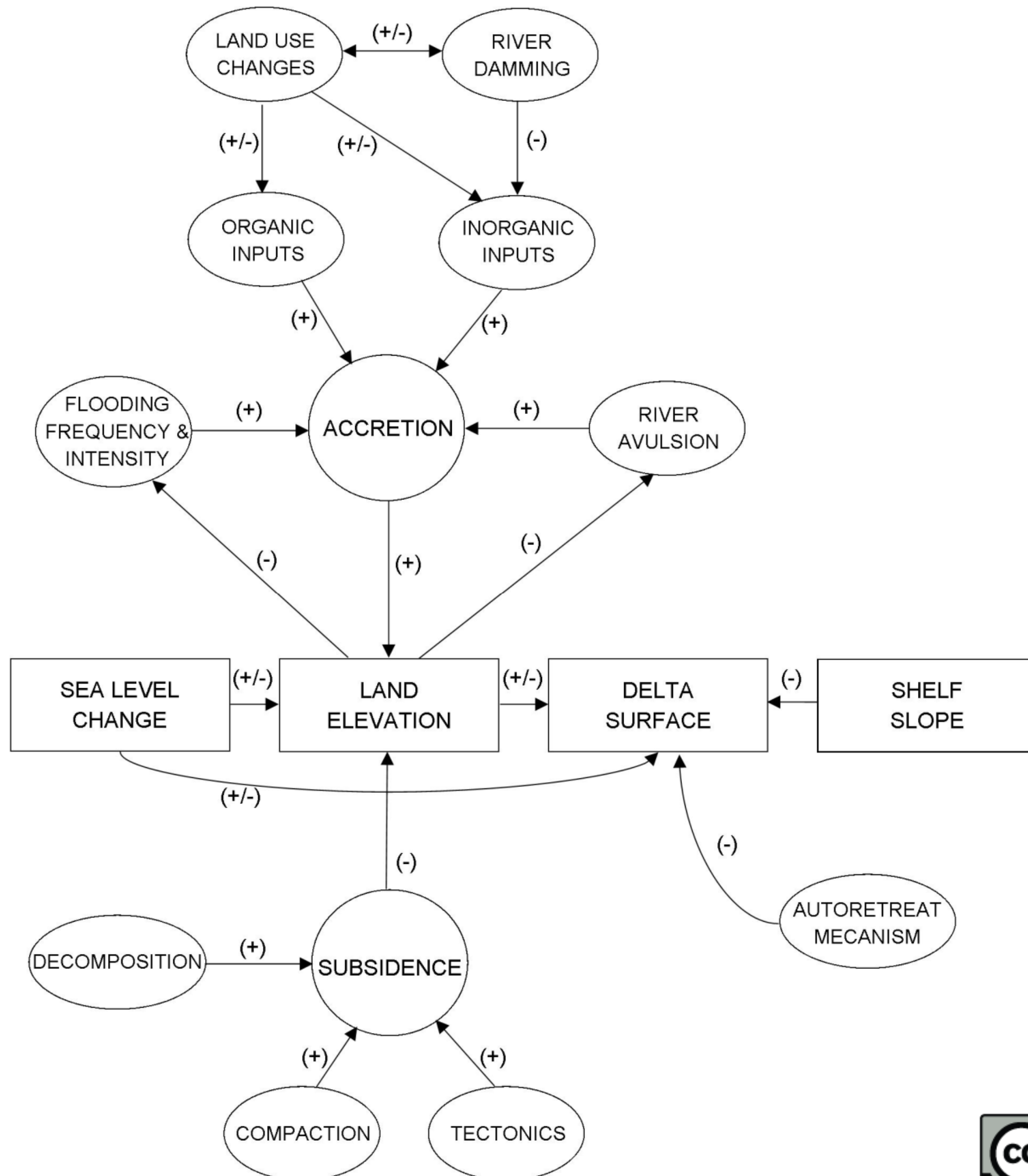
The response of deltas to SLR: mechanisms



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An important mechanism: non-linear and non-equilibrium response of marshes to RSLR

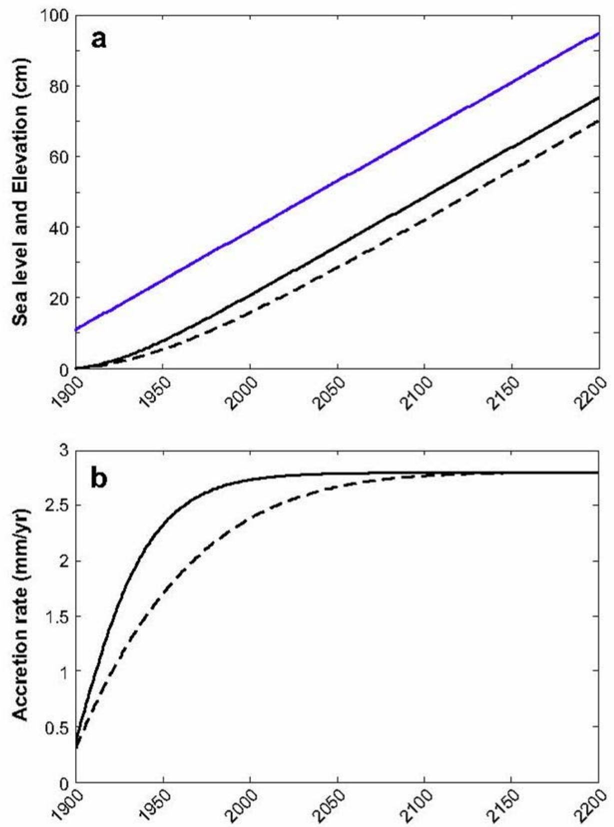

Fig. 1. Modeled response of marsh elevation (a) and accretion rate (b) to an abrupt increase in sea-level rise rate from 0.3 mm/yr to 2.8 mm/yr (Gehrels et al., 2008). Model experiments begin with a surface in equilibrium with a 0.3 mm/yr rate of sea-level rise, and demonstrate adjustment to a step change in the rate of sea-level rise beginning in 1900 AD. Blue line denotes sea level, solid black line denotes Morris model, dashed black line denotes Temmerman model. Since absolute elevations are different in each model (due to different tidal ranges and local model parameters), we plot elevation changes relative to their initial value which we set to zero in all model experiments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Feedback between inundation depth and suspended sediment concentrations allows marshes to quickly adjust their elevation to a change in sea-level rise rate.

Analytical theory suggests that the influence of vegetation on the feedback between inundation and accretion leads to a relationship where marshes adjust to step changes in sea-level rise rates more quickly than predicted by an exponential function. **This leads to the counterintuitive condition where marshes adjust to large changes in sea-level rise rates faster than they adjust to small changes in sea-level rise rates** (Fig. 5)

(Kirwan and Temmerman 2009, *Quaternary Science Reviews* 28: 1801-1808).

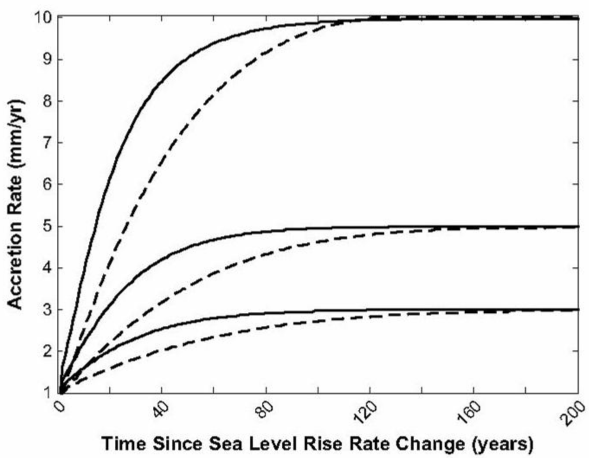

Fig. 5. Response of modeled accretion rates to step changes in the rate of sea-level rise. Experiments begin with a marsh surface in equilibrium with a 1 mm/yr rate of sea-level rise. Sea-level rise rates increase abruptly to 3, 5, or 10 mm/yr at time zero. Black line: Morris model; Dashed line: Temmerman model.

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Did deltas survive high early Holocene rates of SLR ?

The conventional view: deltas disappeared during the Holocene transgression.

• **Stanley and Warne (1994), Science 265: 228-231**

The formation of most modern deltas began in the lower Holocene epoch. **As the rate of eustatic sea-level rise declined, inputs of fluvial sediment began to accumulate along many coasts creating deltas throughout the world**.

• **McManus (2002), *Marine Chemistry* 79: 155-170.**

(1) **During the repeated glaciations** of the past 2.5 Ma, **sea level fell by 100–150 m**. Any sediment carried would have been deposited in these distal areas, possibly creating deltas at such sites. **(self-edge deltas)**

(2) **A rapid rise of sea level accompanied ice melting**, from about 15 ka onwards; more rises until about 8 ka, when the rise decelerated to create sea levels at 2 to 3 m during the period 8–6 ka BP**. (the black hole !)**

(3) This is the **stage at which the modern deltas began to develop worldwide**, so they have been in existence for a relatively brief period of geological time. Since about 6 ka BP, many of the deltas have undergone channel switching, to create multi-lobed features with coastal erosion characterising the abandoned outlet areas. **(present high-stand deltas)**

• **Porebski and Steel (2006), Journal of Sedimentary Research 76: 390-403.**

During transgression, deltas tend to change into estuaries, **although high-discharge rivers can create mid-shelf deltaic lobes as punctuated regressions during a longer-term relative sea-level rise** (Bartek et al. 1990; Anderson et al. 2004). **Little is known of such deltas and their preservation potential in mid-shelf settings**. **(the black hole is not empty ?)**

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Did deltas survive high early Holocene rates of sea level rise ?

Possible evidences of deltas existing during high Holocene RSLR rates:

1. Delta lobes are eroded during transgression, so if we do not find them it does not mean that they did not exist !

Bhattacharya and Giosan (2003), *Sedimentology* 50: 187-210.

In some cases, much of the shallow- water, paralic 'topset' facies of **the delta plain is removed or reworked during transgressions**. **(eroded delta lobes during sea level rise ?)**

2. High sediment supply allowed some deltas to grow with high SRL rates

Goodbred et al. (2003), *Sedimentary Geology* 155: 301-316.

The high and sustained sediment supply (of the Ganges-Brahmaputra) apparently hindered transgression and maintained conditions of **vigorous delta progradation much earlier than other Holocene deltas despite significant sea-level rise**.**(high sediment supply can allow deltas to survive rapid sea-level rise)**

3. Evidences of mid-shelf deltas have been found in some cases:

Porebski and Steel (2006), Journal of Sedimentary Research 76: 390-403.

It is **probable** that mid-shelf deltas on transgressive shelves are transient phenomena. **(are they transient ?)**

Fast (glacioeustatic) rises also hamper the formation of transgressive deltas in mid-shelf settings. However, **for supply-dominated systems and relatively low rates of relative sea-level rise mid-shelf deltas are likely to form a significant component of transgressive systems tracts**. **(the ghost: mid-shelf deltas !)**

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Autogenic response of deltas to sea level changes

A recent body of theoretical, experimental, and field-based work has shown convincingly that fluviodeltaic systems lack an equilibrium configuration under steady dynamic forcing (RSLR = constant, sediment supply rate = constant) and that in general the stratigraphic response of the depositional system proceeds in a non-equilibrium and nonlinear manner. **This fundamental aspect of stratigraphic response has not been recognized in conventional sequence stratigraphy.**
(Muto et al. 2007, Journal of Sedimentary Research 77: 2-12).

The generally accepted notion that transgressive barrier (or estuarine) systems are formed in response to accelerated sea-level rise or subsidence or a reduction in sediment supply is substantially the same as suggested by the A/S ratio concept, and thus **should be reexamined in terms of the autoretreat shoreline mechanism.**

There is no doubt as to the great effect of the latest eustatic rise on modern systems of barriers, beaches, and estuaries. However, **the greatly increased RSLR, which resulted in the coastal transgression, would have been associated with high autoretreat effectiveness**. The Holocene transgressive system models can be more completely understood when shoreline autoretreat is fully taken into account **(Muto and Steel 1997)**.

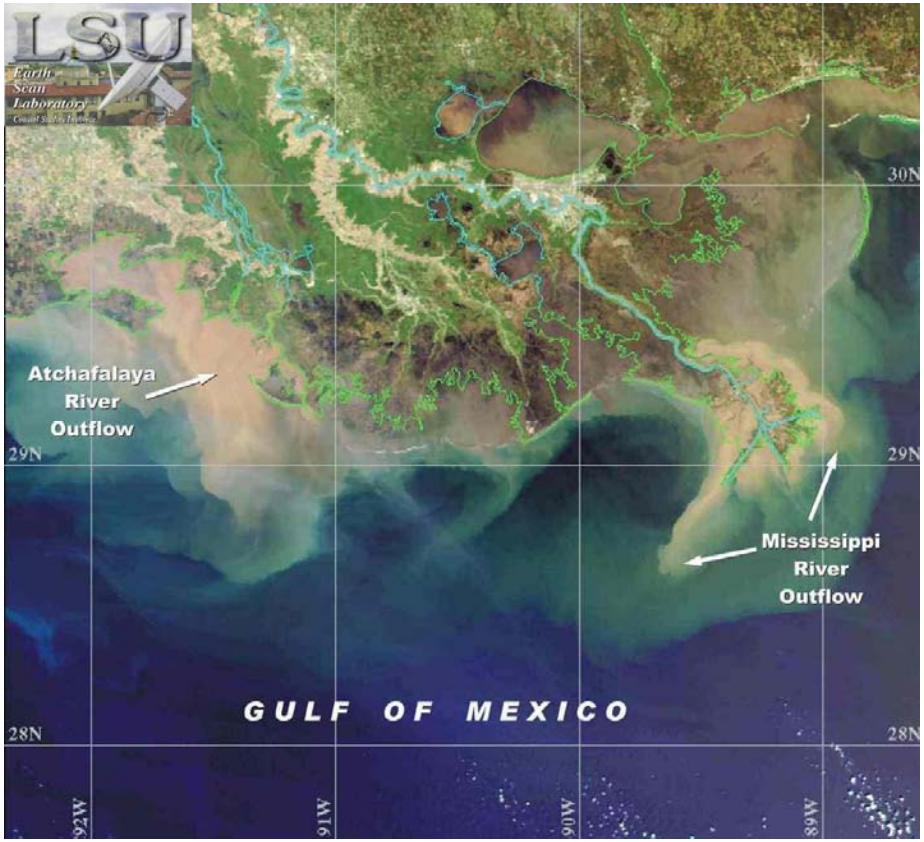
Possible scenarios to be considered:

With a smooth shelf slope, the autoretreat could actually imply an **increasing surface of the delta plain** (landward migration of the inner limit faster than the outer coast) during a SLR period.

The fact that the **delta shoreline undergoes a net retreat** under a RSLR context is compatible with the fact that all deltas have **active lobes growing** and abandoned lobes eroding.

Future scenarios for the Mississippi Delta: allowing river avulsion

We have the possibility to do an efficient sediment delivery through controlled river avulsions (diversions)



Delta lobes that have been built within the confines of the entrenched alluvial valley may have shorter marine-dominated transgressive phases because of accelerated subsidence rates as compared to lobes over a shallow Pleistocene base. **Indications are that because of its thick base of compaction-prone prodelta clay the modern Balize delta would disappear very quickly if the Atchafalaya River stream capture were allowed to divert most of the Mississippi River water and sediment**, as it surely would have done by now without man's intervention **(Roberts 1997, *Journal of Coastal Research* 13(3): 605-627).**

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Future scenarios for the Mississippi Delta: controlled diversions

Blum and Roberts (2009). Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. *Nature Geoscience* 2: 488-491.

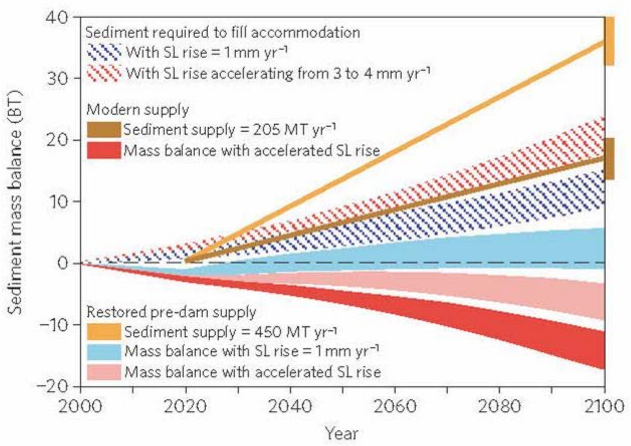

Figure 4 | Sediment mass balance for the delta region with modern sediment loads, and with hypothetical restored sediment loads. Supplies are held to 0 until the year 2020, then projected to the year 2100: the blocks at the right illustrate the standard deviation for modern loads, and ±10 for restored loads. The sediment required to fill accommodation is estimated for steady sea-level rise of 1 mm yr^{-1}, and sea-level rise that accelerates linearly from 3 to 4 mm yr^{-1} between the years 2000 and 2100. Each mass balance estimate uses subsidence models from Fig. 3c to define the upper and lower boundaries, and a 40% trapping efficiency.

• Mass balance considerations ensure that the future deltaic landscape cannot resemble the recent past, and **even the most prudent selection of diversion sites can only slow the overall rate of submergence**.

• **A recent state-of-the-art model provides quantitative estimates for two diversions located to the south of New Orleans**, which would have access to 45% of the lower Mississippi sediment load, or about 25% of the total Mississippi and Atchafalaya loads.

• **With a trapping efficiency of 40%,** and values for subsidence and sea-level rise similar to those above, **700-900 km^2 of new land can be built by the year 2110**.

• These modeling efforts highlight the mass balance problem, because the **new land to be built is <10% of the extra submerged area that we predict for the year 2100**.

• **Diversions that disperse sediment into partially submerged or still emergent areas farther upstream will build or sustain more land-surface area with the available sediment supply**: **upstream diversions can leverage organic contributions to marsh accretion, as well as maximize the trapping efficiency because most sediment would be deposited on marsh and swamp surfaces, in tidal channels or in shallow lakes or bays** where storm-generated sediment resuspension and landward transport is common.

Future scenarios for the Ebro Delta: RSLR and vertical accretion

•Historical **accretion rates in the rice fields of 0.5 cm/yr before dam construction** in the lower Ebro river, mostly through the irrigation network, and recent accretion rates of 0.5 cm/yr in brackish wetlands connected to the river (Ibáñez et al. 1997).

• **The historical accretion rates (0.5 cm/yr) in the rice fields (period 1860-1960) were achieved by using 10% of the Ebro river flow** (irrigation inputs, 50 m^3/s). This means a sediment supply of about 0.5 Million Tn/yr, for a surface of 20000 Ha (70% of the emerged delta plain).

• The sediment load before dam construction is estimated to be about 28 Million Tn/yr (Ibáñez et al. 1996). **To get an accretion of 1 cm/yr for the whole emerged delta plain (27000 Ha) we need about 1.3 Million Tn/yr, which is 10 times more the present sediment load but 20 times less the pre-dam sediment load.**

• Thus, **recovering about 20% of the original load** (5-6 Million Tn/yr) and supplying about 20% of this load to the delta plain **we could obtain a vertical accretion of 1 cm/yr in average (in rice fields and brackish marshes at least !)**.

• This sediment management scheme **is feasible provided that a sediment by-pass system is implemented in the lower Ebro dams**, and we are working with the Water Authority of Catalonia to make it happen in the next decade.

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The Ebro Delta could survive high rates of RSLR

Natural conditions:

•High sediment load.
•Significant overlapping of delta lobes.
•Excess of sand for the delta fringe.
• Positive feedbacks against RSLR: river avulsion and flooding frequency and intensity.

Human-impacted conditions:

•Possibility of restoring the sediment flux of the Ebro river.
• Use of the irrigation network for sediment delivery.
•Low mineral input requirements for rice fields and brackish wetlands.
• Support of local farmers and stakeholders to sediment management.

Conclusions

- **Fluvial-dominated deltas with high sediment supply could survive high rates of RSLR (> 1 cm)** that characterized the post-glacial period and will characterize the next centuries to come due to global warming (delta continuum hypothesis).

- **Deltas have specific feed-back mechanisms to enhance vertical accretion and land gain as a response to RSLR**, specially the increased river avulsion and delta lobe formation in shallow areas

- The **delta continuum hypothesis could be tested through modeling**, lab experiments and (in some cases) field data (startigraphic sequences).

-**Active management of water, sediment and nutrient fluxes across the delta plain can optimize the supply of sediment and organic accretion in wetlands**, in some cases with enough potential to maintain the deltaic system under scenarios of high rates of RSLR.

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DeltaNet Network & International Conference

Impacts of Global Change on Deltas, Estuaries and Coastal Lagoons
Research, observation and management
Ebro Delta, Catalonia, Spain
June 6-10, 2011
http://www.armagedontours.com/Deltanet/
CALL FOR ABSTRACTS OPEN TILL APRIL 15

DeltaNet is a network of European deltas and estuaries (http://www.deltanet-project.eu). The main goal of DeltaNet is to set up a learning and policy network of European delta regions.
The planned exchange of best practices are organised around 5 sub-themes: (1) Integrated delta approach, (2) Flood risk & sediment management, (3) Environmental healthy deltas, and (4) Delta awareness. The 5th phase of activities will gather the results of the sub-themes and integrate them into Sustainable Coordinated Delta Policy (5).

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