Natural Processes in Delta Restoration: Application to the Mississippi Delta

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Abstract

Restoration of river deltas involves diverting sediment and water from major channels into adjoining drowned areas, where the sediment can build new land and provide a platform for regenerating wetland ecosystems. Except for local engineered structures at the points of diversion, restoration mainly relies on natural delta-building processes. Present understanding of such processes is sufficient to provide a basis for determining the feasibility of restoration projects through quantitative estimates of land-building rates and sustainable wetland area under different scenarios of sediment supply, subsidence, and sea-level rise. We are not yet to the point of being able to predict the evolution of a restored delta in detail. Predictions of delta evolution are based on field studies of active deltas, deltas in mine-tailings ponds, experimental deltas, and countless natural experiments contained in the stratigraphic record. These studies provide input for a variety of mechanistic delta models, ranging from radially averaged formulations to more detailed models that can resolve channels, topography, and ecosystem processes. Especially exciting areas for future research include understanding the mechanisms by which deltaic channel networks self-organize, grow, and distribute sediment and nutrients over the delta surface and coupling these to ecosystem processes, especially the interplay of topography, network geometry, and ecosystem dynamics.

1. INTRODUCTION: THE BACKGROUND TO DELTA RESTORATION

1.1. Why Is It Needed?

The world's deltas are, in both literal and figurative senses, the thin end of the wedge in terms of coastal response to changes in sea level. Their typically low surface gradients make deltas potentially vulnerable to relative changes in sea level, in particular rise in global (eustatic) sea level (Cazenave & Llovel 2010) and relative rise caused by natural or anthropogenic subsidence. This vulnerability combined with the large number of people who either live on deltas or depend on them for their livelihoods has led to a recent acceleration of interest in the fate of deltas across the scientific community (Day & Giosan 2008, Syvitski 2008, Blum & Roberts 2009, Kim et al. 2009b, Syvitski et al. 2009, Vörösmarty et al. 2009).

The best-documented case of wetland loss, and the main focus of this study, is the Mississippi River Delta, which has lost approximately one-third of its original wetland area since the European settlement of North America (Craig et al. 1979, Gagliano et al. 1981, Kesel 1989, Day et al. 2000). Land loss begins with the reduction in sediment supply brought on by dam construction across the Mississippi watershed. A local restoration scheme obviously cannot change this. However, the main proximal cause of deltaic wetland loss in the Mississippi River Delta is the construction of levees and other control works on the Mississippi River through the delta, which has cut off the river from its adjoining wetlands. This has turned the river into a superefficient pipeline channel that carries its load of sediment and excess nutrients directly to the Gulf of Mexico rather than distributing some part of it into coastal basins that nourish adjacent wetlands. As a result, coastal wetlands, deprived of the sediments that, in effect, provide their mineral skeleton, are unable to compensate for natural and anthropogenic subsidence and sea-level rise, and they gradually drown. The vegetated landscape and shoreline collapse, and the former self-sustaining wetland is replaced by open water.

Delta restoration seeks to reverse land loss and restore wetlands through diversion of sediment and water from the river onto the drowned wetland landscapes. Large-scale delta restoration has been a major part of coastal management planning in Louisiana for some time (Louisiana Coastal Wetlands Conservation and Restoration Task Force 2006, Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority 1998, USACE 2004). There are a numerous important engineering and social issues in delta restoration that are beyond the scope of this review (for more information, see Boesch et al. 1994, Laska et al. 2005, National Research Council 2005). Our specific goal here is to focus on how understanding natural processes of delta growth contributes to delta restoration.

1.2. How Would Restoration Be Done?

To frame our discussion, we need a basic understanding of what is meant by delta restoration. It is helpful to compare delta restoration with stream restoration, which although far from standardized, has at least been going on for long enough to provide a wealth of example case studies (Bernhardt et al. 2005).

The basic scheme for restoring deltaic wetlands is to reverse the pipeline effect of artificial channelization of the principal river channel(s) by creating controlled openings that divert water and especially sediment onto drowned wetlands. There is an important contrast with the typical case of river restoration, where the restored channel is typically constructed by humans, more or less in the image of a natural channel. In delta restoration, the idea is to allow natural processes to create the new wetlands, although this could be accelerated by, for example, using dredged sediment to help build the platform (Boesch et al. 1994, Day et al. 2007). Restoring a substantial part of the sediment supply to the wetlands is required to allow natural delta-building processes to reconstruct a delta lobe and associated wetlands. In the Mississippi Delta, what is, in effect, being restored are the processes by which the historic delta lobes have grown after avulsions (abrupt shifts in the location of major river channels; Fisk 1944, Coleman 1988, Saucier 1994, Roberts 1997, Coleman et al. 1998, Aslan et al. 2005). In general, delta-lobe growth involves a set of strongly coupled, ecogeomorphic processes that create an intricately choreographed spatial structure of channels, natural levees, vegetation, and nutrients (Boesch et al. 1994, Gosselink et al. 1998, Sasser et al. 2007). The way in which highly patterned landscapes arise spontaneously from the interplay of these processes is sometimes termed co-organization. What is important here is that the new delta lobe and wetlands are not engineered but supplied with the necessary raw materials and then allowed to create their own form. This, added to the scale of restoration of deltas like the Mississippi and the potential consequences of the restoration for coastal communities, makes understanding the natural processes involved even more critical than it is in conventional river-restoration projects.

A possible scheme for restoring the Mississippi River Delta is shown in **Figure 1**. Water and sediment would be diverted from two points along the main-stem Mississippi as shown in the figure, feeding into adjacent shallow waters of Barataria Bay and Breton Sound. The exact locations of the diversion points and the number of diversions are for illustration; neither is critical to the focus of this review. The diversions themselves would be engineered structures that could range from relatively simple gates in the river levees to more complex siphon and/or pump systems. There would almost certainly be some initial length of fixed feeder channel to carry the water and sediment to the initiation point of the new delta lobe. Downstream of the initiation point,

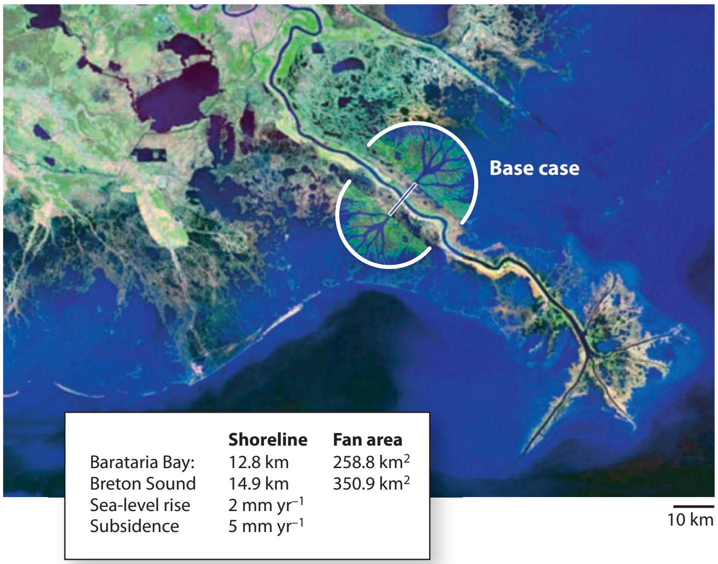

Figure 1

Synthetic image of a possible scheme for delta restoration on the main-stem Mississippi River (Kim et al. 2009b). The wetland areas shown are predictions for 50 years from the initiation of restoration, assuming the values for mean subsidence and eustatic sea-level rise given in the inset and other conditions as described for the base case in Kim et al. (2009b). Adapted from Kim et al. (2009b).

Figure 2

Satellite image of Wax Lake Delta, Louisiana.

the lobe would grow on its own, in the same manner as the lobes that have created the delta over geologic time. Specifically, the restoration would reproduce the initial growth (construction) stage of the classic delta sequence (Roberts 1997), but because the supply would be maintained rather than allowed to shift laterally as in the natural delta, the lobe would stabilize at a size adapted to maintain a balance between sedimentation and subsidence. The specifics of this are discussed below.

Although most of the Mississippi River Delta system is losing ground, vigorous delta growth at the mouth of the Atchafalaya River, the main distributary of the Mississippi, demonstrates that the situation is far from hopeless. In particular, Wax Lake Delta (WLD; Roberts 1998, Roberts et al. 2003, Roberts & Sneider 2003, Wellner et al. 2005) (**Figure 2**) has created over 100 km^2 of new deltaic surface since it began building seaward in 1980 as the unintended consequence of a flood-control project. WLD provides both a vivid example of what a restored river delta lobe would look like and an ideal natural laboratory for study of the coupled natural physical, ecological, and geochemical processes involved in delta restoration. We will refer to WLD often in this review.

Another example that illustrates the full natural cycle of delta lobe growth is provided by Cubit's Gap, a crevasse on the main-stem Mississippi (Roberts 1997, Wells et al. 1983). Between 1862 and 1868, an opening in the channel dug as a fishing shortcut grew to a width of >700 m and diverted enough sediment from the river to create a new lobe that by 1922 was comparable in size to the modern WLD. Without intervention to maintain the sediment supply, the breach eventually healed itself sufficiently to reduce the sediment supply and lead to a phase of wetland drowning that can be seen as a microcosm of the results of cutting off the river from its floodplain across the broader delta. The evolution of the Cubit's Gap lobe illustrates the crucial role played by sediment supply. Whatever else we may consider doing to influence the course of delta restoration, adequate sediment supply is one thing that must be maintained in order for the natural processes to sustain the deltaic coast.

2. NATURAL DELTA PROCESSES IN RESTORATION

Deltas involve a complex web of coupled biologic, geochemical, and physical processes, many of which are as yet poorly understood. It is not possible to review all of them here. Instead, we focus on processes that are critical for problems such as deciding whether restoration is feasible, estimating its benefits in terms of land area and ecosystems, and predicting how a restoration project would evolve in time. We do not evaluate costs of restoration projects, but the issues we examine are critical to understanding the value of restoration projects to society. As explained above, in a basic restoration scheme, the restored wetlands would not be constructed in the conventional engineering sense but rather would be allowed to develop on their own. Another option is to add sediment to quickly provide a substrate for wetlands; this requires a higher level of predictive understanding to make sure the constructed platform is consistent with what the system would have created naturally.

We summarize the overall state of current understanding as (*a*) We know enough about natural processes of delta growth to make sound decisions as to the feasibility of restoring deltaic wetlands under given scenarios of subsidence and sea-level rise; and (*b*) We do not know enough about these processes to make detailed predictions of how the restored wetlands will evolve, to the level of specific distributions of channel properties, elevation, habitat types, etc. We can learn from existing small diversions (Miller 2004, Andrus & Bentley 2007, Snedden et al. 2007, Barras et al. 2009, Day et al. 2009) and ongoing studies of growing deltaic wetlands such as WLD. However, so much deltaic wetlands has been lost that we cannot afford to wait until we understand every detail of deltaic ecogeomorphology before taking action. Large-scale delta restorations must be viewed to some extent as natural experiments that will be used to refine and improve models of delta evolution. This implies intensive monitoring, tight coupling of observations and models, a high level of engagement of the research community, and an adaptive approach to managing the restoration process.

2.1. Overall Form of Deltas

Deltas comprise, at a minimum, two interconnected physical components: a relatively low-gradient, riverine upper part (the topset in stratigraphic terminology) and an offshore part (the foreset) that starts at the shoreline and typically has a higher slope than the delta top. The topset supports the wetland ecosystems, human population centers, and delta-related infrastructure (e.g., shipping and oil-production facilities). The two parts are coupled in that the offshore region must store and/or transport the sediment delivered to the shoreline by the delta-top river system. This typically involves a mix of downslope processes (e.g., mass flows) and transverse processes (e.g., longshore sediment transport). Some of the sediment delivered to the offshore may also be returned to the riverine delta top by onshore sediment transport induced by storms and/or tides (e.g., Goodbred & Kuehl 1998). In longitudinal section, the delta overall has the form of a sediment wave and is thus often called a clinoform (**Figure 3**). Under conditions of constant sediment supply and relative sea level, the clinoform wave propagates forward (i.e., in the direction of mean sediment transport) with a roughly self-similar shape (Pirmez et al. 1998, Lorenzo Trueba et al. 2009). Although on long time scales, the entire deltaic clinoform must be considered as a single linked entity, for the immediate purposes of restoring deltaic wetlands, we focus on ecogeomorphic processes on the delta top.

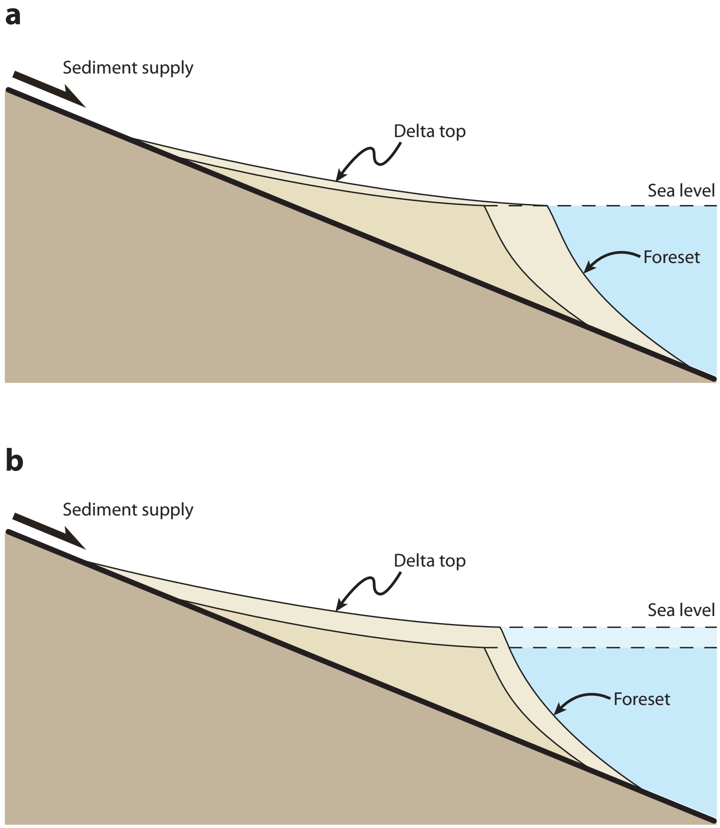

Figure 3

Sketches showing the longitudinal clinoform shape of a river delta. (*a*) A prograding delta with constant sea level. (*b*) A delta subject to a relative sea-level rise comparable to its overall surface relief; instead of passively drowning, the delta responds by depositing sediment to preserve its overall shape. The trajectory of the shoreline (transgression or regression) depends on the balance between relative sea-level rise rate and sediment supply.

Deltas belong, with alluvial fans, fan-deltas, and submarine fans, to the distributary class of channel networks: On average, channels bifurcate moving downstream so that the network creates more but smaller channels. In contradistinction to tributary networks that collect water and sediment and thus converge to fewer but larger channels moving downstream, distributary networks organize themselves to distribute water and sediment over a broad area. Although the relationship is far from precise, tributary networks are typically erosional and distributary networks depositional.

2.2. Delta-Top Mass Balance and the Feasibility of Restoration

Given that deltas typically develop in areas subject to long-term subsidence, the most important natural processes in terms of delta restoration are the ones by which deltas deposit sediment and thus maintain their topset surfaces above sea level. In general, large, fine-grained deltas have very low mean surface slopes—typically of the order of 10^{-5}. Thus, for anyone unfamiliar with how deltas work, it seems obvious that even small amounts of relative sea-level rise (the sum of subsidence and eustatic rise) will drown large areas of the delta top. For example, former U.S. Secretary of the Interior Bruce Babbitt (*The Washington Post* 2007) has written: "Most of the Mississippi Delta, some 10,000 square miles, lies less than three feet above sea level. Beset by land subsidence and rising sea levels, much of this vast area will inexorably sink beneath the waters by the end of this century."

As intuitively reasonable as this point of view may appear, it is profoundly incorrect. The error is in thinking of the delta surface as static—in effect, a tilted board. For a tilted board, a relative sea-level rise ΔH produces a shoreline transgression (landward migration) of length $L = \Delta H/S$, where S is the surface slope. Low slopes thus lead to extensive transgressions. However, observations of the behavior of delta tops and their associated wetlands show that, over time, the surface is dynamic, building itself upward by depositing sediment and organic matter. Thus, far from resembling a static, tilted board, the delta top is a dynamic surface that can maintain itself against relative sea-level rise. In fact, even if sea-level remains constant, the delta surface must continually reconfigure itself; for the delta to propagate forward while preserving the gradient of its topset fluvial system, geometry dictates that the system must deposit sediment over its entire length (**Figure 3*a***). The delta top is thus a naturally organized, self-maintaining surface. The interplay of physical and biotic processes of sedimentation by which this comes about is complex and variable; the relatively simple integrated effect it produces is difficult to observe and measure on short time scales. At present, in many large deltas such as the Mississippi, sediment supply to the wetlands has been drastically reduced by human interference. This deprives the wetlands of raw material for their mineral "skeleton" so that they eventually collapse and drown. Nonetheless, the overall ability of deltas to deposit sediment in their topset regions is abundantly clear in the stratigraphic record, which provides an archive of countless natural experiments on delta evolution under conditions of varying sediment supply, subsidence, and sea-level change. Both stratigraphic observations and laboratory experiments show that deltas can deposit sediment in their topset regions (aggrade) in response to even high rates of relative sea-level rise (Helland-Hansen & Martinsen 1996, Carvajal et al. 2009, Sverre et al. 2009) (**Figure 3*b***), as long as they have a sufficient supply of sediment relative to the rate and duration of sea-level rise (Muto 2001).

Laboratory experiments on delta dynamics, which we discuss in more detail below in Section 2.10, also illustrate the capacity of the delta top to aggrade and maintain itself in response to rising relative sea level. Here, the effect of subsidence has been included by raising base (sea) level; true differential subsidence can be included by using a deformable floor (Paola et al. 2001, Van Heijst et al. 2002). **Figure 4** shows the contrast in shoreline position between an experimental delta propagating into standing water and the same system subject to a steadily rising base level. The rise in base level prevents further progradation, but it does not cause the delta surface to drown. Rather, the rate of sediment deposition in the surface increases, which is associated with modest but readily detectable changes in the surface morphology (Martin et al. 2009). Notably, the rate of channel avulsion increases in the case of a rising base level; evidently the increased rate of aggradation destabilizes the channels and leads to more frequent shifting. Other experiments (Muto 2001; Muto & Steel 1992, 2001) illustrate conditions under which deltas retreat as a result of ongoing relative sea-level rise; and likewise, the stratigraphic record and modern coasts (e.g., Parker et al. 2008) are replete with examples where deltaic shorelines have retreated under relative sea-level rise. The point is that the long-term trend—progradation, maintenance, or retreat—cannot be understood simply in terms of the gradient of the delta surface but rather must be thought of in terms of the dynamic balance between sedimentation and subsidence. For the former, sediment supply is the fundamental control.

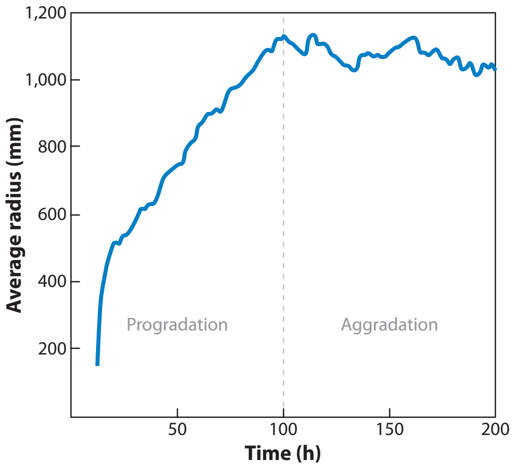

Figure 4

Average delta radius through time for (*left*) constant base level and (*right*) steadily rising base level in an experiment reported by Martin et al. (2009). The rising base level stops the advance of the shoreline but does not cause transgression; for these conditions, the sediment supply is sufficient to maintain the delta at the size shown.

If one pictures the low-lying delta surface as static, it is easy to conclude that even a small amount of relative sea-level rise will lead to extensive and unstoppable flooding. Given the temptation to view deltas in this way, we stress that the most important natural effect in delta restoration is not a single process but the entire suite of processes, biotic as well as physical, that organize themselves over the delta top to create a system that is intrinsically capable of maintaining itself against relative sea-level rise. The basis for this is sediment supply to the wetlands—without this, the static-surface view is nearly correct. But, left to its own devices and supplied with sufficient sediment, the apparently vulnerable low-gradient delta surface can be surprisingly resilient, aggrading and recreating itself (within limits) in response to sea-level rise. It may retreat, but it does not passively drown.

Once we make the transition from a static-drowning model to a dynamic, self-maintaining surface, we also make the transition from asking if restoration is possible to asking how much wetland area can be created under given scenarios of sediment supply and rates of subsidence and sea-level rise. If we take a longer-term view, we may also ask under what conditions the deltaic shoreline might eventually retreat. The fundamental question on which the feasibility of delta restoration hinges becomes: With the available sediment, can we create a sustainable wetland area large enough to justify the cost of the restoration? Sediment availability, already reduced by upstream damming, is further constrained by river-side restrictions (i.e., for navigation, flood control, erosion prevention, etc). We can frame the overall mass-balance constraint as

$$A_w = \frac{f_r Q_s (1 + r_o)}{C_0(\sigma + \dot{H})} \tag{1}$$

where A_w is the sustainable delta-top area, including both vegetated and channel (wetted) area; Q_s is the volumetric rate of sediment supply via diversion; f_r is the fraction of sediment retained in the topset depositional system; r_o is the volume ratio of organic matter to mineral sediment in the wetland sediment column; C_0 is the overall solids fraction in the sediment column (1-porosity); σ is subsidence rate averaged over A_w; and $\dot{H}$ is the rate of eustatic sea-level rise.

Barring effects of longshore sediment transport, any sediment not retained in the delta top is exported to the offshore part of the delta (foreset and deltaic apron and beyond). **Figure 3** shows how, for a delta propagating seaward under constant relative sea level, the overall partitioning of sediment between the delta top and foreset is controlled by the geometry of the delta form. This geometric control offers the hope that the sediment partitioning might be predictable and might be relatively consistent, at least within a given class of deltas. The limited data available from natural deltas for the fraction of total sediment supply that is retained in the delta top, and thus available to support deltaic wetlands, suggest that this is indeed the case. The best partition estimates for modern deltas are from sediment-budget estimates for the Ganges-Brahmaputra Delta by Goodbred & Kuehl (1998), from sediment flux measurements along the Ob River Delta (Bobrovitskaya et al. 1996), and from WLD (Kim et al. 2009b). In these cases, 30–40% of the sediment supply is retained in the delta top. It is worth noting that the Ganges in particular is affected by strong tidal currents and wave transport that would be expected to enhance seaward sediment transport. These field estimates of sediment partitioning are also consistent with laboratory experimental deltas and simple estimates based on self-similar clinoform geometry (e.g., **Figure 2**). Overall, it appears that the fraction of supplied sediment retained in the delta top typically falls in the range of one-third to one-half. Although obviously not extremely precise, and subject to refinement as our understanding of delta-top sedimentation improves, this range suggests that deltas are capable of trapping a significant fraction of the sediment provided to them. Together with Equation 1 the retention fraction values provide a starting point for estimating the wetland area that could be produced with a given sediment supply.

2.3. Spatially Averaged Surface Topography

Although an overall mass balance like that represented by Equation 1 provides a starting point for evaluating, in general terms, the amount of wetland area that can be created for given conditions of relative sea-level change and sediment supply, it is hardly sufficient for planning a restoration. The next level of detail is provided by spatially averaged models of delta growth, for example, the one developed by Kim et al. (2009b). The delta is assumed to have, on average, radial symmetry, such that its average topography can be represented as a function of only radial distance r. The Kim et al. model assumes that, through a combination of spatial channel division and temporal avulsion, channels range over the delta top, delivering sediment to create topography that evolves a consistent mean elevation profile in the radial direction r. The idea is not to locate individual channels, which in any case migrate in time, but to model their composite width and sediment delivery.

The Kim et al. (2009b) model uses a conventional sediment-transport formulation for moving and depositing sand. There is greater uncertainty about the contributions of mud and organic matter to the sediment column that supports the delta surface. Organic matter in the form of peat can make up a significant fraction of the sediment column in the Mississippi River Delta; for example, data from 31 cores (3.5–7.5 m) reported in Morton et al. (2005) indicate an average of 27% organic-rich deposits. The effect of this organic matter has not been included as yet in the model of Kim et al. (2009b). The dynamics of fine-grained cohesive sediment have traditionally been as murky as the fluids they travel in, and unfortunately this is still the state of things today. The Kim et al. (2009b) model uses the assumption of a consistent ratio of mud to sand deposition. This is justified in part because field observations in coastal regions (Curran et al. 2002, Hill et al. 2003, Fox et al. 2004, Larsen et al. 2009a,b) suggest that most fine-grained sediment travels in the environment in a flocculated state in which the fine particles are aggregated, usually with some amount of organic matter, into large (silt-sand-sized) but low-density particles that behave more like sand than like individual clay flakes (Schieber et al. 2007).

There is still much to learn about the formation and transport of mud aggregates in deltaic environments. An especially promising approach to this is the use of movable field flumes

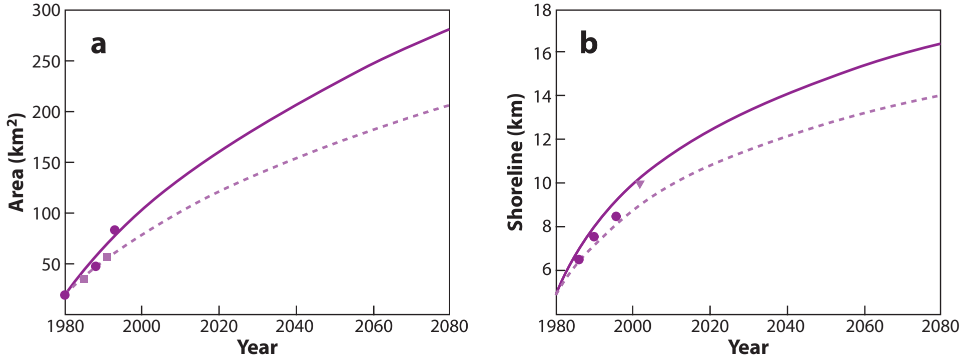

Figure 5

Predictions of growth of (*a*) total area and (*b*) shoreline position from the Kim et al. (2009b) radially averaged delta model compared with observations from Wax Lake Delta (see **Figure 2**). The solid and dashed lines bracket the range of sediment supply (25–38 MT yr^{-1}).

(Larsen et al. 2009a,b) that provide a detailed picture of the erosion, transport, and deposition dynamics of natural clay–organic complexes under in situ field conditions.

The main goal of laterally averaged models like that of Kim et al. (2009b) is to predict the overall rate of shoreline advance, and hence growth in delta area, given input water and sediment supplies, average subsidence rate, and eustatic sea-level rise. The main unknown parameter in the Kim et al. model is the ratio of mud-to-sand deposition, which is set to a value between 0.5 and 1 based on local conditions. The low end of this range is based on information from WLD, which is building directly into the Gulf of Mexico. The high end is based on inferences concerning sand and mud deposition in more protected locations. The model predictions are straightforward and have been tested against the well-documented growth trajectory at WLD, with excellent results (**Figure 5**).

Mine-tailings deltas provide a valuable and easily overlooked data source on which the predictive models of Kim et al. were ultimately based (Parker et al. 1998a,b; Whipple et al. 1998; Paola et al. 1999; Kim et al. 2009, 2009a). These deltas are typically kilometer-scale fan deltas created to store mine waste within a defined area. With braided channel patterns (**Figure 6**), steep surface-gradients, high and noncohesive sediment loads, and no vegetation, tailings fans are in some respects a far cry from typical low-gradient coastal deltas. But tailings fans offer a number of advantages for testing delta-growth models: They are generally created under well-known, controlled conditions, with minimal time variation and extensive monitoring, into a fully enclosed basin where all the sediment is trapped. The latter is especially valuable in that it allows determination of precise sediment budgets, something difficult to do in most field settings. Hence, mine-tailings deltas are an ideal intermediate case between laboratory experimental deltas and full-fledged field cases.

2.4. Deltaic Channel Networks

The next level of detail beyond spatially averaged surface topography and shoreline location takes us to the channel network and the spatial, ecogeomorphic organization of the delta top. The channel network forms the arterial system for the delta top and is thus critical to predicting the detailed evolution of the delta surface and its ecosystems. One major process influencing the structure of the channel network is channel splitting around mouth bars deposited at the channel mouths (Edmonds & Slingerland 2007). To the extent that this process dominates, it opens the way to first-order prediction of the network structure: With each successive bifurcation, the average

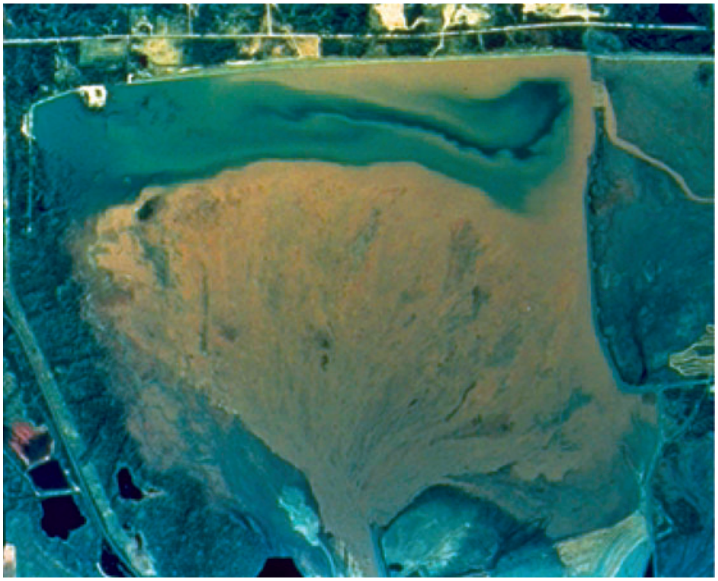

Figure 6

Aerial photograph of a fan delta in a mine-tailings basin in northern Minnesota. Such deltas are a useful source of data for calibrating predictive models for delta restoration.

channel width and depth decrease according to hydraulic geometry scaling, and the distance between bifurcations decreases nonlinearly with the decreasing momentum flux (Edmonds & Slingerland 2007). Based on the Edmonds & Slingerland (2007) mouth-bar model, delta networks should have fractal, self-similar planform geometries. Initial evidence for fractal character of river-dominated delta channel networks is presented by Seybold et al. (2007, 2009) and Wolinsky et al. (2010). On the other hand, analysis of a related coastal landscape feature, tidal channel networks, indicates that these networks are not fractal (Fagherazzi et al. 1999; Rinaldo et al. 1999a,b). It is clear that the overall form of deltas, which is related to the structure of the channel network, varies strongly under the influence of primary external forcing such as waves, tides, and supply grain size (Galloway 1975, Syvitski 2006, Edmonds & Slingerland 2010, Geleynse et al. 2010). These effects certainly reduce the possibilities for generalized geometric properties of delta channel networks. Yet the utility of fractal similarity of drainage basins in predicting network-based hydrological and other properties (e.g., Rodriguez-Iturbe & Rinaldo 1997) suggests that it is worth searching for and exploiting whatever similarity exists in deltaic networks.

2.5. Channel-Resolving Delta Models

One approach to creating models capable of resolving the channel network is through so-called reduced complexity models. Here, the goal is not to represent all the processes in detail but to abstract them so as to get the maximum return in emergent system-scale behavior for the minimum investment in computational complexity. The reduced-complexity approach for deltas is illustrated by recent articles by Seybold et al. (2007, 2009) in which the channel network is represented by links (bonds) between cells on a fixed grid. Water flow is governed by rules that conserve mass but simplify the momentum balance for free-surface flow. The sediment surface organizes itself and evolves via another set of rules that again conserve mass but greatly simplify the details of sediment transport. Reduced-complexity models can produce plausible delta forms (e.g., shoreline geometry) and channel networks; they also have the advantage that external influences such as wave transport can be added relatively easily (Seybold et al. 2007).

A second approach is to include as much of the detailed flow and sediment mechanics as is numerically feasible. Recent work by Edmonds & Slingerland (2010) and Geleynse et al. (2010) exemplifies this. The models use the Delft3D modeling system, which solves the quasi-three-dimensional shallow-water equations numerically and couples them to transport of sand and mud. Edmonds & Slingerland's (2010) work shows that a two-dimensional, depth-averaged approach is sufficient to produce many of the natural features of deltas, including complete topography and bathymetry (**Figure 7**). The deltaic simulations also evolve in a realistic manner as channels bifurcate around mouth bars and avulse (**Figure 7*a***). An advantage of such an approach is that the

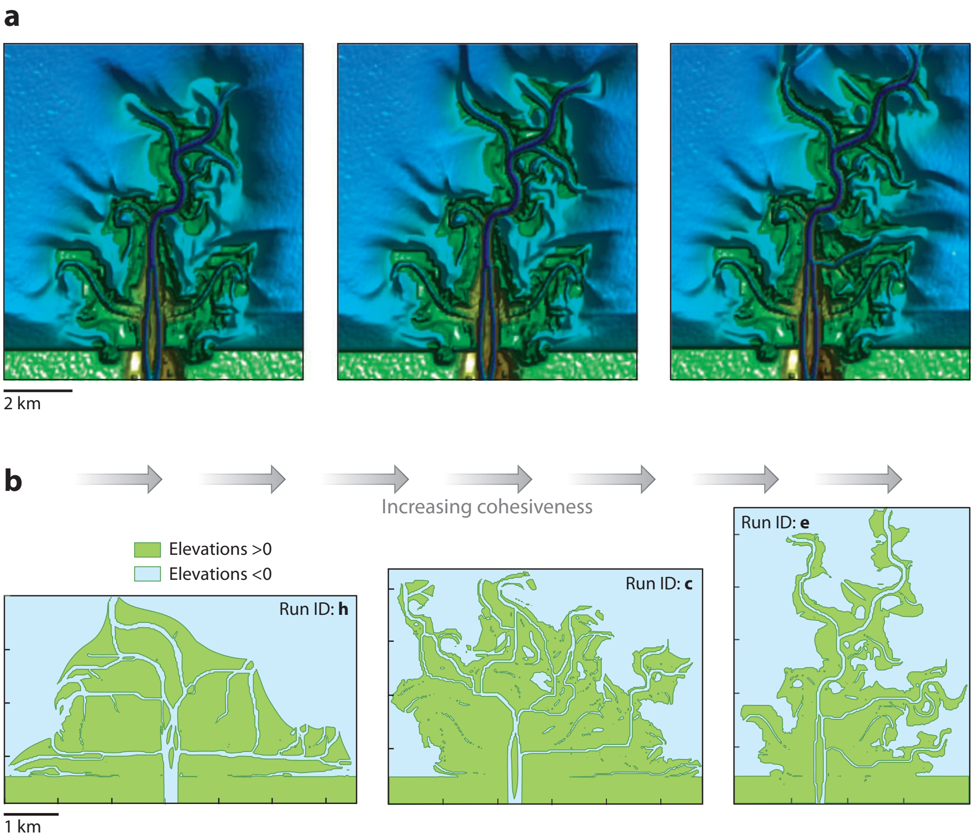

Figure 7

Examples of deltas created using the Delft3D numerical-modeling software. (*a*) Shaded topography maps showing evolution (time increasing left to right) of delta with Run ID "e" from Edmonds & Slingerland (2010). Time frames are ~2 months apart. Note that river mouth bars cause bifurcations and that in frame 3 an avulsion channel forms in mid-delta with flow oriented east. Warm and cool colors indicate high and low elevations, respectively. (*b*) Increasing just the cohesiveness of the sediment changes delta shape from fan-like with a smooth shoreline to bird-foot-like with a rugose shoreline. Cohesiveness was increased by increasing the critical shear stress for erosion of the cohesive sediment fraction. Run ID refers to the model run in Edmonds & Slingerland (2010), where further details can be found.

dynamics of the delta are fully emergent; that is, they are an outcome of the basic equations for fluid flow and sediment transport. This makes such simulation models a useful means of assessing the effects of other variables. Edmonds & Slingerland (2010) showed that cohesion, and by implication vegetation, is a fundamental determinant of delta form (**Figure 7*b***).

Initial studies of the evolution of deltaic channel networks suggest both consistent growth patterns (Edmonds & Slingerland 2008, Wolinsky et al. 2010) and the possibility of significant changes in geometry and dynamics as the network evolves. The most important change would be the onset of conditions for channel avulsion (Jerolmack & Swenson 2007, Edmonds et al. 2009, Reitz et al. 2010). Although such transitions would likely not occur for at least several decades at field scales, they are nonetheless an important research topic for delta restoration.

A major obstacle for detailed delta modeling is the lack of measures by which the results can be compared quantitatively with observations from the field or laboratory. Seybold et al. (2007, 2009) and Wolinsky et al. (2010) use fractal dimension as one measure, but fractal dimension is not a particularly discriminating metric. One of the major research needs in delta modeling is development of a suite of measures that can be used to compare deltas across scales and environments with one another and with theoretical models.

2.6. Ecological Processes

The goal of delta restoration is not simply to build land but to regenerate healthy deltaic wetlands and their ecosystem services (Twilley 2007). Ecological processes are central to the enterprise, and there is no geomorphic environment in which physical, biological, and biogeochemical processes are more closely coupled in creating the landscape.

In most landscapes, elevation plays a central role in determining vegetation type. Thus, it is not surprising that in low-gradient deltas, where the entire range of surface elevations may be of the order of 1 m, vegetation patterns are sensitive to extremely small changes in absolute elevation. The sensitivity is not to elevation itself but to local conditions that it controls, primarily salinity and hydroperiod (a general term to encompass the duration and frequency of wetting). The combination of low gradients and susceptibility to changes in wetting and salinity lead to relatively high rates of ecological change and dynamism in delta-top environments (Gosselink et al. 1998).

Consistent changes in the elevation and inundation characteristics of growing lobes together with natural succession dynamics lead to a sequence of vegetation changes in a growing lobe that appears to be predictable based on observed successions in active lobes (Johnson et al. 1985, Shaffer et al. 1992) (**Figure 8**) and crevasse splays (White 1993). As a delta lobe grows, biotic processes become relatively more influential. The main trends within the biotic system are (Gosselink et al. 1998, Shaffer et al. 1992): (*a*) general increase in total plant cover with time, (*b*) increase in species richness with elevation, and (*c*) increasing development of salt marshes as the delta grows and the amount of freshwater per unit area decreases relative to saltwater intrusion. Species stability with respect to changes in elevation, inundation, and grazing varies. For example, willow develops early on the relatively high (levee) sections of growing delta islands and then remains in place as elevation changes, whereas freshwater pioneer species like broad-leaved arrowhead, which are more susceptible to herbivory, undergo dramatic reduction in total cover area as islands age.

The interplay of elevation and inundation that controls deltaic vegetation can be modeled and predicted. For example, the spatial distribution of elevation and the temporal distribution of river discharge can be combined to predict the average distribution of freshwater vegetation (Visser et al. 1998) over the delta top. A similar approach could be used for the salinity-related effects of

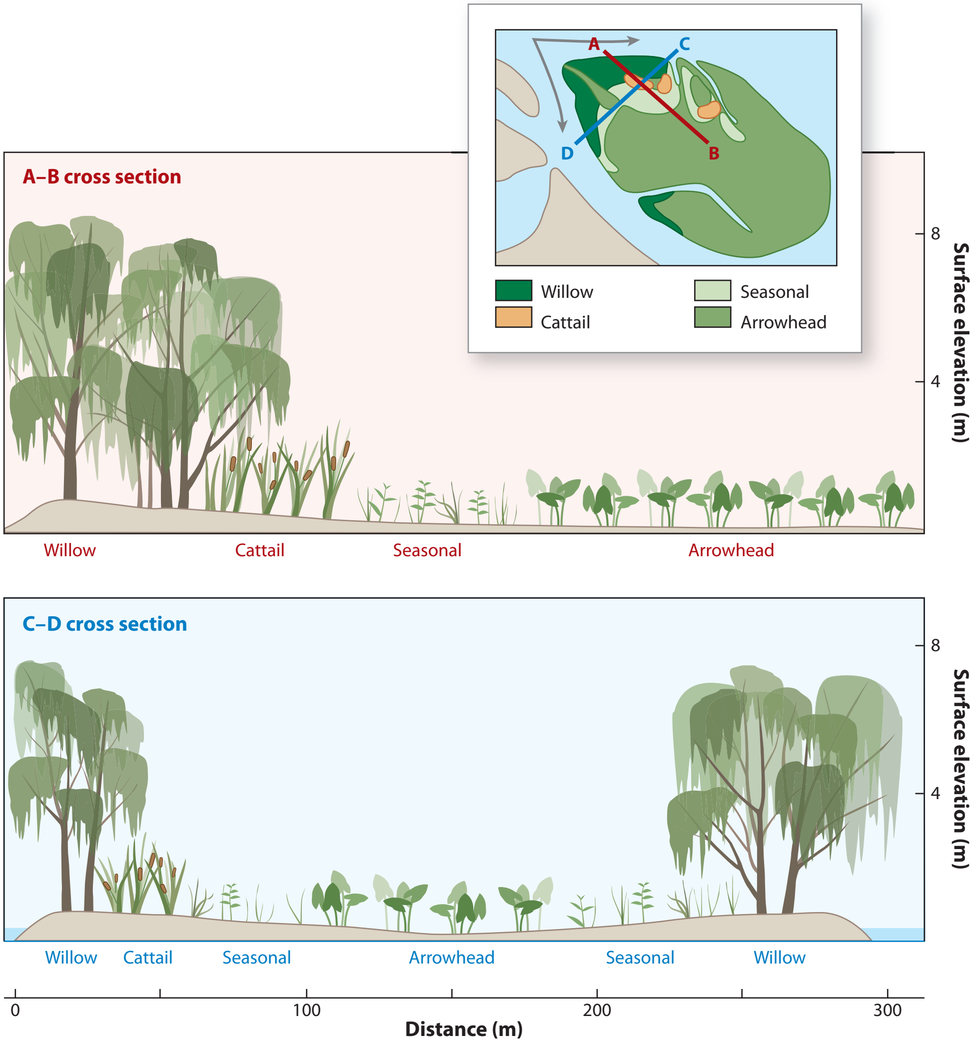

Figure 8

Control of delta vegetation by bed elevation in longitudinal (*upper panel*) and transverse (*lower panel*) directions on a growing mouth-bar island, Atchafalaya River Delta (Johnson et al. 1985). Willow: *Salix*; Cattails: *Typha*; Arrowhead: *Sagittaria*.

saltwater flooding, which strongly influence vegetation types in coastal Louisiana (Holm & Sasser 2001; Visser et al. 1998, 2002).

An important natural feature of marsh vegetation in coastal Louisiana is the spontaneous creation of floating marsh (Gosselink et al. 1998, Sasser et al. 2007). These are rafts of marsh plants that, due to combined effects of organic accumulation and subsidence over time, detach from the sinking mineral substrate and float. Floating marshes appear to account for most of the freshwater marsh in the fully developed Mississippi River Delta system (Gosselink et al. 1998). In general, floating marshes form in freshwater areas where subsidence outpaces sedimentation, and so would not be expected to form naturally on growing, restored delta lobes. But increased flow of freshwater onto deltaic wetlands would enhance stability of nearby floating marshes by reducing overall salt stress (Sasser et al. 2007).

Finally, herbivory (grazing) can play a major role in controlling deltaic vegetation. In the Mississippi River Delta system, rodents (muskrats, nutria) and waterfowl (ducks, geese) substantially reduce vegetation levels, especially during winter months. Herbivory seems to affect mainly freshwater plants, reducing both species richness and total biomass, and thus acts as an important control on early stages of primary succession (Evers et al. 1998). This should tip the sediment mass balance from deposition toward erosion, but the extent to which this actually occurs has not been measured.

Not all parts of the delta surface are created equal in terms of biological productivity, especially of fish and other species that breed in the marshes. The key here seems to lie in edge effects, a concept whereby habitat boundaries are disproportionately productive (Gosselink et al. 1998, Mitsch & Gosselink 2003, Haas et al. 2004, Roth et al. 2008). In salt marshes, total primary productivity is highest along channel margins. Across the delta, productivity is strongly influenced by the availability of shallow channel–bank zones that offer protection from predators (Haas et al. 2004). The edge effect provides another strong link between ecosystem development and geomorphology. The total channel edge length in a delta is a fundamental geometric property of the channel network and is especially sensitive to the fractal properties of the network. Development of theoretical tools for predicting these geometric properties as deltas grow is an essential step in predictive delta ecogeomorphology (Twilley et al. 2008).

The physical form of deltas clearly influences wetland ecology, but there is an equally strong feedback of wetland structure on geomorphic processes. Plants influence flow and turbulence fields in marshes generally (Nepf 2004, Lightbody & Nepf 2006), which in turn influences sediment transport and deposition. Studies on the effects of vegetation on sediment transport are ramping up rapidly (Yager & Schmeeckle 2007, Larsen et al. 2009b). Field evidence from WLD shows that clumps of freshwater grasses such as *Justicia* sp. are associated with enhanced sedimentation, suggesting that the plants are able to trap fine sediment (G. Holm and R. R. Twilley, unpublished data). Sediment trapping by plants could be important to the retention rate of fine sediments in deltaic wetlands—the right plants could act as natural versions of the engineered sediment-retention structures used to enhance coastal sedimentation—so developing the necessary quantitative tools to predict this should be a high priority for current research.

2.7. Biogeochemical Processes

Over the last four decades, the chemistry of the Mississippi River has changed dramatically; the Louisiana coastal region is now at the receiving end of a large input of anthropogenically derived nutrients from upstream agricultural activities (Rabalais et al. 2002). As increasing nutrient loads are delivered to coastal waters, there is a risk of exacerbating eutrophic conditions through seasonal algal blooms, excess organic matter production, low oxygen concentration in water and sediments, and long-term nitrogen and phosphorus accumulation (Brown et al. 2006). There is also concern that the influx of high concentrations of inorganic nutrients, particularly nitrate, will create health risks as a result of toxic algal blooms. As more freshwater diversion projects are planned along major waterways throughout Louisiana, it becomes imperative to gain a better understanding of the effects they will have on wetland and estuarine water quality.

Deltaic wetlands are among the world's great natural biogeochemical reactors, and nutrient processing is a major dimension of wetland restoration (Twilley & Rivera-Monroy 2009). For instance, upstream effects influence the feasibility of restoration through reduction in sediment supply, but they exercise equally important effects via the supply of nitrate and other nutrients in river water. Delta restoration can help mitigate this by providing new wetland area in which denitrification can occur, reducing nitrate loads to the Gulf of Mexico (Mitsch et al. 2001, 2005; Day et al. 2003). Recent measurements in WLD have quantified the efficiency of the newly created wetlands where there is denitrification (Lane et al. 1999, 2003; DeLaune et al. 2005; Twilley & Rivera-Monroy 2009). Despite this evidence that river nitrate is transformed and stays within coastal ecosystems, the overall effectiveness of denitrification in removing nitrate from the system is still unclear. Despite extensive denitrification research in Louisiana (Rivera-Monroy et al. 2010) the application of this research to management decisions is limited due to unclear and often contradictory conclusions as to the mechanisms specifically associated with nitrate loss. These inconsistencies are the result of three main factors: (*a*) the use of a wide variety of methodologies to estimate denitrification rates and nutrient fluxes, (*b*) spatial and temporal variation in environmental factors that control removal processes (e.g., sediment organic matter content, temperature, hydroperiod, and vegetation community), and (*c*) the extrapolation from small-scale denitrification estimates up to the landscape level (Groffman et al. 2006).

Another important biogeochemical issue in delta restoration is carbon processing, and here again, ecology and geomorphology are closely linked. As noted in Section 2.2, buried organic carbon in the form of peat can form a significant fraction of the sediment column. Research conducted in the Mississippi River deltaic plain indicates that organic matter accumulation has been the main determinant in the vertical growth rate of marshes (DeLaune et al. 1978, 1994; Hatton et al. 1983). Although there is less soil organic matter in these marshes relative to mineral matter on a weight basis, the soil organic matter (SOM) occupies considerably greater volume and hence can be more important for accretion of emergent wetlands than soil mineral matter (Nyman et al. 1990). Organic matter contributes to the soil matrix and increases structural strength by forming an interlocking network of roots. Soil mineral matter may be from 50 to 90% of the dry weight of marsh soils, but mineral matter occupies only 2 to 7% of soil volume in Mississippi River deltaic plain marshes (Nyman et al. 1990). Stability of the SOM and the addition of mineral sediments have been recognized as key factors controlling vertical marsh accretion, and hence, C sequestration (Nyman & DeLaune 1999).

2.8. Natural and Human-Induced Subsidence

One could easily think of natural processes in delta restoration just in terms of processes of delta building. But subsidence of the deltaic platform is as much a part of the life and death of natural and restored deltas as lobe growth and ecosystem succession. Once again we begin by turning to the stratigraphic record for information. Even at the level of a simple mass-balance like Equation 1, it is clear that subsidence rate is a first-order control on the feasibility delta restoration. For example, in a recent paper, Blum & Roberts (2009) conclude that most of the Mississippi River Delta will continue to lose land due to a combination of subsidence and eustatic rise associated with global warming. Based on this, they recommend that any large-scale delta restoration projects be sited well upstream of where most current plans would put them, and too far upstream to be of much help in protecting New Orleans from coastal storms. This recommendation is based on projected rates of eustatic rise (Cazenave & Llovel 2010) and on estimated subsidence rates. The latter are especially controversial; short-term rates (Dokka et al. 2006) are an order of magnitude higher than long-term values estimated geologically (Straub et al. 2009). Recent work by Morton & Bernier (2010) indicates that subsidence rates used by Blum & Roberts (2009) for southernmost Louisiana are twice as high as rates measured during the past 19 years. Morton & Bernier (2010) demonstrate that this change in rates is connected to a spike in withdrawal of subsurface fluids between 1960 and 1980. Reducing the projected rates by a factor of 2 changes the outlook for coastal Louisiana considerably. For example, Blum & Roberts (2009) estimate a land loss of $\sim$12,000 km^2 in 100 years, but reducing the subsidence rate to values in the range suggested by Morton & Bernier (2010) reduces this to a range of 3,000–6,000 km^2, which begins to overlap the range of potentially restorable area estimated by Kim et al. (2009b).

Natural processes of subsidence include compaction of the sediment column (Törnqvist et al. 2006, 2008) and deep and shallow tectonic processes. These may be increased by human effects, such as pumping of water and hydrocarbons from the subsurface, which reduces fluid pressures that help support the sediment column (Morton et al. 2005). Some large deltas, such as the Ganges-Brahmaputra, are in tectonically active areas, where crustal-scale subsidence is an important component of overall subsidence rates. In the Mississippi River Delta, crustal subsidence rates are low, but the delta hosts a number of sediment-hosted listric normal faults (growth faults) along which subsidence can be locally rapid. Growth faulting is common in large deltas, so this component of subsidence is likely to be important in other restoration settings as well. At the very least, mapping of growth faults and measurement of recent slip rates is essential to restoration planning—it would be a major blunder to divert sediment onto the downthrown side of an active growth fault—and it would be better still if we could develop a predictive understanding of the mechanics of these relatively poorly understood faults. Fortunately, the locations of many growth faults in the Mississippi Delta are historically well known and can be avoided (Gagliano et al. 2003); in addition, industry seismic data, commonly available for major river deltas of the world, can be used to identify any faults at sites of proposed diversions (George 2008).

2.9. Sediment Transport in Main River Channels

Sediment delivery from upstream is another natural process that is critical to delta restoration, although in many cases it is also among the most highly altered by human influences such as dam construction. Measurements from recent deposits of Wax Lake Delta show that 50–70% of the land-building deposits are composed of sand (Roberts et al. 2003), even though sediment of this size range constitutes less than 10% of the lower Mississippi River load (Nittrouer et al. 2008). This implies that river diversion structures for restoration should optimize the transfer of sand onto the wetland. In transport, sand is not evenly distributed throughout the water column of a river but, rather, high concentrations are skewed toward the river bottom. For example, in the lower Mississippi River during flood, roughly one-third of the total sand discharge is moving within the lowermost 10% of the flow (Nittrouer et al. 2008). Designing diversion structures to tap into sand-laden near-bed flow will clearly benefit land growth.

2.10. Experimental Deltas

Whether or not they are fractal, it is clear that many of the main processes that create the physical form of deltas reproduce themselves over a wide range of scales (Paola et al. 2009). This opens the way to using laboratory-scale experiments to complement field studies, with all the advantages of experimental study: rapid evolution that allows real-time study of processes of long-term evolution and multiple realizations of stochastic variability, and the chance to collect detailed, consistent data sets under fully controlled conditions. Because many of the deltas of interest in restoration, including the Mississippi, are fine-grained, methods for introducing cohesive effects at laboratory scales are especially important. A major advance in this regard is the development of a weakly cohesive sediment mix by the research group at ExxonMobil Upstream Research (Hoyal & Sheets 2009). The mix avoids previous difficulties with adding cohesive sediment to laboratory experiments and produces deltas that are both strikingly consistent with the form of field-scale

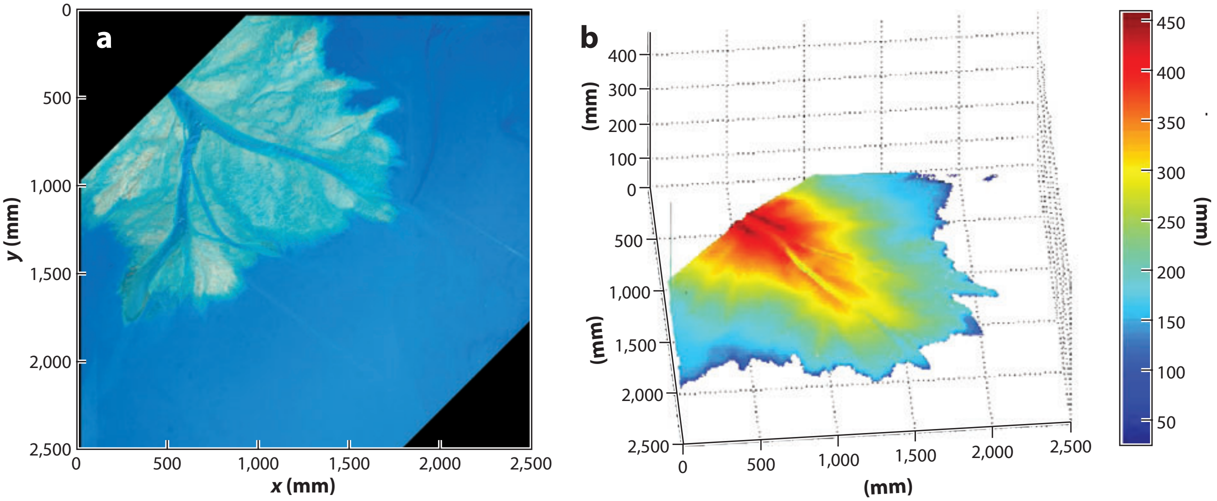

Figure 9

(*a*) Overhead image and (*b*) measured surface topography (all units, including the vertical color-bar scale, in millimeters) from an experimental delta created under steady forcing conditions at St. Anthony Falls Laboratory, University of Minnesota, using the weakly cohesive sediment mix described in Hoyal & Sheets (2009) and Martin et al. (2009).

cohesive deltas (**Figure 9**) and contrast strongly with the braided, sandy deltas that are typically produced at laboratory scales.

Overall sediment budgets, channel patterns, and planform morphology for experimental deltas are similar to those observed in the field (e.g., Hoyal & Sheets 2009). In addition, as discussed in Section 2.2, experimental deltas vividly demonstrate the capacity of low-gradient, apparently vulnerable, delta-top channel systems to maintain themselves in the face of relative sea-level rise as long as they are supplied with sediment to deposit. Experimental deltas also allow study of temporal evolution under controlled conditions. The elevation and surface morphology of growing deltas evolve in a predictable and self-consistent way, indicating that it should be possible to predict these properties, and the ecosystem properties that depend on them, in the context of delta restoration. Although the delta surface in experiments is generally steeper than most field cases, and the channel flow is generally near critical rather than strongly subcritical, the channel network appears to develop and ramify in the same fashion as in the few field examples where this has been observed. This opens the way to using laboratory experiments to quantify laws of delta growth under precisely controlled conditions (Wolinsky et al. 2010). Of course, these conditions can also be varied, for example, by adding subsidence and sea-level changes (e.g., Paola et al. 2001). Among other things, experimental studies with subsidence will allow testing of the limits over which a delta restoration can withstand relative sea-level rise without unacceptable retreat.

3. RESEARCH PROSPECTS IN DELTA RESTORATION

Making confident, detailed predictions of the geomorphology, ecology, and biogeochemistry of a growing restored delta lobe will require understanding the entire suite of natural processes that create and control deltas. Clearly, we are not to that point yet. But it is also clear that there is accelerating interest in delta dynamics, giving us good reason to be optimistic about the prospects for progress in the near future. A particular highlight is the advent of a new research organization for deltas, called Deltares, headquartered in The Netherlands. Deltares produced, for example, the software used for the delta simulation shown in **Figure 7**. With some 800 people, including earth scientists, engineers, ecologists, and social scientists, Deltares represents the largest single concentration of effort on delta science anywhere in the world. As such, it has the potential to do a great deal of good, both for delta restoration and for the worldwide delta research community. At this point, Deltares' relationship to the larger research community has yet to be worked out, but nascent collaborations with universities in Europe and elsewhere are an encouraging sign.

There is enormous scope for using the sensitivity of deltaic ecosystems to geomorphology to advance predictive wetland ecology. One promising starting point for ecologic prediction is to exploit the strong influence of elevation and hydroperiod, including fresh and saltwater, on vegetation, and the influence of channel edges on primary productivity and spawning.

Relatively little is known at present about the microbial ecology and dynamics of delta-top sediments, for any part of the salinity continuum. There is no reason to think deltaic microbial communities are any less complex than those of upland soils, and it is clear that microbes control the major bioreactor processes that govern the transport and fate of nitrate, phosphate, carbon, and other key geochemical constituents. The evolution of mineral deposits, during initial lobe formation, to soils that continue to develop through growth and decay of the vegetated surface influences biogeochemical processes. In addition, this vegetation has a feedback effect, increasing sediment retention and lobe development. The annual increment of organic matter storage in deltaic soils is a potential carbon and nitrogen sink in these dynamic, non-steady-state ecosystems. In addition, the role of disturbance from both physical storms and biological grazers is important for ecological patterns of deltaic landscapes. Each of these represents a potential major avenue for future research in delta microbiology.

Theoretical models are the means by which understanding of natural delta processes are converted to testable predictions. In most cases, these models will be implemented numerically. Thus one of the most positive recent developments in delta prediction is the creation of the Community Surface Dynamics Modeling System (CSDMS), an open-source, community effort to develop tools for Earth-surface prediction, headquartered at the University of Colorado in Boulder. Deltas are only one aspect of CSDMS, but having an organization devoted to organizing worldwide collaboration on Earth-surface prediction is of enormous benefit to delta prediction.

In several places throughout this review, we have used insight on long-term delta behavior obtained from study of the stratigraphic record. For deltas and other depositional systems, the stratigraphic record represents an archive of countless natural experiments over time scales ranging to millions of years. So far, the deltaic stratigraphic record has mainly been applied within the oil industry. Geomorphologists, engineers, and ecologists have focused on studying processes on modern deltas, but these groups and stratigraphers studying long-term sedimentary records are beginning to see their common interests. This is impelled both by the realization that questions such as the response of deltas to sea-level rise have already been answered many times over in the stratigraphic record and by the drive in the oil industry to develop quantitative delta models that rely on the same set of processes as delta restoration does. Better integration of stratigraphic and modern-process studies and the development of tools for quantitative reconstruction of system evolution from stratigraphic records are both fertile areas for delta research.

We have also mentioned laboratory experiments, which have now reached the stage where they can capture many of the main morphologic features of deltas at field scales. This capability, much of which has been developed in or for the oil industry, must be exploited to test theoretical models of delta evolution for restoration as well. Inclusion of the effects of waves and (if possible) tides is an important priority for experimental research.

In addition to the geomorphic and ecologic functions described in this review, deltaic landscapes with potentially forested wetlands provide a first line of defense in storm surge reduction. This is of obvious potential importance given the increased risks from sea level rise to coastal communities. Thus a major research imperative for delta restoration is to develop precision techniques for storm-surge prediction under various restoration scenarios, taking account of the natural structure of the restored wetlands and forests.

Perhaps the single most effective step that could be taken to advance understanding of natural processes of delta growth that are essential for restoration would be to establish a network of field observatories in active deltas worldwide. There is good precedent for this, starting with the very successful program of ecological observatories in the United States known as the Long Term Ecological Research (LTER) network. LTER comprises sites on which ecological structure and dynamics are monitored over decadal periods. This model has been extended to soils and landscapes via the U.S. National Science Foundation's Critical Zone Observatories (CZO) program; it could be readily ported to active delta sites such as WLD but with a broader focus including ecology, geomorphology, engineering, and stratigraphy. The technology of environmental sensor networks, combined with rapid repeat surveying using semiautonomous vehicles, is now sufficiently advanced to create what might be termed a "self-aware" delta, capable of sensing environmental events such as river floods and hurricanes and triggering its network of autonomous instruments to respond and measure accordingly. The data from such delta observatories would accelerate development of predictive ecogeomorphic models that integrate understanding of natural processes to provide the basis for delta restoration.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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Errata

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