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When is restoration not? Incorporating landscape-scale processes to restore self-sustaining ecosystems in coastal wetland restoration

Charles Simenstad [a,*], Denise Reed [b], Mark Ford [c]

[a] *School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195-5020, USA*
[b] *Department of Geology and Geophysics, University of New Orleans, New Orleans, LA 70148, USA*
[c] *Coalition to Restore Coastal Louisiana, 746 Main Street #B101, Baton Rouge, LA 70802, USA*

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Abstract

With increasing restoration initiatives for coastal wetlands, the question of 'What are we restoring to?' becomes more pressing. The goal of this paper is to explore restoration concepts, examples, and challenges from the Pacific and Gulf coasts. One of the fundamental concepts explored is change over time – either in the controlling processes or the restoration structure – and how such changes can be meshed with the goals of various restoration efforts. We subsequently review the concepts of ecosystem trajectories, alternative restoration approaches, and the ideal attributes of functional self-sustaining restoration in the context of realities of restoration planning, design, and implementation. These realities include the dynamics of the ecosystems being restored, very real constraints that are imposed by the contemporary physical and human landscape, and the need to plan for the long term development of restoration sites recognizing that both project performance and expectations may change over time.

Keywords: Restoration; Landscape-scale process; Coastal wetland; Self-sustaining ecosystem

1. Introduction

Coastal wetland restoration is rapidly approaching a scale of planning, design, and implementation that has surpassed its origins in individual mitigation and restoration actions. Large, complex, landscape-scale programs occurring in the Everglades, San Francisco Bay, and coastal Louisiana require additional scientific understanding of entirely different spatial and temporal perspectives. While it is argued that even the performance of individual regulatory wetland mitigation actions suffer from a lack of consideration of watershed setting and landscape function (NRC, 2001),

* Corresponding author.
E-mail address: simenstd@u.washington.edu (C. Simenstad).

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restoration designed to address increasing degradation of entire coastal zones will likely not approach or meet their goals without promoting self-sustaining landscapes and incorporating large-scale disturbance dynamics.

At the beginning of the 21st century, considerable environmental science is focused on fixing the problems wrought by generations of environmental exploitation combined with either ignorance of or disregard for the consequences. Current Federal initiatives call for the restoration of tens of thousands of kilometers of stream corridor and hundreds of thousands of hectares of wetlands (EPA, 2000). The cumulative effects of mining waste, dams, land use change, and urbanization have left few watersheds intact and river restoration is in such demand that curricula and professional training courses are now commonplace. In the lower reaches of rivers, in estuaries, and at the coast, fundamental changes in riverine inputs combined with local landscape alterations mean that few traces of historical ecosystem function remain. This is most commonly the case in terms of natural disturbance effects—management of river flows and 'protective' measures for local communities have removed regular hydrologic pulsing as a normative agent of ecosystem change and only the largest and most catastrophic events, for the most part uncontrollable, remain.

With increasing restoration initiatives, the question of 'What are we restoring to?' becomes more pressing. For society exposed to the rationale, whether scientific or economic, that more natural ecosystems provide critical goods and services (Daily et al., 1997), the answer is usually easy. People desire that which they used to have that is now gone, or, if the degradation occurred prior to the current generation's experience, that which is more 'natural'. Society also wishes that 'restoration' be made permanent—that ecosystem degradation be reversed and conditions in the future be improved over their current state. For science, such goals raise important questions about not only how we might achieve desirable recovery of natural ecosystems, but also whether they can be sustainable. In terms of disturbance regimes, the societal context for restoration makes things even more challenging. The value of a dynamic range of ecosystem processes, including interannual variations and occasional extreme events, may be well established from a scientific perspective. But floods, fires, droughts, and storms disrupt everyday life of local communities and frequently lead to calls to return again to more 'management' or 'prevention' measures.

As restoration plans proceed for almost all large rivers and estuaries around the U.S., the disconnect between societal goals and ecosystem functions is perhaps most obviously shown in the lack of a clear understanding of the term "restoration". NRC (1992) defined the term to mean returning an ecosystem to "a close approximation of its condition prior to disturbance" which requires "reestablishment of predisturbance aquatic functions and related physical, chemical and biological characteristics." Thus, the NRC recognized both ecosystem structure and function must be addressed in conjunction with the natural ecosystem dynamics of processes: "the term restoration should be applied only to those activities directed to rebuilding an entire ecosystem." Among restoration practitioners, the importance of the 'indigenous, historic ecosystem' as a template for restoration was noted by the Society for Ecological Restoration (Aronson et al., 1993) and clearly distinguished from rehabilitation. Middleton (1999) summarizes an evolving view of restoration as seeking to establish 'a site that is self-regulating and integrated within its landscape, rather than to reestablish an aboriginal condition that can be impossible to define and/or restore within the context of current land use or global climate change'.

The goal of this paper is to explore restoration concepts, examples, and challenges from the Pacific and Gulf coasts. One of the fundamental concepts explored is change over time – either in the controlling processes or the restoration structure – and how such changes can be meshed with the goals of various restoration efforts. We subsequently review the concepts of ecosystem trajectories, alternative restoration approaches, and the ideal attributes of functional self-sustaining restoration in the context of realities of restoration planning, design, and implementation. Although our focus is on coastal wetlands, many of the principles explored are equally applicable to other seriously threatened ecosystems.

We herein argue that, to be ecologically functional and self-sustaining, restoration requires understanding and reinstating fundamental ecosystem processes from site to landscape scales. Our emphasis is on: (1) realistic goal setting; (2) ecological functions; (3) the emerging paradigms of a relatively young science; (4) the need to recognize high uncertainty in restoration technologies and responses; (5) the rationale behind taking a precautionary, adaptive approach.

2. Trajectories of change

A fundamental premise of restoration ecology is that release or diminution of stressors will reinitialize physical, geochemical, ecological, and other ecosystem processes in a direction toward a more natural, unstressed state. This progression of ecosystem recovery over time has been characterized as a pathway or trajectory of ecosystem redevelopment toward a less compromised state, or even the attainment of a fully functioning system comparable to "target" reference sites. In graphical form, these trajectories have been referred to as "performance curves" (Kentula et al., 1992), "restoration trajectories" (Hobbs and Norton, 1996) or "functional equivalency trajectories" (Simenstad and Thom, 1996). The validity of such trajectories, or at least the reality and predictability of the time required to reach equivalency, has often been called into question (Zedler and Callaway, 1999). Despite notable cases where wetland mitigation or creation sites have not followed particularly rapid or definable trajectories, there are well-documented cases where restoration of natural processes has resulted in obvious trajectories and often over relatively rapid time periods (Morgan and Short, 2002; Tanner et al., 2002; Thom et al., 2002; Warren et al., 2002). Such wide variation in response patterns and rates is hardly surprising given the variability of approaches to "restoration," the types and levels of stressors, antecedent conditions, and changes in the landscape setting.

Aronson and Le Floc'h (1996a,b) describe three alternative ecosystem phases of ecosystem recovery (Fig. 1) that differ in their ability to actually reverse the processes that led to degradation: (1) *restoration*, which requires reactivating hydrological and other ecosystem processes and allowing reintroduction of indigenous species to the point that "thresholds of irreversibility" are circumvented; (2) *rehabilitation*, where one group of species or ecosystem service is favored by modified management over the short term; (3) *reallocation*, where entirely new trajectories promote new ecosystems and uses over the long term. As opposed to the previous definition for restoration, rehabilitation (as well as *enhancement*) is confined to the isolated manipulation of individual ecosystem elements to a less degraded state, rather than full restoration of the structural and functional attributes and processes of the predisturbance state (NRC, 1992; Middleton, 1999). It might be argued that many rehabilitation activities are knowingly conducted under the guise of restoration, but perhaps many more activities result unavoidably and unexpectedly in reallocation even when the explicit objective is restoration. At the risk of corroborating more jargon in the restoration literature, the Aronson and Le Floc'h (1996a,b) concept of reallocation is a useful concept because both intentional *creation* and unintentional shifts in ecosystem state are typically the consequence of deviating from restoring the full complement of natural ecosystem processes.

Some constraints to achieving restoration in the strict sense of the term also result from pervasive changes to the ecosystem processes that promoted the pre-existing condition that even vastly improved resource management cannot resolve. Often, the resulting steady state ecosystem is in the short term comparable to or undetectable from the pre-existing ecosystem. However, the lack of fully vetted ecosystem processes may be ultimately expressed in widening differences between the restoring and pre-existing states, or even the eventual shift to rehabilitation or reallocation.

While the desirable functions may result from the structure of ecosystems, it is typically the dynamics of ecosystem processes that sustain that structure at the landscape scale or in some cases may even be the underlying mechanism behind the function. Thus, sustainable restoration is contingent on recovering both ecosystem structure and processes: "*Restoration means returning an ecosystem to a close approximation of its condition prior to disturbance. Accomplishing restoration means ensuring that ecosystem structure and function are recreated or repaired, and that natural dynamic ecosystem processes are operating effectively again*." (NRC, 1992). However, the crux of achieving sustainable restoration still hinges on expectations of a predictable endpoint, and the recognition that 'desirable' trajectories are often based on uncertain and unpredictable responses of ecological communities.

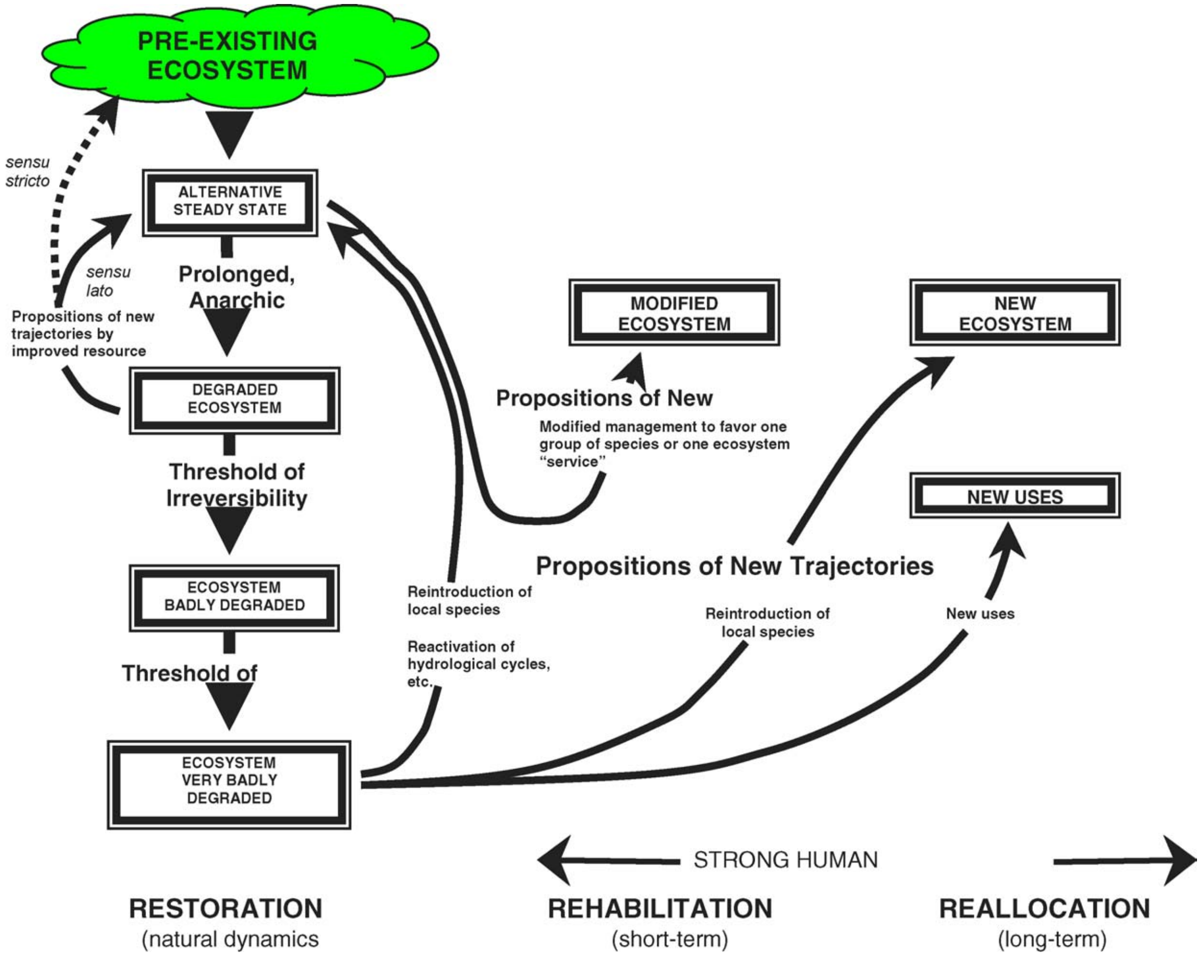

Fig. 1. Alternative ecosystem trajectories over three phases, illustrating the notions of restoration, reallocation and rejuvenation as well as that of "thresholds of irreversibility" (Aronson and Le Floc'h, 1996a).

3. Approaches to ecosystem recovery

There are three basic approaches to ecosystem recovery that purposefully address ecosystem structure but which encompass the reintegration of dynamic processes to varying degrees: *passive*, *active*, and *creation*. The alternative pathways of ecosystem recovery often vary as a function of these approaches, as well as the restoration, rehabilitation or reallocation end-points (Fig. 2; Kauffman et al., 1995; Middleton, 1999).

In passive approaches, the accidental or incidental removal of barriers to degraded ecosystem processes lead to their reinstatement either in whole or to a large part. No further actions are, or need to be, taken to

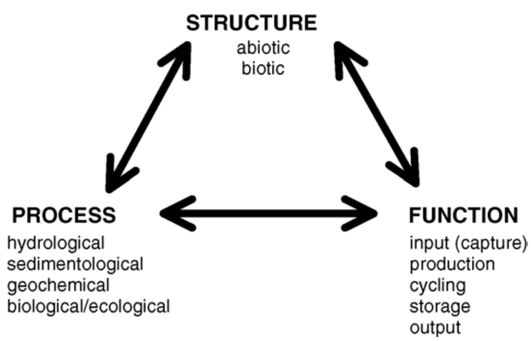

Fig. 2. Interactions among wetland structure and function with ecosystem processes.

facilitate restorative ecosystem change. In most cases of passive restoration, the re-establishment of natural hydrological cycles increases disturbance to the site, promoting natural dynamic, rather than static, ecosystem processes. For example, many studies evaluating ecosystem responses to removal or gapping of levees surrounding a former wetland often describe how flooding events or natural pulses influence both the near-term development of the site (e.g., sedimentation rate) and its response to long-term factors such as sea level rise (Simenstad and Warren, 2002; Orr et al., 2003). Cessation of practices that lead to the degradation of wetlands, such as cattle grazing, will also assist in passive restoration of an ecosystem by removing a detrimental disturbance (Esselink et al., 2000; Bos et al., 2002).

Active approaches to restoration are accomplished through more “engineered” actions that intentionally and specifically re-create wetland structure and processes. This occurs in areas where these processes once existed or where they still exist, but in a much degraded form. This may involve removal of process barriers (passive restoration if conducted in isolation) and active management or enhancement of processes beyond those which passively reoccur. For example, reestablishing tidal hydrology to a drained and leveled estuarine wetland might be combined with digging pilot channels to encourage tidal channel development and vegetative plantings to promote growth of native marsh vegetation and prevent colonization by invasive species. In most cases such restoration seeks to achieve specific goals and an ‘adaptive management’ approach is sometimes employed to guide the continual modification of the system to achieve the goals in a purposefully modified ecosystem.

Creation is the establishment of wetlands where none previously existed. In this case the concept and design may be based on wetlands elsewhere in the system. The process regime dominating these wetlands, such as hydrology, will depend on local conditions but most such restoration efforts focus on attempts to create structure rather than natural process or function (NRC, 2001).

However, our point is not to focus on technical semantics about approaches to ecosystem recovery, but to convey to restoration managers and the public the very real differences in expectations, sustainability and investment involved with each of these approaches. Ultimately, the long-term performance of a restored wetland as a functioning ecosystem, regardless of the approach, will depend on reintroducing some form of natural dynamics and disturbances into the wetland system (Middleton, 1999; Orr et al., 2003). Such restored wetlands, if they persist and become self-sustaining, are most likely to resemble natural wetlands in the region if hydrological and topographical variability, subsurface processes, and the hydrogeomorphic and ecological landscape and climate are considered (NRC, 2001).

Socioeconomic, public safety and other legitimate constraints often do not allow ecosystem restoration. Anthropogenic disruption of naturally dynamic ecological processes has often allowed, as designed, human infrastructure to occupy coastal wetlands; complete restoration would in turn threaten this more contemporary human “footprint” in marshes. In some cases, “partial restoration” (Fig. 3), essentially rehabilitation, has allowed muted recovery of some fundamental ecosystem processes. In many coastal areas, marsh rehabilitation has been promoted by manipulated reintroduction of tidal influences through various water control structures (e.g., slot gates, self-regulating tide gates, etc.). The rationale in acknowledging these constraints is that some recovery of natural ecosystem processes, albeit significantly truncated from natural dynamics, rehabilitates natural functions to some degree. This is certainly true in many cases but there are trade-offs and negative effects are common. At the minimum, some functions are enhanced while others may either be unaffected or even negatively affected. Water control structures in coastal Louisiana saline marshes do sustain vegetation but preclude much nekton exchange (Rozas and Minello, 1999) in what is typically a dynamically pulsed system (Rozas, 1995), and limit sedimentation and other geochemical processes (Reed et al., 1997, 1999; Kuhn et al., 1999). What is important in such “partial restoration” is to acknowledge that it is not restoration at all, but exceedingly targeted (and often legitimately so) rehabilitation that will seldom allow full ecosystem recovery and may even impact ecosystems outside the project area (Hood, 2004).

A fourth constraint on tidal wetland restoration is scale. Although as yet poorly quantified, the relationship between tidal ecosystem restoration and the attributed functions of a natural marsh is highly scale dependent. Many relationships are, in fact, non-linear and dictated by thresholds. A 0.1 km^2 marsh restoration

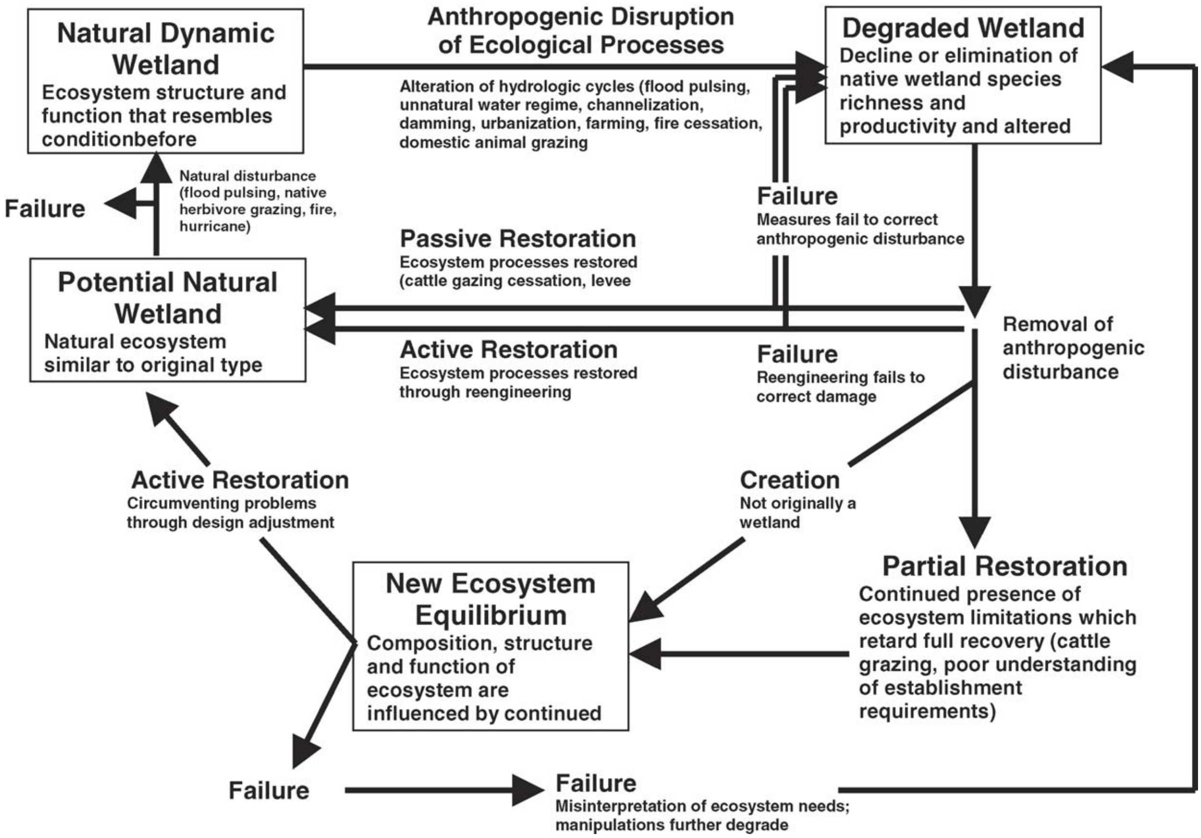

Fig. 3. Pathways of ecosystem recovery and the reintegration of disturbance processes (Kauffman et al., 1995; Middleton, 1999).

should not be expected to necessarily function as a 0.1 km^2 segment of a 10 km^2 natural marsh. This is illustrated most definitively in the tidal geometry relationships between marsh size and tidal channel metrics (Williams and Orr, 2002; Williams et al., 2002). Restoration expectation should acknowledge these constraints and be equally scale dependent.

4. Prerequisites of functional, self-sustaining systems—restoration realities

4.1. Restore processes, not structure

The ability of specific actions and approaches to achieve functional, self-sustaining restoration is contingent on the goals the project. Not every restoration project is necessarily dependent upon a “walk-away” assurance that the restoration will ultimately result in a naturally functioning system with little to no human intervention or management. Conversely, stakeholders and decision-makers do not always understand that some of the more engineered or uncertain restoration projects will require intensive, and potentially long-term, investment in public resources to maintain their expected level of performance. In Louisiana, where loss of coastal wetlands has exceeded 52 km^2 per year for decades (Barras et al., 2003) manipulation of marsh hydrology is still used as an arguable approach to restoration (LCWCRTF, 2003). Structural marsh management in coastal Louisiana is usually designed to impact both channel flow and marsh water levels. Hydrology is altered in order to achieve the stated goals of the management, which normally include restoration, conservation or enhancement of emergent marsh or specific vegetation types. Historically this was a relatively successful manipulation for the specific purpose of enhancing waterfowl habitat (Baldwin, 1967) but more recent plans seek to achieve restoration goals through the control of salinity and/or water levels using systems of control structures and levees (Cowan et al., 1988). These plans can be used to control marsh hydrology passively or actively. Several studies (Boumans and Day, 1994; Cahoon, 1994; Reed et al., 1997) indicate that this restoration approach severely impacts the natural flow of material, especially sediments, into the marshes during both tidal and extreme events. Even though this impairment of natural process regimes has been noted as a fundamental feature of such marsh management (EPA SAB, 1998) there are still proposals to employ such techniques in new restoration initiatives in San Francisco Bay (Harrison et al., 2001).

4.2. Recover natural ecosystem dynamics

Natural ecosystem dynamics are the source of many functions and services attributed to coastal wetlands and other hydrologically structured ecosystems (Middleton, 1999). However, recovering natural system dynamics must include the fluctuations and disturbances that in most cases account for the long-term structure and function of coastal wetlands. Some of these disturbances cannot be controlled or manipulated in initiating restoration, but must be considered nonetheless when designing restoration projects. For example, drought can have a serious negative effect on an ecosystem (e.g., Visser et al., 2002), while tropical storms and hurricanes can result in both negative and positive impacts (e.g., Dingler et al., 1995; Cahoon et al., 1995).

Alteration of the natural dynamics of fluvial flooding is one of the more important landscape processes that have led to degradation of many coastal ecosystem processes (Middleton, 1999). Seasonal, and particularly 'pulse', flooding is one of the more important ecosystem processes that has shaped the natural composition, variability and diversity of wetlands throughout coastal zones of the world. The consequences to wetland integrity of altering the historically dynamic hydrologic regime are amply evident for the Kissimmee River in the greater Everglades ecosystem (Kobel, 1995; Toth et al., 1998), coastal Louisiana (Boesch et al., 1994; Roberts, 1997; DeLaune et al., 2003) and the Columbia River estuary (Simenstad et al., 1992), to name just a few systems currently under intensive restoration activity or consideration.

Tropical storms and hurricanes can affect coastal wetlands in a variety of ways. Low intensity hurricanes and tropical storms can deliver excess rains, which will both flood a system, and also help flush saltwater from the system. This is especially true for restoration efforts using dedicated dredged materials, which often carry high salinities. Higher intensity hurricanes often have associated large tidal surges, which contain high sediment loads but can also flood coastal wetlands with salt water for periods of time beyond normal tidal cycles. Such tides can assist in the die-back of less flood- and salt-tolerant plant species and promote new plant germination. Many plants, for example, are also adapted to water borne seed dispersal, water borne propagule dispersal, or vegetative reproduction. Although existing plant assemblages and wetland geomorphology may be tolerant to disturbance conditions, sediment restructuring may readjust the local mosaic of plant assemblages. For instance, floods routinely cause large-scale introduction of large logs into coastal estuaries of the Pacific Northwest. These can disturb estuarine marsh plains as the wood settles and refloats at higher tides (Simenstad et al., 2003).

Neither hurricanes nor floods can be controlled, but both positive and negative effects of such large-scale disturbances need to be incorporated into restoration planning. Restoration designs can be adaptable to, or even embrace, the ultimate consequences of disturbance. Conversely, the cost and other disadvantages of investing in a restoration project that is contingent on resisting disturbance in order to maintain a specific, targeted function may ultimately be futile. Importantly, ranges of impacts in terms of spatial scale and intensity of specific disturbances must be considered and incorporated into restoration planning and assessment. Frequency, intensity (high, medium, low), and duration of such events can be important controls on the outcome of restoration efforts. A high level flood of short duration may not have the same geomorphic effect as a low level flood of long duration (Wolman and Miller, 1960), but both scenarios may be important and beneficial aspects of the disturbance regime of an ecosystem.

The nature of the relationships among disturbance, complexity, resistance and resilience of an ecosystem is often hard to determine, but must be attempted if adequate disturbance regimes are to be reintroduced by restoration of coastal ecosystems. Life history requirements of faunal and floral species should also be taken into account in restoration planning, to ensure target species can persist in restored systems. Land or hydrologic restoration without the associated plant establishment and animal usage should not be considered restoration. Just one example of the role of disturbance regimes can be seen in flood pulsing which is well documented as providing several ecological benefits to wetlands such as flushing, sediment and nutrient input, and the limitation of non-flood tolerant upland species (Middleton, 2002). From a hydrological standpoint, reestablishing natural hydrologic regimes may be difficult, and in some cases impossible. Crevasse cuts (breaches) and cut tidal channels in restoration projects can help replace some of this action and are potentially effective mechanisms to allow influence of extreme flood and drainage events.

Fire, whether from lightening strikes or prescribed burns, and often viewed as a negative disturbance in any ecosystem, can reset the plant community allowing less competitive, "pioneering" species (Grime, 1977) a chance to establish, as well as sending a pulse of nutrients and minerals to the soils. Mangroves are thought to be, at least in some cases, fire dependent (Middleton, 1999). Similarly, allowing native herbivores to graze reintroduces natural disturbance into the restoration process, which can improve diversity and accelerate nutrient cycling through the deposition of fecal material. In large-scale herbivory events, called "eat-outs" for wildlife such as muskrat (*Ondatra zibethica*) and nutria (*Myocastor coypus*), the soil surface is exposed and the root zone is often disturbed allowing many opportunistic plant species a chance to grow (Ford and Grace, 1998). In both of these cases, growth of the plant community will take a successional path different than if left undisturbed.

4.3. Incorporate landscape context

Coastal wetland restoration is unlikely to achieve maximum desired performance without considering the approach, location, size and other "design" characteristics in the context of the greater landscape setting (NRC, 2001). The function of coastal wetlands has a strong landscape context, although it may be extremely scale-dependent. For instance, the role of coastal Gulf of Mexico wetlands to protect more inland ecosystems from major physical disturbances, such as hurricanes and related storm surges, is associated with the hundreds of square kilometers of the coastal wetland fringe (Suhayda, 1997). Conversely, strategically located and often narrow wetlands such as fringing mangroves may account for significant filtration of nutrients fluxing from landward watersheds, thus protecting seaward seagrass and reef ecosystems. The essential landscape ecology concept is that important processes and their interacting functions can be very explicit spatially. Restoration must consider two issues in this landscape context: (1) the role of landscape processes on the function of the restoration project, and (2) the potential outcome and sustainability of a restoring wetland in a landscape with extensively modified processes (see below).

The performance of restoration with a goal of recovering habitat of motile species can depend very much on the landscape context. Anadromous fishes, such as juvenile Pacific salmon, can benefit considerably from strategically positioned restoration sites that offer unique functions (e.g., refuge from predation, highly nutritional food resources) that are disproportional to similarly designed restoration sites in other locations along the estuarine gradient (Gray et al., 2002). Even if restoring marshes are still early in their development toward equivalency with natural reference systems, and may actually provide less than optimum conditions for feeding or refuge from predation, the opportunity for fish to occupy a particular position along the estuarine gradient may be more important for their physiological adaptation than other saline habitats further seaward in their migration.

Ignoring landscape setting in restoration planning can affect the overall cumulative performance, including the spatial distribution, time and trajectory required to achieve the desired level of performance and dynamic equilibrium. Spatial lags have been described between simulated restoration of an organism's habitat and the recovery of the organism's populations, and this has been attributed to a "percolation" effect (O'Neill et al., 1992; Tillman et al., 1997; Huxel and Hastings, 1999). The cumulative response to restoration that is based on opportunistic, ad hoc selection of restoration sites and designs is likely to be additive at best; only strategic, spatially explicit restoration planning incorporating landscape scale processes is likely to create a cumulative response that is synergistic and complementary.

4.4. Recognize and adapt to system-scale constraints

Many coastal systems are now so highly altered that restoration efforts are subject to fundamental constraints. In some cases these constraints reflect current landscape or ecosystem characteristics, such as limited sand resources for barrier island rebuilding in Louisiana (Van Heerden and DeRouen, 1997) and invasions by non-native species in San Francisco Bay (Cohen, 1998; Nichols et al., 1986). More commonly, these constraints represent societal preferences for allocation of physical or financial resources. Altered freshwater flow regimes may be one of the most pervasive constraints on coastal ecosystem restoration (Dynesius and Nilsson, 1994), both in terms of restoring historic structure and in meeting assumptions and expectations of process-limiting factors such as sediment accretion rates. The altered flow regimes of almost all U.S. rivers constrain restoration of riparian and estuarine habitats that rely on annual flood cycles but in many cases the dams causing the alteration are considered permanent landscape features—their water supply, hydropower, navigation and recreational purposes considered by society of more import than natural variations in river flow. However, even dams should not be considered immutable constraints, as exemplified by dam removal that has occurred as part of restoration (Hill et al., 1994; Kanehl, 1997) or is increasingly planned around the world (Wunderlich et al., 1994; Shuman, 1995). Yet, the associated constrained floodplains lower in the watersheds are often not included in restoration planning following dam removal.

The management of water resources in the Sacramento-San Joaquin river system is viewed as imposing severe constraints of the restoration of former tidal marshes which have been drained and used for agricultural land for almost a century. Wright and Shoellhammer (2004) estimate that between 1999 and 2002, 4.4 million metric tonnes of sediment were deposited in the Delta, largely derived from the Sacramento River. Assuming that these sediments are deposited in the $\sim$75 km^2 of tidally connected wetland remaining in the Delta, many of them wetland restoration sites, this amounts to 2.0 g/cm^2/yr which is similar to field estimates of sediment accumulation by Reed (2002) of 3.6 g/cm^2/yr. While the current rate of sediment input appears adequate to maintain the elevation of the remaining marshes in the Delta, further restoration may well be sediment limited. The Delta has been converted into agricultural land and the resulting drainage has caused subsidence rates of 3–5 cm/yr (Deverel and Rojstaczer, 1996). Thus, as years pass the amount of sediment needed to restore these lands to their former intertidal elevation becomes greater and sediment availability emerges as a real constraint on success.

Antecedent conditions and the extent of restoration opportunities may be most limited in urban and industrialized estuarine and coastal settings. This is aptly represented by the attempts to restore critical segments of the Duwamish River estuary in Puget Sound, Washington State, where at best only rehabilitation is feasible (Simenstad et al., 2005). The Duwamish River estuary is a system that has been heavily assailed by toxic contamination, intense anthropogenic disturbance, extensive modification of the watershed and hydrogeomorphic driving forces, resulting in an urban/industrial landscape that leaves only scattered, small patches offering opportunities for rehabilitation. Less than 3% of the historic estuarine wetlands remain, more than 65% of the historic watershed area and 70–75% of the freshwater inflow have been diverted from the estuary, and a legacy of contamination by metals (chromium, cadmium, copper, lead, zinc), pentachlorphenol, polychlorinated biphenyls and other halogenated hydrocarbons, and polycyclic aromatic hydrocarbons persists. This landscape limits any restorative efforts to planning around the few opportunities rather than strategic planning for optimum allocation across a less impacted landscape. The cost of rehabilitation can be numbing ($ 1.0–8.0 million ha^{-1} in the Duwamish) and long-term sustainability of rehabilitation sites may be jeopardized by the lack of contaminant source control. However, the commitment to compensate for loss of historic estuarine functionality and to recover endangered species (in the case of the Duwamish, two evolutionarily significant units (ESU) of Pacific Salmon) has prompted a coordinated, rehabilitative effort that has realistic goals and is rebuilding a public investment by recovering elements of natural landscapes in an urban/industrial setting.

Even if some systems are not irreversibly altered, many natural processes may require considerably longer to implement or facilitate restoration than might be expected under more natural conditions. Subsidence of leveed wetlands can result in considerable elevation "debts" that will require decades to recover under natural sediment accretion regimes, and perhaps centuries if available sediment sources have been significantly reduced (Deverel and Rojstaczer, 1996). The prospect of long-term tidal lakes does not necessarily fit most stakeholders' definition of coastal wetland restoration! Other examples of system constraints include: reduced recruitment of native flora and fauna due to restricted sources proximal to a restoration site; conversely, extensive recruitment of non-indigenous species; influence of unnaturally high exposure to ecosystem engineers and other disturbance factors such as grazing by domesticated geese (Simenstad et al., 2005).

4.5. Avoid conflicting goals

Compromising wetland restoration may in some cases be counterproductive to the intent of both sides of the compromise. Restoration projects are often subjected in the planning stage to sharply divergent purposes among stakeholders. The easiest solution is to incorporate a compromise into the restoration design. This may involve modification of the restoration goal and its manifestation in the overall design, or even division of the available restoration site into different but adjoining restoration projects. However, compromising goals do not necessarily result in a "different but equal" situation because the likelihood of desirable performance of one or both may be threatened by the compromise situation. For example, in the Pacific Northwest region, competing pressures for both estuarine fish habitat and waterfowl habitat has on numerous occasions resulted in the partitioning of large restoration sites into two: one parcel reconnected to the estuary with full tidal dynamics and the remaining parcel left as a freshwater impoundment. In cases such as the Spencer Island restoration project in the Skokomish River estuary, the two restoration projects are actually contained within one relict levee system and hydrology of one is linked through the other (Tanner et al., 2002). While dual objectives may sometimes be effectively met by this approach, it may also lead to less than the maximum potential benefit for either goal because function is frequently dependent on restoration site size (e.g., functions associated with tidal channel geomorphology; Hood, 2002) or may even result in depressed function (e.g., predator attraction from one site to the adjacent site, or persistent external impacts; Hood, 2004).

4.6. Plan for the long-term landscape

If it is scientifically prudent to incorporate landscape context in designing and implementing restoration projects, it is imperative also to plan strategically and deploy restoration at the landscape scale. The demand for instant gratification often results in a "gardening" approach to restoration that circumvents life-history, natural variability and meso- or long-term cycles, disturbance, succession and other long-term facilitating processes that dynamically shape landscapes. Ecosystem processes that dictate a long-term approach to restoration include soil development and stochastic event-driven disturbances that "reset" landscape structure (Middleton, 1999). Similarly, sea level rise, tide regime changes and other emerging changes in regional forcing factors cannot be ignored, especially in regions where they are already a contingency (Orr et al., 2003).

4.7. Learn and adapt, by monitoring process-based performance measures

Given the inherent uncertainties and constraints on coastal ecosystem restoration we have described above, it is incumbent that restoration programs become more explicit learning and experimental platforms. While there is often a token tribute to this recognized need in many restoration plans, adaptive management needs to be applied as it was designed in all its scientific rigor (Walters, 1986; Halbert, 1993; Lee, 1993; Lee and Lawrence, 1986). One of the more applicable aspects of adaptive management is that it is an objective process or framework that characterizes scientific uncertainties, develops strategies to test hypotheses, measures the response to the test and incorporates the results into future decisions. Perhaps the most important point is that (restoration) strategies must be treated as experiments in a framework that enables learning from the results (Lee, 1993). Particularly in the case of coastal ecosystem restoration, where the link between processes, structure and function are typically poorly understood, assessment of restoration "experiments" cannot typically be limited to monitoring structural attributes. The ability to learn and correct or realign your experimental restoration strategy, or to apply an improved strategy to subsequent restoration, depends upon understanding the ecosystem processes that resulted in the response (structure). Monitoring ecosystem processes is not typically included in restoration monitoring plans, but process-based performance measures can provide a much more direct indication of what "needs to be fixed" to avoid continued or future restoration dysfunction.

Understanding system responses to natural variations and extremes of ecosystem processes can be misleading if based solely on restoring ecosystems. Reference or "benchmark" sites are fundamental in explaining how ecosystem processes affect structural and functional attributes and scales of the natural variation in these processes and responses (NRC, 1992, 1995). Tracking variation in both structural attributes and ecosystem processes at naturally dynamic sites provides critical context in interpreting comparable information from restoration sites in the same landscape, exposed to the same landscape-scale forcing. Optimally, multiple reference sites at different positions in the landscape should be monitored to capture the most likely range of functional equivalency trajectories.

5. Summary and conclusions

Restoring aquatic ecosystems is far from an "off-the-shelf" science or technology, and restoration practitioners have a poor track record of addressing the prerequisites described above, much less conducting effective pre- and post-assessment monitoring with standardized methods (Bernhardt et al., 2005). Understandably, the number and difficulty of challenges that must be overcome to actually address, much less accomplish, coastal ecosystem restoration are endless. The greatest difficulty is to assess expectations of what restoration can realistically accomplish, and determine whether it can even approach the definition of restoration at all. Conversely, acceptance of rehabilitation and enhancement is not tantamount to failure; a rehabilitated or enhanced ecosystem may be the only achievable goal given the antecedent, landscape and socioeconomic constraints. The actual challenge is not whether or not restoration is acceptable, but whether we have the technical and scientific abilities to accomplish it. At the present state of knowledge, we will never know what we have accomplished with restoration actions if we do not address them as structured experiments within a broader application of implementing adaptive management. We particularly need to start learning from dedicated case or "demonstration" studies that are intended to develop tools for comprehensive planning of integrated watershed-coastal wetland restoration at landscape scale. To understand the broader context of how these natural and restoration settings fit into a dynamic landscape requires commitment to long-term monitoring of dedicated reference sites, preferably a "benchmark system." Only by such a scientific deployment of restoration experiments might we reach a stage where we can apply adaptive models (conceptual to simulation) for mechanistic understanding, predictability and management of restoration processes, and what can and cannot be realistically achieved.

Choi (2004) effectively synthesized the need for such a 'futuristic' approach to restoration, which is to: (i) set realistic and dynamic (instead of static) goals for future, instead of past, environment; (ii) assume multiple trajectories acknowledging the unpredictable nature of ecological communities and ecosystems; (iii) take an ecosystem or landscape approach, instead of ad hoc gardening, for both function and structure; (iv) evaluate the restoration progress with explicit criteria, based on quantitative inference; (v) maintain long-term monitoring of restoration outcomes.

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