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CHAPTER FOUR

PRACTICAL PROXIES FOR TIDAL MARSH ECO SYSTEM SERVICES: APPLICATION TO INJURY AND RESTORATION

Charles H. Peterson,* Kenneth W. Able,† Christin Frieswyk DeJong,‡ Michael F. Piehler,* Charles A. Simenstad,§ and Joy B. Zedler‡

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Abstract

Tidal marshes are valued, protected and restored in recognition of their ecosystem services: (1) high productivity and habitat provision supporting the food web leading to fish and wildlife, (2) buffer against storm wave damage,
(3) shoreline stabilization, (4) flood water storage, (5) water quality maintenance, (6) biodiversity preservation, (7) carbon storage and (8) socio-economic benefits. Under US law, federal and state governments have joint responsibility for facilitating restoration to compensate quantitatively for ecosystem services lost because of oil spills and other contaminant releases on tidal marshes. This responsibility is now met by choosing and employing metrics (proxies) for the suite of ecosystem services to quantify injury and scale restoration accordingly. Most injury assessments in tidal marshes are triggered by oil spills and are limited to: (1) documenting areas covered by heavy, moderate and light oiling; (2) estimating immediate above-ground production loss (based on stem density and height) of the dominant vascular plants within each oiling intensity category and (3) sampling sediments for chemical analyses and depth of contamination, followed by sediment toxicity assays if sediment contamination is high and likely to persist. The percentage of immediate loss of ecosystem services is then estimated along with the recovery trajectory. Here, we review potential metrics that might refine or replace present metrics for marsh injury assessment. Stratifying plant sampling by the more productive marsh edge versus the less accessible interior would improve resolution of injury and provide greater confidence that restoration is truly compensatory. Using microphytobenthos abundance, cotton-strip decomposition bioassays and other biogeochemical indicators, or sum of production across consumer trophic levels fails as a stand-alone substitute metric. Below-ground plant biomass holds promise as a potential proxy for resiliency but requires further testing. Under some conditions, like chronic contamination by organic pollutants that affect animals but not vascular plants, benthic infaunal density, toxicity testing, and tissue contamination, growth, reproduction and mortality of marsh vertebrates deserve inclusion in the assessment protocol. Additional metrics are sometimes justified to assay microphytobenthos, use by nekton, food and habitat for reptiles, birds and mammals, or support of plant diversity. Empirical research on recovery trajectories in previously injured marshes could reduce the largest source of uncertainty in quantifying cumulative service losses.

1. Introduction

Like other wetland habitats, tidal marshes are recognized for the wide range and high value of the services they provide to the coastal ecosystem and to human welfare (Mitsch and Gosselink, 1993). Because of intense coastal development, the total area of coastal wetlands including tidal marshes has declined dramatically in the United States (US) over the last two centuries and even in recent years (Dahl, 1990, 2006). Despite regulations to protect remaining tidal marsh habitat in the US, the European Union and other regions globally, human activities in the coastal zone frequently lead to further unintentional degradation of marsh habitat
through spills of oil and other biologically harmful contaminants and through various types of physical disturbance. Resultant tidal marsh degradation often triggers governmental actions to decontaminate the marsh and also to conduct habitat restoration to replace the lost ecosystem services (e.g., Fonseca et al., 2000). In addition, wetland restoration is also often required as part of a permitting process in the US as compensatory mitigation to help achieve a policy of ‘no net loss of wetlands’. Indeed ecological restoration may represent the most rapidly growing sub-discipline of ecology (Young, 2000; Zedler, 2000). The challenges implicit in implementing restoration now demand a more unified conceptual basis for assessment of ecosystem services (Palmer et al., 1997). Improving the scientific foundations for restoration is critical because flaws in site selection and design have inhibited wetland restoration from compensating for lost wetland area and particularly its ecosystem services and functions (Bernhardt et al., 2005; NRC, 2001).

In the US, the assessment of injury to natural resources, habitat and ecosystem services from coastal oil spills and contaminant releases is primarily the responsibility of federal and state government agencies. These agents serve by law as ‘trustees’ of publicly owned natural resources and are responsible for ensuring that restoration successfully compensates for the quantitative loss of the resources and their ecosystem services over the entire period of injury (Burlington, 1999; NOAA, 1997). A similar governmental role in habitat restoration is increasingly being adopted by European Union countries. Tidal marshes pose challenges to quantifying injury and scaling compensatory restoration because of the unusually wide range of their important ecosystem services, the geographic differences among marsh systems and the importance of connectivity between tidal marshes and other habitats. Nevertheless, trustee organizations must conduct quantitative injury assessments under emergency situations with limited time and money. This requires application of scientifically justified and readily applied metrics of ecosystem services of tidal marshes. Developing the scientific support for choice and application of practical proxies and methods to measure injury and scale restoration to account for lost ecosystem services represents one of many challenges to the fields of ecology and interdisciplinary restoration science (Peterson and Lipcius, 2003).

Here, we review and categorize the ecosystem services attributable to tidal marshes, discuss how these services can vary in importance as a function of geological framework and physical environmental factors, as illustrated by differences across the continental US, evaluate currently applied and potential alternative proxies for quantifying injury to and recovery of the important marsh services and then discuss ways of refining injury assessment. We recognize that the tidal marsh is best viewed broadly as a system of several interconnected sub-habitats, specifically (1) irregularly flooded marsh surface including marsh pools, (2) regularly flooded intertidal marsh surface, (3) intertidal marsh creeks, (4) subtidal marsh creeks and
(5) bay-marsh fringe (Rountree and Able, 1992). We also acknowledge that at a larger landscape scale, this system of marsh habitats is strongly interconnected to other estuarine habitats, such as broad intertidal flats, submerged aquatic vegetation beds, oyster reefs, deeper unvegetated subtidal bottom and the water column. Indeed, the level of ecosystem services provided by tidal marshes can be determined by the spatial arrangement of these landscape components. Nevertheless, we focus on that portion of tidal marsh habitat largely occupied by vascular plants, so as to match the habitat partitioning currently used during assessment of injury to coastal systems. Our assessments implicitly nest the vegetated marsh within the more complex mix of sub-habitats to evaluate how well each alternative metric might serve as a suitable proxy for marsh ecosystem services.

2. Specification of Ecosystem Services of Marshes

Specifying the key ecosystem services of tidal marshes (Table 4.1) is a necessary first step in determining how to assess injuries to this habitat. Such a list of services can guide the selection and design of both injury assessment and restoration projects expected to replace lost services. In addition, explicit specification of operative ecosystem services implies potential assessment metrics that could quantify levels of each service after injury and then during recovery of those key services. Ironically, while this table isolates the tidal marsh habitat and ascribes important ecosystem services to it, the most valuable marsh services to terrestrial, estuarine and coastal ocean ecosystems are generated through the functional interconnectivities between the tidal marsh and other habitats (e.g., Weinstein et al., 2005).

The provision of highly productive habitat (Service #1) that offers structural refuges for feeding animals (Adam, 1990; Teal, 1962) formed the initial basis for public stewardship of tidal marshes. Historic efforts to assess marsh habitat value were largely focused on the vascular plants that visually distinguish a tidal marsh from other shoreline habitats (Odum, 1961). Yet, scientists also recognize the ‘secret garden’ of MPB as extremely productive and directly utilized by consumers without passing through energetically costly decomposer intermediaries (MacIntyre et al., 1996; Sullivan and Currin, 2000). These decomposers are known to be vital food chain links to detritivory, implying that fungal and bacterial production deserves inclusion among the important habitat functions of tidal marshes (Kreeger and Newell, 2000). Secondary production of herbivorous and detritivorous invertebrates on the marsh provides the trophic support for primary predators, composed mostly of small fishes, shrimps and crabs. However, because coastal marshes export detritus that is consumed in
adjoining systems, the in situ production of herbivorous/detritivorous invertebrates on the marsh underestimates the marsh’s contribution to that trophic level (Seitz et al., 2006; Weinstein et al., 2005). Small fishes and crustaceans comprise the final important trophic link from marsh primary production to larger predators (Kneib, 1997; Nemerson and Able, 2003, 2004; Tupper and Able, 2000). The use of tidal marsh by larger fishes and crabs (including horseshoe crabs of special significance in Delaware Bay), birds, mammals and reptiles reflects a combination of both trophic services and structural habitat services for the common higher-order predators (Able et al., 2008; Adam, 1990). Most metrics used to assess the value of ecosystem services of tidal marshes are intended to represent proxies for production at one or more of these trophic levels.

### Table 4.1 Ecosystem services provided by tidal marshes that may imply metrics for quantitative assessment

<table>
<thead>
<tr>
<th>Marsh Ecosystem Service</th>
<th>Practical Proxies for Tidal Marsh Ecosystem Services 225</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Habitat and food web support</td>
<td></td>
</tr>
<tr>
<td>High production at base of food chain</td>
<td></td>
</tr>
<tr>
<td>Vascular plants</td>
<td></td>
</tr>
<tr>
<td>Microphytobenthos</td>
<td></td>
</tr>
<tr>
<td>Microbial decomposers</td>
<td></td>
</tr>
<tr>
<td>Benthic and phythal invertebrates (herbivores and detritivores)</td>
<td></td>
</tr>
<tr>
<td>Refuge and foraging grounds for small fishes and crustaceans</td>
<td></td>
</tr>
<tr>
<td>Feeding grounds for larger crabs and fishes during high water</td>
<td></td>
</tr>
<tr>
<td>Habitat for wildlife (birds, mammals, reptiles)</td>
<td></td>
</tr>
<tr>
<td>2. Buffer against storm wave damage</td>
<td></td>
</tr>
<tr>
<td>3. Shoreline stabilization</td>
<td></td>
</tr>
<tr>
<td>4. Hydrologic processing</td>
<td></td>
</tr>
<tr>
<td>Flood water storage</td>
<td></td>
</tr>
<tr>
<td>5. Water quality</td>
<td></td>
</tr>
<tr>
<td>Sediment trapping</td>
<td></td>
</tr>
<tr>
<td>Nutrient cycling</td>
<td></td>
</tr>
<tr>
<td>Chemical and metal retention</td>
<td></td>
</tr>
<tr>
<td>Pathogen removal</td>
<td></td>
</tr>
<tr>
<td>6. Biodiversity preservation</td>
<td></td>
</tr>
<tr>
<td>7. Carbon storage</td>
<td></td>
</tr>
<tr>
<td>8. Socio-economic services to humans</td>
<td></td>
</tr>
<tr>
<td>Aesthetics</td>
<td></td>
</tr>
<tr>
<td>Natural heritage</td>
<td></td>
</tr>
<tr>
<td>Ecotourism</td>
<td></td>
</tr>
<tr>
<td>Education</td>
<td></td>
</tr>
<tr>
<td>Psychological health</td>
<td></td>
</tr>
</tbody>
</table>
In addition to the productivity/habitat value to biota (Service #1), other ecosystem services of tidal marshes are identified in the scientific literature (e.g., *Millenium Ecosystem Assessment, 2005*) and are often considered in justifying and designing tidal marsh restorations, although they rarely serve as metrics for injury or restoration. Tidal wetlands help buffer the adjoining higher ground from damaging effects of storms (Service #2) by their ability as an emergent structure to dissipate wave energy. The extraction of energy from waves and baffling of current flows reduces erosion of shorelines during storms and promotes sedimentation during calm conditions. Sedimentation maintains the relative elevation of the marsh and shoreline position in the face of sea-level rise (Service #3). Hydrologic services of tidal marshes include water storage, especially flood waters (Service #4). The role of tidal marshes in maintaining estuarine and coastal ocean water quality by intercepting, trapping and metabolizing dissolved and particulate pollutants, such as inorganic nutrients, eroded sediments and human pathogens, is widely appreciated (Service #5). Tidal marshes contribute to regional biodiversity (Service #6) by serving as habitat for several threatened and endangered species and by preserving endemic species, such as several voles, rails (birds in the family Rallidae) and marsh sparrows (*Greenberg et al., 2006*). Biodiversity can also be a predictor of community resilience to perturbation (*Bertness and Leonard, 1997*). Carbon storage may be viewed as a service of coastal marshes (Service #7) as peat is accumulated, buried and stored, thus buffering greenhouse gas emissions. Finally, tidal marshes offer socio-economic benefits (Service #8), such as sustaining the aesthetics of coastlines, maintaining a heritage and historical culture, supporting ecotourism, serving as a living laboratory for nature education, promoting psychological health and supporting fishing and waterfowl hunting. The means of measuring and evaluating these socio-economic services are reviewed elsewhere (*Thayer et al., 2005*).

### 3. Regional Variation in Tidal Marshes

#### 3.1. Distribution and characteristics across the United States

Tidal marshes differ regionally as a function of variations in coastal tidal hydrology, geomorphology, human encroachment and biotic province. Much of this variation is related to regional differences in geologic legacy and disturbance regime. Here we use patterns in tidal marshes of the continental US to illustrate general principles. Tidal marshes vary across the US to such a degree that all important general patterns can be demonstrated by examples from this single continental area.

First, salt marshes and other shallow-water wetlands are non-uniformly distributed among major regions of the US (*Table 4.2*) because of
Table 4.2 Regional differences in US coastal wetlands

<table>
<thead>
<tr>
<th>Region</th>
<th>WA</th>
<th>EDA</th>
<th>FDA</th>
<th>PD</th>
<th>%U</th>
<th>%A</th>
<th>ACF</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Atlantic</td>
<td>1200</td>
<td>23</td>
<td>36</td>
<td>211</td>
<td>7</td>
<td>7</td>
<td>250</td>
</tr>
<tr>
<td>Mid-Atlantic</td>
<td>3500</td>
<td>48</td>
<td>123</td>
<td>822</td>
<td>19</td>
<td>27</td>
<td>500</td>
</tr>
<tr>
<td>South Atlantic</td>
<td>9200</td>
<td>55</td>
<td>148</td>
<td>104</td>
<td>4</td>
<td>22</td>
<td>169</td>
</tr>
<tr>
<td>Gulf of Mexico</td>
<td>16,600</td>
<td>96</td>
<td>1562</td>
<td>122</td>
<td>5</td>
<td>30</td>
<td>648</td>
</tr>
<tr>
<td>Pacific</td>
<td>1800</td>
<td>38</td>
<td>362</td>
<td>529</td>
<td>12</td>
<td>11</td>
<td>337</td>
</tr>
<tr>
<td>Contiguous</td>
<td>32,300</td>
<td>260</td>
<td>2231</td>
<td>309</td>
<td>9</td>
<td>23</td>
<td>1904</td>
</tr>
</tbody>
</table>

WA, wetland area by region (in square miles); EDA, estuarine drainage area (in thousands of square miles), defined as the 'land and water component of a watershed that drains directly into estuarine waters' (NOAA, 1990), assuming that 'natural processes and human activities near estuarine waters generally affect them the most' (NOAA, 1990); FDA, fluvial drainage areas (in thousands of square miles), defined as land and freshwater portions of watersheds upstream of EDAs, corresponding with cataloging units of USGS; PD, population density (people per square mile in 1980); %U, percentage of EDA that was urban; %A, percentage of EDA that was agriculture; ACF, value (in millions of dollars in 1989) (e, estimated) of all commercial fisheries considered estuarine dependent. All data are from NOAA (1990).

Second, historic losses of tidal marshes vary by region in response to differences in intensity of a diverse suite of coastal development activities, such as filling to build cities, dredging for navigation and oil development canals, levee building to exclude tidal inundation and provide for agricultural and pasture lands, and excavation to create lagoons for commercial harbours, aquaculture or public recreational use. For example, San Diego’s Mission Bay, with its Sea World, artificial sandy beaches, sailing, water skiing and jet skiing facilities, is called the nation’s largest aquatic park—all dredged from ‘False Bay’, a former salt marsh. While the highest percentage loss (90%) of historic coastal wetlands has occurred in California (NOAA, 1990), the greatest losses in marsh area have occurred in Louisiana and Florida [extrapolated from total wetland loss statistics in Dahl (1990)].

Third, biotic provinces vary with latitude, tidal regime, ocean circulation patterns, climate and freshwater inflows. As an example, the Mississippi River drains 40% of the continental US, and it discharges water and
sediments into the nation’s largest delta. In combination with the unique geomorphology of the Gulf of Mexico, which limits mixing of coastal and Atlantic Ocean water, high inflows of fresh water, accumulation of sediments and minimal amplitudes of astronomical tides produce large areas of low-salinity marshes more influenced by seiches (standing waves that develop in enclosed basins) and storm surges than lunar stage. In contrast, the Mediterranean-type climate of Southern California (cool moist winters and long, dry and warm summers) interacts with coastal geomorphology (nearby mountain ranges and mostly small watersheds) and semi-diurnal tidal regimes to produce hyper-saline soils in the salt marshes, which select for halophytes of extraordinary salt tolerance. In the Pacific Northwest, prolonged, high rainfall and extensive river discharges with high sediment loads and an active tectonic setting (creating periodic subsidence) tend to promote more tidal freshwater and oligohaline–mesohaline wetlands, with narrower polyhaline salt marshes, and extensive mud- and sandflats. In New England, narrow coastlines are battered by winter storms and experience ice damage, selecting for hardy species and limiting vegetation to protected coves. In South Florida, the subtropical climate supports mangroves instead of salt marshes as the tidal wetland, providing greater structural buffering of hurricanes. Depending on both coastal setting (e.g., broad deltas and coastal plains vs narrow pocket estuaries along steep shorelines) and the level of human disturbance (e.g., proximity of upland development), coastal wetlands can be confined to narrow fringing emergent marshes dominated by herbaceous plants or encompass a broad continuum from emergent marshes to scrub–shrub and forested wetlands that extend deep into tidal floodplains.

The geographic extent and wide regional variation in physical conditions combine to cause regional variation in tidal marsh biota around the US, but this variation does not preclude overlapping distributions of species and genera of both plants and animals. Among plants, for example, the perennial grass genus *Spartina* is widely represented, with *S. alterniflora* along the Atlantic and Gulf coasts and *S. foliosa* along the California coast. There are no indigenous *Spartina* marshes in the Pacific Northwest, but non-native *S. alterniflora* and *S. anglica* have invaded several estuaries in that region, and non-native *S. alterniflora* (and hybrids), *S. anglica*, *S. densiflora* and *S. patens* have invaded San Francisco Bay marshes to various degrees. *Batis maritima* occurs in Southern California and from the Gulf coast through the Mid-Atlantic in the eastern US, and *Salicornia bigelovii* is found in Southern California and other *Salicornia* species throughout the Gulf and Atlantic coasts. Sedges such as *Carex lyngbyei* are prevalent in brackish and tidal fresh marshes, and the number of *Carex* species becomes considerably greater in freshwater tidal marshes in the Pacific Northwest. Similarly, northeastern US tidal marshes harbour diverse assemblages of bulrushes (*Scirpus/Bolboschoenus/Schoenoplectus* spp.). Some species, such as pickleweed, *Salicornia virginica* (= *Sarcocornia pacifica*) and saltgrass, *Distichlis spicata*,

\[\text{Author’s personal copy}\]
are more ubiquitous, occurring from Puget Sound to San Diego on the Pacific coast and throughout the Gulf and Atlantic coasts.

Coastal wetlands can also demonstrate high variability as a function of shoreline geomorphology, such as elevation gradient and tidal (dendritic) channel complexity. Because of the often dramatic difference in elevation and subsequent flooding frequency and duration, tidal marshes exhibit substantial spatial heterogeneity in ecosystem services. Zonation of tidal wetland plants is a pervasive feature, with low and high marsh differing in plant assemblages and animal use. Although many of the coastal plain marshes in the southeastern Atlantic and Gulf coasts exhibit an extremely low elevation gradient with graded transitions in species, in the Pacific Northwest, the marshes at the lowest edge of vascular vegetation tend to be colonized by emergent sedges and rushes, whereas a distinct higher-elevation marsh is occupied by an extremely speciose complex of herbaceous plants, often with woody (scrub–shrub) vegetation at the upland transition (Simenstad et al., 2000). An analogous marsh geomorphic and vegetative structure also occurs in New England (Orson et al., 1987), where tidal salt marsh has expanded during the last 4000 years of rising sea level on the submerging uplands and over tidal flats. In the Pacific Northwest, the low marsh is often the consequence of natural disturbance, such as sedimentation events (shoaling) or erosion. Plant zonation also occurs around dendritic tidal channels, where slightly higher sediment accretion rates promote natural ‘levees’. The interaction of flooding regime, drainage and local soil salinity promotes vegetation zonation aligned with the tidal channel drainage structure (e.g., Sanderson et al., 1997 and Culberson, 2001 for San Francisco Bay/Delta).

Among animals, killifishes of the genus Fundulus are the dominant fish of the salt marsh surface, with F. parvipinnis in Southern California, F. heteroclitus in Atlantic and F. grandis in Gulf coastal marshes. Among invertebrates, fiddler crabs (Uca) are widespread, with U. crenulata in California and U. pugilator in Atlantic and Gulf coastal marshes. Probably in response to the high tidal amplitude, Pacific Northwest marshes harbour fewer resident fishes and mobile macroinvertebrates, particularly in comparison to the diverse fish assemblages that are found in the South Atlantic and Gulf coast wetlands. However, a variety of nektonic species routinely migrate from subtidal estuarine habitats onto the marshes during the tidal exchange, epitomizing Kneib’s (1997) ‘trophic relay’. Benthic epifauna and infauna are abundant, and particularly so in low marshes. Higher-elevation scrub–shrub and forested tidal wetlands are particularly rich in avifauna and mammals. Despite intrinsic similarities, heterogeneity in biota and food webs leads to a diversity of tidal marsh types, varying in functions and services.

Tidal marsh types are poorly characterized in the US, although some early (e.g., Chapman, 1960) and recent (Ferren et al., 1996a,b,c) authors
have sought to classify marshes on the basis of their vegetation. Human activities have created substantial modifications of tidal marshes, so many do not resemble historic baselines. For example, the intrinsically limited extent of salt marshes in Southern California coupled with their high rate of loss to development has left ‘postage stamp’ wetlands among urban landscapes without connectivity to one another or their natural watersheds or uplands. Even though vast expanses of coastal marsh still characterize the Gulf of Mexico margin, a complex combination of natural subsidence and anthropogenic modifications for oil and gas development, navigation and flood protection has resulted in an increasingly fragmented marsh mosaic and an annual loss rate of 65 km² year⁻¹ in the historic and extant Mississippi Delta region (Britsch and Dunbar, 1993). Although hurricanes and similar extreme storm events can intensively disturb coastal marshes, especially when the coastal marsh landscape is compromised by human modifications—exemplified by recent Hurricane Katrina and Rita experiences (Working Group for Post-Hurricane Planning for the Louisiana Coast, 2006)—storms also account for considerable sedimentation that subsidizes marsh redevelopment (Turner et al., 2006).

The prevalence of invasive species also varies regionally in tidal marshes, creating differences in how well marsh ecosystem services are being preserved or replaced. Other than some expansion of a more invasive form of Phragmites australis, many Atlantic coastal marshes are relatively unaffected by invasive species. Conversely, in San Francisco Bay, marshes are much more extensive, but they are plagued by introduced species of both plants and animals. For example, S. alterniflora has replaced much of the native S. foliosa directly and has also hybridized with it, further jeopardizing its gene pool. Shipworms have invaded and spread to destabilize channel banks. The invasive Australian pine, Melloluca, has colonized and now dominates marsh edges through much of South Florida.

3.2. Regional patterns in marsh ecosystem services across the United States

Variations among tidal marshes lead to differences in their ecosystem services, as well as in how they are valued by resource managers and the public. We contrast four broad geographic regions of the continental US (Table 4.3) and address how the relative importance of each specific ecosystem service varies regionally. The importance of fixing carbon, producing food for higher trophic levels and offering habitat to allow energy transfer to animals of high value is high in all four geographic regions. This complex service of biotic production forms a core value of tidal marshes everywhere. Nevertheless, distinctions exist among regions that could affect choices of metrics to use for injury assessment and compensatory restoration projects. For example, the relative rarity of tidal marshes in Southern California
<table>
<thead>
<tr>
<th>Services (from Table 4.1)</th>
<th>Pacific Northwest</th>
<th>Pacific Southwest (see NOAA, 1990)</th>
<th>Mid- and Northeast Atlantic</th>
<th>Southeast Atlantic and Gulf of Mexico</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habitat (food production and feeding refuge)</td>
<td>High productivity and standing crop, due to high frequency and duration of tidal flooding and minimal physiological stress due to desiccation; extensive use by migratory and transient fishes and macroinvertebrates due to geomorphological and biotic complexity; high trophic transfer of marsh production to nektom in greater ecosystem.</td>
<td>High primary productivity due to Mediterranean-type climate (year-round growing season) and high proportion of algal productivity, which leads to efficient energy transfer in the algae–invertebrate–fish food web; high fish and shellfish production.</td>
<td>Highly seasonal in structure from New Jersey northwards because of ice damage, with wrack accumulations much peat and numerous pools. Productive killifish, grass shrimp, marsh mussel and periwinkle populations. Greatly modified by mosquito ditching.</td>
<td>Includes areas of highest primary productivity and important marsh-dependent fisheries (penaeid shrimps, red drum and snook).</td>
</tr>
<tr>
<td>Buffer (wave dissipation and water absorption)</td>
<td>Particularly important for fringing marshes along open estuaries where long fetch accentuates shoreline wave impact; entrain large wood that</td>
<td>Locally important; total length of marsh-urban buffer is low, but real estate value is exceptionally high.</td>
<td>Probably limited in north during winter when ice has removed above-ground structure. Most important for</td>
<td>Very important, human development along coastlines is both destroying and confining migration</td>
</tr>
</tbody>
</table>

(continued)
<table>
<thead>
<tr>
<th>Services (from Table 4.1)</th>
<th>Pacific Northwest</th>
<th>Pacific Southwest (see NOAA, 1990)</th>
<th>Mid- and Northeast Atlantic</th>
<th>Southeast Atlantic and Gulf of Mexico</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoreline stabilization and sedimentation to accommodate sea-level rise</td>
<td>would otherwise cause damage in high intertidal; shrub–scrub and forested wetlands completely dissipate waves.</td>
<td>San Francisco Bay has most of California’s salt marsh; marsh and salt ponds help protect homes, industry, highways and three major airports.</td>
<td>coastal barriers as in New Jersey, New York and Massachusetts, especially as sea level rises and marsh traps sediments.</td>
<td>of marshes, thus increasing shoreline vulnerability; high tropical storm activity.</td>
</tr>
<tr>
<td>Hydrologic services (floodwater storage)</td>
<td>Sustain high rates of sediment accretion and shoaling, and promote marsh transgression; reduce water column turbidity.</td>
<td>High importance as illustrated by Elkhorn Slough, where sediments are dredged in the marina at the mouth, and the entire salt marsh appears to be eroding and disappearing as a result.</td>
<td>Extremely important function on highly developed coastal barriers of New Jersey, New York and Massachusetts, but not on steeper mainland shorelines.</td>
<td>Critically important, particularly in the Gulf region.</td>
</tr>
<tr>
<td></td>
<td>Constitute significant portion of tidal prism and flood water storage, particularly in low marsh systems and in tidal floodplains where</td>
<td>Only San Francisco Bay are tidal marshes and the adjacent estuary large enough to</td>
<td>Impervious surface increases and historic wetland loss make flooding a growing problem so any extensive tidal</td>
<td>With growing likelihood of intense tropical storms, flood water storage by these broad tidal marshes</td>
</tr>
<tr>
<td>Water quality improvement</td>
<td>Extensive nutrient uptake, especially by associated algae, accentuated by high flooding frequency and duration.</td>
<td>Most are sediment traps, accreting much faster than the sea level is rising; one (Elkhorn Slough) is eroding.</td>
<td>Huge extent of urbanized watershed with multiple-point source discharges and storm-water runoff makes this service extremely important.</td>
<td></td>
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</tr>
<tr>
<td>(sediment, nutrient and pathogen removal in estuary and ocean waters)</td>
<td>High diversity and productivity of invertebrate fauna, especially aquatic insects, support important nekton, such as threatened/ endangered ocean-type Pacific salmon.</td>
<td>Extremely high due to historical loss of more than 90% of wetlands. Salt marshes support federal- and state-endangered birds and one federal-endangered plant in California. Also, the Pacific flyway is constrained by the few coastal locations that have large mudflats.</td>
<td>Very important, trapping sediments and removing nutrients in river deltas and from adjacent landscapes.</td>
<td></td>
</tr>
<tr>
<td>Biodiversity support</td>
<td>Dramatic structural modifications by ditching and filling along with community modifications by introduced species, like Phragmites, green crabs, a periwinkle and fishes, imply that natural resilience may be compromised.</td>
<td></td>
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<tr>
<td>(including threatened and endangered species and resilience to perturbations)</td>
<td>High, though not due to scarcity. Support manatees and endangered birds.</td>
<td></td>
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</tr>
<tr>
<td>Carbon storage</td>
<td>Moderate to low due to lack of peat-building</td>
<td>Low due to warm year-round climate</td>
<td>High in microtidal areas despite warm</td>
<td></td>
</tr>
<tr>
<td>Services (from Table 4.1)</td>
<td>Pacific Northwest</td>
<td>Pacific Southwest (see NOAA, 1990)</td>
<td>Mid- and Northeast Atlantic</td>
<td>Southeast Atlantic and Gulf of Mexico</td>
</tr>
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<td>--------------------------</td>
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<tr>
<td>Socio-economic services</td>
<td>High non-extractive tourism use, especially associated with migratory and resident bird watching; recreational extractive uses generally restricted to waterfowl hunting; very important native American traditional harvest for weaving, therapeutic and other cultural uses; many small community groups have instituted stewardship and monitoring of local coastal wetlands.</td>
<td>High value due to highly populated coast; thousands of outdoor coastal recreation sites within the estuarine drainage areas (the highest among US regions; NOAA, 1990); high value for ecotourism, education and open space (e.g., Ballona Wetland is the only salt marsh left in Los Angeles County; it has long been the subject of many lawsuits to retain open space).</td>
<td>Relatively high given large peat accumulations.</td>
<td>High heritage value throughout much of the region, aesthetic value in areas with extensive marshes, growing ecotourism value.</td>
</tr>
<tr>
<td></td>
<td>assemblages and high decomposition; high sediment accretion accounts for some burial?</td>
<td>and semidiurnal mixed tides that favour decomposition.</td>
<td>Very high because of important contrast with highly urbanized coastline. Many institutions of higher education in this region, popular tourism destinations and a history of water-dependent culture.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>climate, lower in areas with larger tidal influence.</td>
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implies that the value of each remaining marsh as a stopover for refuelling migratory shorebirds is extremely high. Similarly, conservation and restoration of habitat for the high proportion of endemic vertebrates including threatened or endangered species that occupy tidal marshes (Greenberg et al., 2006) should be a high priority in Southern California, where their marsh habitat is so limited. In contrast, the huge area of tidal marsh on the Gulf coast renders each marsh acre less critical for supporting bird migrations but vital to sustaining marsh-dependent commercial shrimp and crab fisheries (Zimmerman et al., 2000). Florida marshes play a more important role in supporting a particular high-value fish (snook: Centropomus undecimalis), whereas the entire Gulf and South Atlantic coast produces red drum (Sciaenops ocellatus), which support valuable sports fisheries. The naturally restricted tidal marshes of New England and the Pacific Northwest also support populations of key fisheries species. New England marshes contribute to the abundance of winter flounder (Pseudopleuronectes americanus), the basis for important commercial and recreational fisheries (Collette and Klein-MacPhee, 2002), whereas mid-Atlantic marshes do the same for summer flounder, Paralichthys dentatus (Able and Fahay, 1998). Certain species and life history types of Pacific salmon are disproportionately enhanced by feeding and growing in estuarine marshes of the Pacific Northwest (Bottom et al., 2005; Magnusson and Hilborn, 2003; Simenstad et al., 2000).

The value of tidal marshes as buffer against shoreline erosion from storms varies with risk of intense storms and estuarine size because of wind fetch. The Pacific Southwest does not experience hurricanes directly and, with the exception of San Francisco Bay, possesses little tidal marsh on shores of large bodies of water, implying that protection of other habitats from erosion may not be as important in this region (Table 4.3). The Pacific Northwest contains many fringing marshes on larger water bodies and experiences violent winter storms with sufficient frequency to render the buffer protection important. Within the Northeast Atlantic, marshes on the thin coastal barriers play a large role in protecting other shoreline habitats from erosion and storm damage, but winter ice damage renders the marsh protection ineffective during a period of frequent northeasters. The Southeast Atlantic is characterized by a high risk of hurricane landfall so marshes there function significantly to lower risk of storm damage to its extensive low-lying lands.

The ability of emergent marsh plants to trap sediments and thereby maintain shoreline position as sea level rises is a valuable function of tidal marshes in every geographic region. This process requires a sediment source and some marshes exist in locations where inputs of suspended sediments are insufficient to keep pace with rising sea level. Few such marshes exist along the Pacific Northwest coast, where rainfall runoff and sediment delivery are generally intense. Other regions of the continental US possess some areas in which suspended sediment inputs are low. For example, marsh shorelines of Elkhorn Slough in California are rapidly eroding. Modifications of river
channels in the Mississippi River system have enhanced submergence of tidal marsh habitat where flow has been diverted and thus sediment supply cutoff.

The values of both hydrologic services and water quality support by tidal marshes vary over the continental US (Table 4.3). San Francisco Bay and San Diego Bay, the only relatively large bodies of tidal waters in Southern and Central California, along with Puget Sound and many coastal estuaries of the Pacific Northwest, have lost substantial fractions of their historic marsh habitat, thus diminishing the level of these hydrologic and water quality support functions. The tidal marsh service of maintaining water quality in estuaries and the coastal ocean is of critical importance everywhere, except in Southern California where so little marsh acreage exists to treat the waters. Nutrient loading is a significant issue across the US, not merely high in urbanized regions but wherever storm–water runoff drains urban/suburban development and agricultural fields, as in the Mississippi River basin, creating the vast hypoxic dead zone in the Gulf of Mexico. Sedimentation is most strongly associated with land development activities that fail to contain the soils. Land development is occurring throughout the US along coastal watersheds. Another universal problem around the US is growing volumes of storm–water runoff, which serves as the conduit for pathogen pollution of estuarine and coastal ocean waters. Again, the fraction of tidal marsh acreage remaining in Southern California may limit the effectiveness of marshes of this region to provide a water cleansing function, perhaps reflected in the high frequency of ocean beach closures relative to the rest of the US.

Tidal marshes are a hub of coastal biodiversity. North America as a whole is noteworthy for the large number of terrestrial vertebrate taxa that are endemic or largely restricted to tidal marshes. Greenberg et al. (2006) report 25 such species or subspecies including turtles, snakes, shrews, rodents, sparrows and rails. This number is larger by far than in any other continent, perhaps because only China may come close to equalling the acreage of tidal marsh in North America (Greenberg et al., 2006). Within the US, 15 of these marsh–dependent taxa of terrestrial vertebrates are found along the Atlantic and/or Gulf coasts, while 8 occur along the Pacific coast. The historic destruction of tidal marshes in Southern California and their present rarity render biodiversity preservation an especially valuable ecosystem service in this region. Furthermore, the vascular plant biodiversity in Southern California is comparatively high, as is the marine invertebrate biodiversity. The value of biodiversity in supporting ecosystem resilience is particularly great for tidal marshes (Callaway et al., 2003; Keer and Zedler, 2002) because of the tremendous challenges posed by rising sea level as climate continues to warm. There is little information to suggest that regions of the continental US differ in how tidal marsh biodiversity confers ecosystem stability and resilience, but the absence of such information may be the result of incomplete scientific investigation of this question.
The ecosystem service of carbon storage by tidal marshes varies geographically across regions of the continental US. Carbon storage appears to be significant only in the marshes of the Northeast Atlantic and in microtidal areas of the Southeast Atlantic and Gulf coasts (Table 4.3). Judging from the minimal peat accumulations elsewhere, the lack of peat-building plant assemblages in the Pacific Northwest and the warm climates that promote decomposition in Southern California and the Southeast Atlantic and Gulf coasts minimize this service in those regions. Higher rates of peat accumulation also are associated with marshes in lower salinity settings.

The suite of diverse socio-economic services provided by tidal marshes confers high value across the entire continental US. The relatively high and rapidly growing human populations of the coastal zone make green space, educational opportunities, bird and wildlife viewing, recreational fishing and enjoying natural open vistas to refresh the spirit increasingly rare but still valuable opportunities around tidal marshes. Cultural significance of coastal marshlands is recognized in places like the Pacific Northwest, where many Native American societies are still active, but similar importance may have prevailed elsewhere across the US because of the extent to which the marsh nurtures life and supports higher trophic levels, including Homo sapiens. Complete treatment of these socio-economic ecosystem services is beyond the scope of this chapter (see Thayer et al., 2005), but cultural services to humans are no less susceptible to injury from oil spills and releases of hazardous chemicals than the services of tidal marshes to nature.

4. **Standard Metrics of Injury to Marsh Services**

The response taken by US federal, state and tribal trustees of public natural resources to restore damages caused by oil spills or discharges of other hazardous chemicals into tidal marshes is broadly similar in the majority of cases, although details vary with characteristics of the pollutant, release scenario and anticipated environmental consequences. The basic framework for assessing tidal wetland injury involves first documenting the spatial extent and degree of contamination. When the pollution involves oiling (the most common situation), one or more ecosystem services of the habitat is then selected for detailed assessment as a function of degree of oiling (typically using objective categorization as heavy, moderate, light, often very light and unoiled controls). Finally, the loss of services is determined for the entire spill area based on information on exposure of organisms to oil, the chemical and physical characteristics of the oil and biological impacts observed in the field (e.g., Michel et al., 1998). From this process comes a quantitative estimate of percentage loss of marsh ecosystem services,
which is then mitigated by compensatory restoration (Fonseca et al., 2000; NOAA, 1997; Strange et al., 2002).

Whereas the basic framework of the injury assessment remains similar across oil spills, independent of apparent severity, the range of data collected will vary according to characteristics of the specific incident. Every spill into a tidal marsh triggers systematic surveys to document degree of oiling by geographic area and sub-habitat type (such as unvegetated intertidal margin vs vegetated marsh). Because tidal marshes are commonly occupied by extensive monospecific stands of characteristic vascular plants, the oiled areas can often be segregated by dominant marsh plant such as S. alterniflora and Juncus roemerianus in Atlantic coastal marshes. This process yields estimates of oiled area for every combination of sub-habitat setting, oiling intensity and dominant vascular plant. Other common data collections include numbers of dead vertebrates (fish, birds, turtles or mammals) recorded by species and location. In addition, the presence/absence and condition of dominant epibiotic invertebrates like oysters, snails, crabs and mussels will be noted and recorded by species.

As the severity of the spill increases, additional injury data are collected. Sediment samples are collected to characterize the toxicity of the oil, to determine the depth of penetration and to estimate persistence into the future. If vegetated marsh is oiled, then sampling of replicated, presumably representative quadrats documents the status of vascular plants within each combination of sub-habitat setting, oiling degree and dominant vascular plant. Stem densities and heights of the five tallest plants per quadrat are recorded, by species if more than one is represented, so as to indicate vascular plant biomass (Craft et al., 2003; Daoust and Childers, 1998; Morris and Haskin, 1990). Plant condition and appearance are also recorded, so field notes indicate the relative degree of apparent health (lack of fungus or chlorosis). Parallel sampling in unoiled reference marshes chosen to control for identical geomorphic setting is stratified by sub-habitat and plant species to allow computation of unbiased differences in biomass. Proper selection and assessment of the status of these reference marshes is critical to successful injury assessment (Morgan and Short, 2002; Neckles et al., 2002). The plant sampling is typically repeated after the first growing season, so as to provide a time-integrated indication of percentage loss of seasonal production of vascular marsh plants by oiling category and some indication of likely recovery rate, based on previous science (e.g., Callaway, 2005; Simenstad and Thom, 1996).

In the case of larger oil spills or spills that contact marshes of suspected sensitivity, sampling will also be conducted by coring to extract macro-infauna in each combination of sub-habitat stratum, oiling degree (at least the heavy, moderate and controls) and dominant vascular plant type. These samples may simply be examined for presence/absence of invertebrates or, rarely, used to provide quantitative measures of density or biomass. In rare
cases, infaunal sampling and quantitative analysis is repeated over time to indicate the recovery trajectory for secondary producers that represent prey for higher trophic levels. In larger spills, especially when sediments are known to be oiled and oil is likely to persist because of a low-energy environment, sediment toxicity testing is commonly performed and repeated over time until toxicity disappears.

Finally, where endangered or threatened species occupy the oiled marsh or where highly prized species are present, directed quantitative assessment of value and use of the oiled and control marshes by these species or groups of might be undertaken. For example, in Southern California, further assessment of marsh plant heights would need to be more extensive because shorter plants do not support nesting by the endangered light-footed clapper rail, *Rallus longiristris levipes* (Zedler, 1993) and because shorter *S. foliosa* plants are susceptible to further loss by insect damage (Boyer and Zedler, 1996). Similarly, an oil spill into a Florida salt marsh would likely require special assessments of habitat characteristics required to sustain the endangered *duke-campbelli* subspecies of meadow vole (*Microtus pennsylvanicus*). Other special assessments may be made to ensure protection and support of highly valued species on a case-by-case basis. These may include determination of abundance and effects of non-indigenous species, like invasive *Phragmites* on the mid-Atlantic or invasive *Spartina* spp. in Pacific marshes so that restoration could focus on re-establishment of the native system.

Probably the least certain methods of quantifying injury to natural resources of tidal marshes involve estimating the duration of injury and the temporal trajectory of quantitative recovery. Under the guiding federal legislation, the Oil Pollution Act of 1990, the federal, state and tribal trustees in the US must work together with the responsible parties to reach a settlement on a claim for liability that will cover both primary injury costs (cleanup and assessment costs) as well as costs of the compensatory restoration required to replace losses. The rapidly paced timetable specified by this legislation often limits longer-term monitoring to document recovery of injured habitats and resources for each new incident, so recovery rates are estimated from the best scientific information from past spills.

In many spills, including all minor incidents, the trustees may forgo all quantitative biological sampling and use only qualitative observations of vascular plant appearance to estimate the degree of injury and knowledge of past spills to project recovery trajectories. Even for larger spills, the impediments to committing funds for detailed injury assessment and recovery monitoring are sufficient to make impractical much expansion of the scope of the current assessment process by inclusion of additional metrics. Nevertheless, alternative proxies that might better characterize the net value of marsh ecosystem services deserve consideration. Furthermore, additional metrics for specific services of high value may be justified when a spill is large or when an oiled marsh is known to serve a particularly valuable
function. For example, an oil spill into a marsh occupied by one of the three federally endangered subspecies of clapper rail might elevate assessment of benthic invertebrate prey resources and perhaps sediment toxicity testing to a high priority for inclusion in the injury assessment plan.

In cases of chronic contamination by pollutants other than petroleum hydrocarbons but also including PAH (polycyclic aromatic hydrocarbons) residues from oil, vascular marsh plants may not be sensitive and would thus serve as poor or incomplete indicators of ecosystem services. Chronic heavy metal contamination of sediments or groundwater and chronic sediment contamination by organic pollutants like PCBs, DDT and other organic chemicals can diminish animal production on the marsh and render shellfish and fish unsafe for human consumption without necessarily creating a signal in the vascular plants and without acting through impacts on primary production. The metrics appropriate to such cases are ones based on toxicity and toxic effects, using both lethal and sub-lethal effects as measures of service losses, and on human health risks. Benthic infaunal cores of infaunal invertebrates may reflect reduced secondary production in some cases of chronic sediment contamination. Sediment toxicity bioassays using amphipods, especially *Rhepoxynius,* provide a useful standard with much precedent to allow comparative assessment of impacts. Long-lived suspension-feeding bivalves accumulate some contaminants like heavy metals, so that sampling their contaminant burden provides an index of intensity of contamination and also reflects the potential for transfer to higher trophic level consumers. In those cases where the tidal marsh serves as seafood habitat whose contamination leads to tainting, rendering the seafood unfit for human consumption, one component of injury from the contamination would be measured by lost opportunity for seafood harvest. Many marsh animals may have been used in previous toxicity tests from which exposure concentrations have been mapped against biological endpoints at various levels from biochemical responses like concentration of CYP proteins, growth rate, reproductive impairment and mortality. Such a range of multiple responses of multiple species can be combined in principle to provide a curve relating service loss to dose and combined to yield an indication of cumulative impacts (*Cacela et al.,* 2005). Such research on metrics for service losses from chronic contamination by animal toxicants is still developing and the indices used (e.g., *Penn and Tomasi, 2002*) do not yield immediately obvious measures against which to scale compensatory restoration. Consideration of such challenges to measuring injury and quantitatively compensating for chronic contamination injury with restoration lies largely outside the scope of this chapter. Nevertheless, the approach that develops sediment quality standards relating the percentage decline in benthic invertebrate production to contaminant concentrations and then further reduces the ecosystem services by the degree of injury from transfer of toxicity up the food chain (*MacDonald and Ingersoll, 2004*) has great promise as a standard metric for cases of chronic sediment contamination.
5. Potential Alternative Proxies for Quantifying Injury

5.1. MPB production assay

Primary production of all types of plants is the core ecosystem service of tidal marshes. Although marsh habitat is defined by its vascular plants and distinguished by their high productivity, recent research has underscored the high contribution of MPB to the total primary production of tidal marshes and to food supply for higher trophic levels (Sullivan and Currin, 2000; Zedler, 1980). Because the MPB does not require colonization by fungi and bacteria in the same fashion as vascular plant biomass to gain nutritional value (Newell and Porter, 2000), transfer of energy to consumers is inherently more efficient (Kneib, 2003). Additionally, production by the MPB enhances sediment stability and contributes to nutrient cycling (Sullivan and Currin, 2000). Biomass and production from the MPB vary within estuarine habitats, such as flats and marsh strata (Pinckney and Zingmark, 1993), but do not always scale predictably with structural metrics of vascular marsh plants. Because vascular plants in the marsh cast shade, one might expect MPB production to vary inversely with biomass of the vascular plants. Impacts on the MPB from petroleum spills (Piehler et al., 2003) and contaminated sediments (Carman et al., 2000) have been examined. As demonstrated for other primary producers such as kelp (Spies et al., 1988), effects of oil and chemical spills on MPB can range from toxic suppression to organic enrichment. Toxicity to grazers has been shown to enhance primary production from the MPB (Carman et al., 2000), and organic matter enrichment can alter nutrient cycling in tidal marshes (Capone and Bauer, 1992; Piehler et al., 1997). Because of simultaneous effects of oil on top-down and bottom-up controls on the MPB, acting on unknown but probably different timescales, additional research is required before MPB metrics could be reliably interpreted in evaluations of injury to services of tidal marshes.

5.2. Organic matter decomposition: Cotton-strip bioassay

Decomposition of organic material is among the critical roles of microorganisms in marshes (Valiela et al., 1982; reviewed by Good et al., 1982). Tidal marshes maintain their elevation relative to rising sea levels by trapping inorganic particles and accumulating organic matter from primary production (Reed, 2000). Microbial decomposition affects rates of accretion of peat and other organic material and catalyses remineralization of organic matter, which forms an important component of the pool of available nutrients (Rozema et al., 2000). Refinements to the detrital-dominated food web...
model described by Teal (1962) have also underscored the importance of the microbial community in facilitating energy flow through the detrital pathway (Newell and Porter, 2000).

Recent work has examined the potential impacts of oil spills on marsh organic matter decomposition (Mendelssohn and Slocum, 2004). Because many petroleum products are both potentially toxic and also a source of organic matter for microbial populations, the effects of spills on organic matter decomposition in marshes may be confounded and difficult to predict. If a spill were toxic to the native microbial community, decomposition of organic material in the sediments would likely be reduced, potentially enhancing rates of organic matter accretion and reducing the utility of vascular plant production to higher trophic levels. However, decreased organic matter decomposition could also lead to decreased supplies of remineralized nutrients, and result in a net decrease in primary productivity and thus organic matter production. If a spill were not toxic to the sediment microbial community, the pulse of labile organic matter could accelerate decomposition of organic matter in the sediments.

Proxies for organic matter decomposition in marshes can range from measures of diversity of specific micro-organisms (Kerkhof and Scala, 2000) to measures of rates of particular degradation processes. Common approaches to assess rates of organic matter decomposition in marshes include litter bag deployment (Valiela et al., 1985) and in situ incubation of standardized materials such as cotton strips (Mendelssohn and Slocum, 2004). Litter bag deployments measure decomposition as a weight loss per unit time (Verhoef, 1995) and have the advantage of using native materials. Because of the difficulty in obtaining uniform litter, however, native materials may not be preferred for an assay comparing rates through time or among marshes.

The cotton-strip bioassay (Latter and Howson, 1977) provides a direct and unambiguous measurement of cellulose decomposition that can be used as a relative measure of overall organic matter decomposition (Harrison et al., 1988; Mendelssohn et al., 1999). Loss of tensile strength of the cellulose fibres is measured following incubation using a tensometre and is expressed as cotton tensile strength loss in units of percent loss per day (Mendelssohn and Slocum, 2004). Because cellulose constitutes a large fraction of the organic material derived from marsh plants, the cotton-strip bioassay is a reasonable proxy for organic matter decomposition in marshes. The method is amendable to cross-site comparisons and seasonal evaluations. Because it uses standardized and relatively simple procedures, its application does not require significant technical training. Weaknesses of the cotton-strip bioassay include its focus on a single component of marsh organic matter decomposition, reliance on a surrogate substrate and dependence on some amount of specialized equipment for tensile strength measurements. These limitations along with the present uncertainties...
about the likely short- and long-term consequences of oil and other contaminants on microbial processes in marshes make the cotton-strip bioassay an inappropriate single metric for marsh function and services.

In addition to indexing rates of microbial decomposition in soils of tidal marshes, other biogeochemical processes could be examined to provide insight into marsh ecosystem services. One parameter of particular importance to production of *Spartina* and other vascular plants of salt marsh is pore-water hydrogen sulphide. Water flushing of marsh soils has a strong influence on subsurface sulphide concentrations. The enhanced flushing of marsh soils near the channel edges as compared to in the marsh interiors and the influence on sulphide concentrations may play a dominant role in creating the high form—low form zonation in *Spartina* (Mendelssohn and Morris, 2000). Sulphide is important to *Spartina* production and thus to many other biogeochemical processes because at concentrations above 1 mM, soluble sulphide is toxic to the plants, causing greatly suppressed growth (Mendelssohn and Morris, 2000). However, at lower concentrations, dissolved sulphide stimulates *Spartina* growth (Morris et al., 1996). Thus, like many other chemicals and biogeochemical indicators, soluble sulphide is actively engaged in complex interactions in soils of tidal marshes and does not scale in any monotonic fashion with productivity of vascular plants. Consequently, sulphide concentrations do not appear to provide a viable alternative metric for ecosystem services, despite its importance in biogeochemical interactions related to productivity.

5.3. Tidal creek geomorphology: Tidal prism

Estimating ‘tidal marsh prism’ has been suggested as one metric of function for tidal marsh restoration projects involving bathymetric and geomorphological modification of shorelines. Tidal prism is defined as the ‘volume of water contained between two defined tidal datums’ (Coats et al., 1995). Perhaps the most appropriate elevations that might be used in this metric are MHHW (mean higher high water, also known as mean high water spring) and MLLW (mean lower low water, or mean low water spring). The resulting (diurnal) tidal prism represents the maximum volume of water that is exchanged between the marsh and the adjacent estuary during a single tidal cycle. This metric is important because tidal water exchange carries nutrients, dissolved and particulate organics and invertebrate larvae, as well as providing the opportunity and pathway for fish and mobile crustaceans to move between the marsh and subtidal habitats. Water exchange thereby affects production at all trophic levels and access to marsh habitat that affects its use.

Although this metric of tidal prism can guide restoration of marshes that involve engineering and shoreline modification activities to distribute water through channel networks and to sustain channel depths and widths
(Coats et al., 1995; Williams et al., 2002), the marsh geomorphology and tidal prism would generally not be expected to be modified by an oil spill or a release of hazardous substances. The lack of geomorphological impacts from a spill may be especially true in the absence of large astronomic tides, as along the Gulf coast. Only in instances where the spill response included closing channels to curb oil spread, ditching to promote cleanup or possibly excavation to remove contaminated sediments would geomorphology be altered. Consequently, tidal prism would not be an adequate general proxy for injury to marsh ecosystem services. Even in guiding massive tidal marsh creation projects, tidal prism should be elaborated by more complete assessment of other components of the drainage system, specifically including the total channel length and the numbers and lengths of channels of each order to reproduce a dendritic system of greatest functional value (Coats et al., 1995).

Quantifying the length or area of marsh edge versus interior has value because proximity and access to incoming tidal flows and fluxes of materials can influence production of vascular plants, benthic microalgae and shallow-burrowing invertebrates (Whaley and Minello, 2002) and use by mobile predatory fishes and crustaceans (Minello and Rozas, 2002). However, the relationship between tidal prism and tidal channel system order (Coats et al., 1995) can promote different functional associations of fishes accessing the marsh. For instance, the timing and penetration of different fish species or life history types, or even prey availability and diet composition, can vary across a spectrum of channel system order (Visintainer et al., 2006). Furthermore, the function of marshes as nursery habitats for fishes and mobile crustaceans may ultimately decrease if there are more high-order entrance channels because these larger channels will not drain during most tidal cycles and can provide refuge for larger fishes that will prey on those smaller fishes and crustaceans forced to the margins of the marsh at low tide.

Because ecosystem services of tidal marshes typically differ between marsh edges and interiors (e.g., Minello and Rozas, 2002; Peterson and Turner, 1994; Simenstad et al., 2000), injury assessment is best stratified by these two regions of the marsh surface. The actual boundaries between edge and interior might be best determined by observation on site, after which injury assessment can be made separately within these two zones. Such a stratification procedure would reduce unexplained error variance in virtually any metric likely to be applied, thereby better enabling injury to be detected and quantified. Moreover, failure to account for these marsh strata separately could lead to problems in compensating for the injury if the ecosystem value of any restored marsh is estimated by area alone without accounting for proportions of the more productive edge habitat. This change in injury assessment would require modest changes in accounting and record-keeping and would not be expected to add substantially to time and costs of injury assessment.
5.4. Summing injuries across multiple consumer trophic levels

Some pollutant releases, especially those involving dissolved, emulsified or floating pollutants, never encounter a shoreline or bottom habitat. In these cases, injury occurs to animals (and perhaps also plants) at one or more trophic levels, not to a shoreline or bottom habitat. If such injury involves a highly valued species, its losses are typically quantified at the population level and restoration projects are scaled according to expected contributions to the population (e.g., Donlan et al., 2003). This approach works best for animals that are endangered or threatened and covered by the Endangered Species Act, those that fall under the Endangered Species Act of 1973; Marine Mammal Protection Act of 1972 and those that are commercially important species for which fisheries management plans exist. For such species, preexisting management or recovery plans are in place to guide restoration. Yet, the vast majority of animals and plants that are present in a tidal marsh or any other habitat and that can be injured by a pollutant release are not the target of such population-level enhancement plans. In the absence of observable injury to a shoreline or bottom habitat, spill-related mortality for the injured species, which can include tidal marsh inhabitants, is typically quantified by modelling of exposure and using known taxon-specific sensitivities to estimate mortalities and lost production by groups of consumer taxa. Occasionally, mortality rates are confirmed by collections of dead animals during and after the spill. Combining injuries of several species or species groups of animals requires a method to sum across species and trophic levels because compensatory mitigation will be established by restoration of a productive habitat at the scale computed to match the total injury to this suite of species.

As an example, the North Cape oil spill off Point Judith in Rhode Island involved vigorous mixing of oil into the water column, where component PAHs caused acute mortality of benthic invertebrates and fishes of the coastal ocean, shellfish and other invertebrates in coastal salt ponds, and death of many seabirds after external oiling (French McCay and Rowe, 2003). Lobsters, fishable shellfish, seabirds and a federally listed shorebird were the target of species-specific restoration actions at the population level (e.g., the piping plover: Donlan et al., 2003), whereas the injury to benthic invertebrates and birds in salt ponds was quantified by estimating the total loss of production by the group of organisms (French McCay and Rowe, 2003). The total injury to this suite of affected species was then computed by assigning a trophic level to each taxon and applying energetic efficiencies to convert all losses back to the amount of primary production of salt marsh habitat required to produce that lost biomass (Kneib, 2003). Then the total injury across all trophic levels was estimated by summing the equivalent marsh production (combining both vascular plant and MPB) required to replace the losses (French McCay and Rowe, 2003).
Details of computing the injuries and developing compensatory restoration differ between consumers that are treated at a population level and those pooled by trophic level. For animals of sufficient importance to deserve attention at the population level, injury is computed as the numbers of individuals or the biomass killed (or lost by sub-lethal effects on growth) plus the numbers of future individuals or biomass production foregone. For example, all piping plovers killed by the North Cape oil spill were assumed to have reached maximum body size because of the precocial nature of their (and most birds') growth and development (Donlan et al., 2003). Thus, the numbers of chicks absent from the next generation because of deaths of breeding birds were computed and added to the direct mortality from oiling to reach a total population-level injury requiring restoration. This assumption that the abundance and production of future generations is dependent on current numbers of breeders is also common to population dynamics of many fishes (Myers and Barrowman, 1996). However, it conflicts with another even more pervasive assumption that habitat limits abundances of many consumer species, including many threatened and endangered species. Because of this concern about limited nesting habitat for piping plovers, the component of injury contributed by production foregone after the North Cape spill was limited to just one subsequent generation (Donlan et al., 2003). Population-level estimation of injury is facilitated by the existence of species recovery plans for threatened and endangered species or species management plans for exploited species, in which much careful scientific assessment of population limitation has already been done. However, one must carefully examine the assumptions in these plans of whether limited reproduction, limited critical habitat or some other factors prevent population increase.

For injuries assessed by lost production at the trophic level rather than at the population level, production is assumed to be driven by bottom-up processes. In other words, to achieve more production of benthic invertebrates as a group (of primary consumers), one needs only to provide more food resources, and so on up the food chain. While there is a substantial body of evidence supporting this assumption for shallow estuarine ecosystems (e.g., Bishop et al., 2006), increasing primary production does not always predictably translate into enhanced secondary production. For example, in deeper regions of highly eutrophied estuaries, increasing microalgal production fails to transfer to higher production at consumer trophic levels because of induction of oxygen depletion, which diverts this primary production into microbial loops instead of consumer biomass (Baird et al., 2004). Suitable habitat may limit production of many species and trophic levels.

For these consumer species that are grouped by trophic level to assess injury and then scale mitigation, total injury is typically computed as the biomass killed plus the biomass production foregone because subsequent growth of those individuals is precluded by untimely death (French McCay
Production foregone is computed by applying a demographic model of age-specific mortality and age-specific growth, available for many species of fish and a few important invertebrates, but largely lacking for species at lower trophic levels. The application of this bottom-up forcing assumption to salt marsh ecosystems becomes more uncertain as trophic level increases, where habitat requirements and other limitations need careful consideration. To total the injuries across all trophic levels, the primary production equivalents required to grow the animal biomass killed and foregone is simply summed, yielding the salt marsh primary production required to replace what is lost. Such summation is justified by recognition that the necessary primary production required to produce each consumer killed and its production foregone must be included. This computation also needs to include well-founded estimates of the duration of injury, which often possess high uncertainty. Information about persistence of contaminants, including petroleum hydrocarbons, in biologically available reservoirs and the importance of chronic contamination to reproduction and survival of many fish, birds and mammals are relatively recent (e.g., Peterson et al., 2003) and not included in commonly applied injury models. However, the potential for long-term contamination of fine sediments in low-energy environments of salt marshes is well documented (Sanders et al., 1978; Teal and Howarth, 1984). Compensatory restoration incorporates additional complexity to include discounting for time lags between injury and replacement and to model the expected trajectory of approach of restored habitat towards full functionality (Simenstad and Thom, 1996).

5.5. Below-ground biomass of vascular plants

Primary production of vascular plant biomass has direct and indirect impacts on the structure and function of marshes. Significant proportions of total vascular plant biomass in marshes are found below ground (Good et al., 1982). Seasonal variations in the proportion of biomass found below ground have been identified and generally are related to the translocation of resources below ground during senescence of above-ground vegetation (Anderson et al., 1997; Valiela et al., 1976). Below-ground biomass accumulation has been identified as an important control of marsh elevation (Turner et al., 2004), a source of dissolved organic matter source in marshes (Howes et al., 1985) and inversely correlated with the distribution of some benthic organisms (Capehart and Hackney, 1989). The relationships between above- and below-ground biomass have been modelled in Delaware (Gross et al., 1991), and that model was applied to predict below-ground biomass at other sites on the US Atlantic coast. Below-ground biomass has also been used as a metric to assess the function of constructed marshes (Boyer et al., 2000; Broome et al., 1986; Edwards and Mills, 2005). Marsh impairment was also shown to have significant effects
on below-ground but not on above-ground biomass in Louisiana marshes (Turner et al., 2004).

Below-ground biomass is a potentially meaningful proxy for marsh injury assessment because of its direct links to marsh function, including carbon storage as well as productivity and habitat provision. Determining whether a spill has affected the marsh primary production over longer timescales may be better assessed using measures of below-ground than the more ephemeral above-ground biomass. However, measuring below-ground biomass is labour-intensive, destructive of habitat and potentially problematic. Good et al. (1982) identified issues with sampling methodologies and others have observed similar problems related to high levels of variability (Gross et al., 1991). Nevertheless, with more basic research to standardize methods, better control variance, and relate below-ground biomass to subsequent dynamics of plant production, this metric could be developed to replace or at least augment above-ground measures. The intent of using a below-ground metric would be to provide better insight into resiliency and recovery than is now provided by above-ground measures (e.g., Simenstad et al., 2005).

6. Discussion

We evaluated the present widely applied metric (leaf area index of vascular plants) plus five alternative proxies for marsh ecosystem services that may have application to assessing injury from oil or other chemicals that affect ecosystem services through acting on primary producers: productivity of MPB, cotton-strip bioassays of biogeochemical decomposition rates, tidal prism, summing injuries across multiple consumer trophic levels and quantifying below-ground biomass of vascular plants. Each of these measures has limitations, such as an incomplete conceptual and empirical understanding of their behaviour, limited numbers of correlated ecosystem services, necessity for destructive sampling and high variability, which prevent them from immediate use as a substitute for present injury metrics based on vascular plant standing stock biomass (Table 4.4). On the other hand, each has justification and, if applied in addition to the standard metric, could more completely characterize tidal marsh function. Clearly, the contribution of MPB to the total production of foods consumed by primary consumers in the marsh and in nearby habitats is significant (Kwak and Zedler, 1997; Sullivan and Currin, 2000), and is now poorly incorporated into assessments of tidal marsh function. Unfortunately, the conceptual basis for interpretation of MPB production is incomplete and this index does not necessarily vary directly with the most important ecosystem services (Table 4.4). Most of the vascular plant biomass produced in a tidal marsh passes first through microbial intermediaries, fungi and bacteria, before being consumed by
Table 4.4  Potential metrics (proxies) for tidal marsh ecosystem services

<table>
<thead>
<tr>
<th>Metric</th>
<th>Positive aspects</th>
<th>Negative aspects</th>
<th>Overall assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microphytobenthos production assay</td>
<td>Microalgae contribute directly to primary consumers.</td>
<td>Production may not scale directly to marsh ecosystem services or even to energetic transfers because of top-down control by grazers.</td>
<td>Needs much additional testing to be reliable.</td>
</tr>
<tr>
<td>Cotton-strip bioassay and other biogeochemical measures like sulphide</td>
<td>Organic decomposition is vital to marsh production processes and materials fluxes. Sulphide is known to suppress <em>Spartina</em> production above 1 mM. Cotton-strip method standardized and relatively simple to use.</td>
<td>Mixed effects of oil as toxicant and organic enrichment complicate interpretation of organic decomposition index. Sulphide affected by numerous variables and difficult to measure without exposing to oxidation.</td>
<td>May have utility in combination with other assays.</td>
</tr>
<tr>
<td>Tidal creek geomorphology: tidal prisms</td>
<td>Amount of water exchange between the marsh and estuary affects material transfer and facilitates biotic movement of small fish, crustaceans and larvae.</td>
<td>This measure is part of engineering marsh hydrology—important to function but not an index of biological or biogeochemical services.</td>
<td>Very useful in engineering marsh restorations, but not an index of ecosystem services per se.</td>
</tr>
<tr>
<td>Summing production across multiple consumer trophic levels</td>
<td>Relates to the invertebrates, fish and birds of most concern to the public. Involves a suite of organisms</td>
<td>Can be costly and time-consuming to compute. Method of combining across multiple trophic levels makes untested assumptions about</td>
<td>Useful when pollutant does not ground in the marsh but affects animals in the water column; this is not typical. Augments plant</td>
</tr>
</tbody>
</table>
Table 4.4  (continued)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Positive aspects</th>
<th>Negative aspects</th>
<th>Overall assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below-ground biomass of vascular plants</td>
<td>and thus is not reliant on a single species.</td>
<td>top-down vs bottom-up controls.</td>
<td>metric in cases with numerous dead animals.</td>
</tr>
<tr>
<td></td>
<td>Below-ground biomass is considered less ephemeral and likely an indicator of future productivity and thus may serve better than above-ground biomass. This component better reflects carbon sequestration.</td>
<td>Sampling is necessarily destructive and more costly. Unclear if below-ground biomass more accurately predicts future production.</td>
<td>A promising metric after additional research establishes relationships to above-ground processes and indicator value.</td>
</tr>
<tr>
<td>Stem densities and heights of plants (as an index of vascular plant biomass) by species and marsh zone</td>
<td>Traditional measure with substantial database available. Readily measured without need for specialized instrumentation or training. Relates not only to production but also to habitat structure, shoreline protection and other ecosystems services.</td>
<td>Is not sensitive to all contaminants so inapplicable to cases of chronic sediment contamination by organic toxicants. Is but one metric and cannot reflect all ecosystem services.</td>
<td>Still the best single choice for oil spills (but not chronic contamination) because of low cost to apply and relationship to many ecosystem services but must be augmented with survey of direct toxic affects on vertebrates and other animals of high value.</td>
</tr>
</tbody>
</table>
primary consumers (Kneib, 2003; Kreeger and Newell, 2000), rendering the inclusion of measures of microbial decomposition rates highly relevant to marsh trophic functions as well as to biogeochemical cycling processes. Nevertheless, even the most completely developed method, the cottonstrip bioassay, does not permit confident inferences about the full suite of marsh functionality (Table 4.4). There is a standardized methodology available and there is only one tricky part of its application, the measure of tensile strength. The hydrology of tidal marshes fundamentally affects their productivity and their accessibility to mobile consumers, making measures like tidal prism (Williams et al., 2002) a useful indicator of tidal marsh hydrology, but not an adequate indicator of ecosystem services, especially given that most contaminant spills leave tidal prism unaffected (Table 4.4). Summing injuries across multiple affected animals is a conceptually acceptable approach, but because of the high level of effort required, this metric is likely of use only in special situations, especially where dissolved or emulsified contaminants kill many animals in addition to or instead of injuring vascular plants (Table 4.4). Sampling dead animals, projecting those collected using models to estimate how many actually were killed and summing them across all species, is labourious and costly, therefore justified only when spill injuries are likely to be large. The below-ground portion of vascular plants on tidal marshes represents a large fraction of total vascular plant production, one not included in examinations of visible plant structure above-ground, and probably predicts resiliency and duration of injury better than above-ground measures. Augmenting injury assessments with below-ground measurements has promise and could be reliably developed with some additional research on methods and relation to other marsh ecosystem services. Unfortunately, the sampling is destructive and time-consuming, and replication may need to be high to overcome high variance and lack of firm knowledge about covariates on which stratification might ultimately be done to reduce unexplained error variance (Table 4.4).

Despite the value of these metrics that relate directly to important aspects of marsh functionality, none is as readily measured or, when employed alone, as likely to provide as good a proxy for the trophic productivity/habitat provision service of the marsh or for the full suite of marsh ecosystem services as currently used measures of above-ground vegetation. The present proxy for productivity, combining stem density and height of vascular marsh plants (Craft et al., 2003; Daoust and Childers, 1998; Morris and Haskin, 1990), indicates both primary production and habitat structure, with a large empirical database from which to infer recovery rates. Use of this metric becomes much more effective, however, when it is applied separately to the marsh edge and interior because of intrinsic differences in value of services of those two strata. Using above-ground vegetation metrics to quantify injury from oil and other spills that damage vascular plants also has the advantage that this measure can be applied to gauge the benefits of marsh restoration, thereby
applying a common metric for ecosystem services to produce compensatory restoration without the added uncertainty of conversions between metrics. Of the five alternative metrics that we consider, only below-ground biomass of marsh vegetation has the same potential for use in both injury assessment and value of restorations. Unfortunately, the destructive sampling required to excavate roots and rhizomes implies that each sampling of the restored marsh would carry a cost of removing vegetation and thus subtracting value. MPB is at least as productive on tidal flats as in tidal marshes, so this metric would not serve well to gauge value of salt marsh restoration. Various biogeochemical measures like the cotton-strip bioassay have potential application to quantifying the functional value of marsh restorations, but a lack of a comprehensive database relating this measure to other ecosystem services renders risky use of this index in place of a measure of vascular plant biomass. Tidal prism is an important engineering consideration in designing marsh restorations but is largely unaffected by the status of the biology or chemistry of the marsh ecosystem and therefore inapplicable as a measure of ecosystem services in restorations. Finally, summing the production of marsh animals at multiple consumer trophic levels would provide a direct measure of one of the most important ecosystem services, but such an effort is grossly impractical because of the resources required for sampling unless a spill causes obvious widespread mortality of valued animals at higher trophic levels justifying a costly injury assessment.

We concur that stem density and height of the dominant vascular plants is the best single proxy for marsh ecosystem services, but this metric is not perfect, universally applicable, or always sufficient. In particular, our consideration of tidal prism as an alternative metric led to a recognition that the proximity to a tidal channel typically influences vascular plant (Culberson, 2001; Sanderson et al., 2000) and benthic invertebrate (Whaley and Minello, 2002) productivity, marsh plant height (and thus structure) and accessibility to mobile fishes and crustaceans (Able et al., 2000, 2008; Minello and Rozas, 2002; Minello et al., 2003; Simenstad and Cordell, 2000). Consequently, with minimal additional record keeping, vascular plant injury metrics could be stratified by edge and interior strata to improve estimates of injury and provide more confidence that restoration is truly compensatory. Areas of restored marsh surface distant from a tidal distributary would not be expected to provide the same level of ecosystem services as enhancing edge habitat. In addition to stratifying injury assessment and restoration scaling, inclusion of limited assessment of differences in below-ground vascular plant biomass should be a future goal. Some additional research is needed to develop the reliability of this metric, but its potential for better predicting resiliency and future recovery makes a compelling case for its inclusion in future assessments.

In spills that produce obvious sediment contamination, or mortality of benthic invertebrates, nekton of the marsh and/or birds, current protocols
dictate expansion of injury assessment to include these additional trophic levels (Table 4.4). Dead fish and crustaceans are counted and recorded, as are dead epibiotas, whereas the sediment cores that are commonly taken to observe the presence and condition of infaunal macro-invertebrates are subjected to formal quantification if mortality appeared substantial. Under such circumstances, when injuries are measured at multiple consumer trophic levels, scaling injury to the size of a restoration project to achieve compensation is a challenge. We endorse the approach of French McCay and Rowe (2003) that involves using risk assessment and exposure modeling to estimate mortalities by taxonomic group. These estimates are then used in summing losses across all consumer trophic levels after conversion to equivalents at a single trophic level based on the amount of primary production required to produce the biomass lost at each injured higher trophic level. This metric will be applied most frequently when the contaminant is dissolved or in emulsion and does not coat and detectably injure vascular plants of the marsh. Under other situations where mortality is evident across consumer trophic levels and where oil or another toxic contaminant penetrates to depth into marsh soils, injury assessments should also include toxicity bioassays, such as sediment toxicity testing with amphipods, to aid in projecting the temporal duration of impacts.

One questionable assumption underlying the use of vascular plant production as a proxy for all ecosystem services is that ecosystem services scale in a linear fashion in a tidal marsh. Where oil or contaminant spills cause injury to an unusually valuable ecosystem service, the injury assessment should be, and often is, expanded beyond basic vascular plant metrics to include another metric that more directly evaluates the level of that service. Where the injury involves a US federally or state-listed species, or a marine mammal, such an expanded scope of injury assessment would routinely be employed anyway, but recognition of a particularly valuable resource or service in an injured tidal marsh justifies additional explicit evaluation even in the absence of listed species. Marshes inhabited by threatened or endangered species may also require more elaborate structural metrics to complete the injury quantification. For example, the presence of the listed light-footed clapper rail, or California rail, indicates the need to quantify the height distribution of S. foliosa in oiled California marshes (Zedler, 1993). Our scientific understanding of how habitat structure influences its use by birds is more complete simply because of their visibility, especially relative to fishes and other nektonic species. By extension, fish and mobile crustaceans doubtless are affected by any structural injury to the marsh, such that marsh use by nekton should also be quantified in injured and reference marshes where fisheries production value is high, such as along the Gulf coast.

Using only metrics that relate to biological productivity and plant architecture to assess injury and match it against proposed compensatory restoration might appear to ignore seven of the eight generic ecosystem
services that we attribute to a healthy tidal marsh (Table 4.1). However, many of these other ecosystem services are likely to be directly and positively related to productivity and height of the vascular plants of the marsh. For example, the flood and storm mitigation, the shoreline stabilization, the water quality treatment, much of the faunal biodiversity maintenance, the carbon storage and many socio-economic services, such as providing aesthetic green space, ecotourism opportunity and natural heritage value, and educational settings, will usually be enhanced by enhancing the structure and abundance of the signatory vascular plants of the tidal marsh. Despite the importance of alternative processes facilitated by a healthy marsh, none of the possible alternative metrics of marsh condition that we considered (production of MPB, microbial decomposition rate, tidal prism, summing injuries across multiple consumer trophic levels, below-ground biomass) would necessarily provide a viable alternative proxy for even the majority of ecosystem services. With additional research, below-ground biomass holds promising potential to augment or possibly even substitute for above-ground measures as a proxy for the suite of marsh ecosystem services, but the additional costs and destructive nature of below-ground sampling may outweigh the enhanced capability to predict resilience and thus prevent using below-ground biomass as a substitute metric.

The linkage between measures of tidal marsh vegetation and ecosystem services is assumed but rarely tested. Some functions are obvious; for example, vegetation provides shade, substrate, refuge and food for a wide variety of animals, especially those of commercial value (Boesch and Turner, 1984). Also, shorelines are stabilized where vegetation holds sediment in place (Turner, 1997) or traps inflowing sediment (Ward et al., 2003). Yet, it is not always clear which fundamental structural attribute (plant cover, plant species richness, plant height or all three) is the best proxy for each ecosystem function. Additionally, other services are less clearly linked to structural components of vegetation. For example, denitrification requires a source of organic matter, but it is not clear whether denitrification rates depend on vascular plant biomass (Lilleboe et al., 1999), benthic microalgae (Hamersley and Howes, 2003), plant species richness or some other structural attribute.

Vascular plant primary productivity can be readily estimated non-destructively using various computational and sampling methods (Craft et al., 2003; Daoust and Childers, 1998; Morris and Haskin, 1990) based on the density and height of vegetation and has been done repeatedly when vegetation consists of near monotypes of grass, like Spartina spp. (Bergen et al., 2000; Dai and Wiegert, 1996; Penn and Tomasi, 2002; Thursby et al., 2002). However, this method is less effective in more diverse vegetation (such as in tidal freshwater marshes) because the diversity of plant forms, involving sprawling or trailing species, like Sarcocornia and Batis, complicates density and height measures (O’Brien and Zedler, 2006). This implies a need to modify injury assessments in more
structurally and botanically rich marshes. Alternative metrics of structure beyond simple stem density and maximum height will be needed when grass monocultures do not dominate the oiled marsh. In many west coast marshes, invasive *Spartina* spp. represent problems by crowding out native vegetation and creating dense vegetational barriers inhibiting use by many native marsh animals, including some threatened and endangered species. Clearly, blind application of vegetational proxies for ecosystem services cannot be applied without consideration of the species of vascular plant. In addition, simple metrics of species richness and diversity should be added to injury assessment in botanically rich marshes because of their importance to marsh function.

Estimating species cover is one rapidly achieved alternative method of visually assessing plant abundance and is often used by itself (Grismer et al., 2004; Hester and Mendelssohn, 2000; Traut, 2005) or in conjunction with another abundance measure (Morgan and Short, 2002; Penn and Tomasi, 2002; Roman et al., 2002) to monitor restoration progress. Cover estimates may be appropriate metrics to apply to estimate injury of botanically diverse marshes, although they would need to be augmented by measures of plant architecture and layering to describe aspects of vertical habitat value. The cover class method, often based on Braun-Blanquet (1932), has been criticized as being too subjective (Guo and Rundel, 1997), but plot scale discrepancies among field crews are negligible at the site scale and frequent calibration of field crews could improve repeatability (Kercher et al., 2003). The line-intercept method is more objective, but it overestimates cover compared with the cover class method (Kercher et al., 2003).

In geographic regions where marshes possess a single dominant vascular plant, structural proxies for biomass and productivity, such as stem counts and heights for *Spartina*, may serve adequately to indicate levels of ecosystem services. However, in more diverse marshes, species richness plays a role that would be overlooked using structural measures alone. In tests of the role of plant species diversity and marsh function, Keer and Zedler (2002) and Callaway et al. (2003) demonstrated that three- and six-species assemblages differed from one-species assemblages in several attributes: root, shoot and total biomass, soil surface nitrogen concentration, plant tissue nitrogen concentration and canopy layering. Greater species richness can provide stability (Bertness and Leonard, 1997) and diversity at higher trophic levels (spiders: Traut, 2005). Species composition is easily recorded along with abundance measures and can then be used to compute metrics like species richness, Shannon diversity (H'), evenness and community similarity to compare to reference marshes. In addition to these methods, comparisons of dominant species and their forms of dominance using a new species dominance index (Frieswyk, 2005; Frieswyk et al., 2008) have proven useful in quantifying vegetation change and function in California salt marshes (Zedler and West, 2008).
The identity and number of species contributing to productivity are also important to ecosystem services. This is true of tidal marshes composed of differing mixes of native plant species, but it is particularly relevant where non-indigenous species are involved. Invasive species, like *P. australis* along the Atlantic coast, can decrease plant, insect and bird diversity (Chambers *et al.*, 1999); infaunal and epifaunal abundance and diversity (Angradi *et al.*, 2001; Robertson and Weis, 2005) and fish abundance, species composition and nektonic production (Able and Hagan, 2000, 2003; Able *et al.*, 2003). Invasive *Phragmites* represents a particular challenge in injury estimation and restoration planning because it affects some marsh ecosystem services positively and others negatively (Blossey and McCauley, 2000; Fell *et al.*, 1998; Wainright *et al.*, 2000). Its dense stands do a better job of inducing sedimentation, stabilizing shorelines and treating storm-water runoff than alternative native grasses (Rooth and Stevenson, 2000; Rooth and Windham, 2000), are used by transient fishes and crustaceans to about the same degree (Able and Hagan, 2000), but represent an almost impenetrable thicket that excludes much bird access and use and negatively influences the small individuals of the ecologically important mummichog, *Fundulus heteroclitus*. Non-native *Spartina* invasion of San Francisco Bay poses a similar challenge to management. It grows at lower elevations than native *S. foliosa*, thereby providing more structure to the shoreline marsh, but this extension of vascular plants has negative effects on shorebird and sparrow feeding by displacing mudflats. Injury assessments and restoration plans for tidal marshes should pay special attention to introduced species in their definitions of value. Large-scale perturbations of natural ecosystems tend to favour and promote successful invasion and spread on non-indigenous species, so trustees of natural resources should assess this potential for longer-term injury to tidal marshes and consider eliminating undesirable invasive species as part of compensatory restoration projects.

For many apparently minor spill incidents, no quantification of even the vascular plant injury is conducted in the US by government trustees of natural resources. Injury is instead estimated as the proportion of the marsh ecosystem services lost, based on a subjective assessment of marsh vascular plant condition and persistence and chemical toxicity of the oil or other contaminant. This assessment is made by experts who are knowledgeable about the previously quantified effects of similar spills and the documented recovery rates of marsh function. This process resembles the use of expert opinion in the construction of prior expectations in preparation for Bayesian modelling. Consequently, there exists a scientific basis to support application of this low-cost approach to injury assessment. Probably the largest source of uncertainty in adopting this approach, and even in cases where the vascular plant and perhaps other metrics are quantified, lies in estimating the duration of injuries and the trajectory of natural recovery processes (Callaway, 2005; Simenstad and Thom, 1996). Long-term impacts of oil contamination have
been documented in tidal marsh (Teal and Howarth, 1984) and other (Short et al., 2006) sediments where oil can be sequestered under conditions of limited physical, chemical and biotic degradation. Despite knowledge of marsh sequestering of oil and documentation of resulting long-lasting biotic injuries, we do not yet have the scientific capability to predict these long-term biological effects with confidence (Peterson et al., 2003). Further research on long-term consequences of oiling and otherwise injuring tidal marshes, factors affecting their recovery trajectories and promising metrics of resilience, like below-ground biomass of vascular plants, is urgently needed to support these expert predictions of recovery rates of marsh services. These predictions can greatly influence the scope of compensatory mitigation that is required.

7. Conclusions

1. Tidal marshes are valued for a suite of ecosystem services, including productivity, trophic transfer and habitat functions; flood/storm mitigation; shoreline stabilization; hydrologic processing; water quality maintenance; biodiversity preservation; carbon storage and socio-economic services to humans.

2. For most tidal marshes dominated by native monospecific stands of grasses, the metric formed by stem density and plant height by dominant species is the most compelling basis for injury assessment because it is non-destructive, simple to assess and well understood through past application. This metric forms the best single proxy for the full suite of marsh ecosystem services. This and other potential metrics should be assessed not only in injured marshes but also compared with nearby reference marshes of similar geomorphology to provide a rigorous baseline condition. For spills that contaminate the sediments sufficiently and for cases of chronic sediment contamination, sediment toxicity testing must be conducted and toxic effects estimated from taxon-specific data sets on sediment toxicity.

3. Because of typical zonation in tidal marshes with distance from channels and corresponding variation in level of ecosystem services, even within a monospecific stand, injury assessment and restoration of tidal marshes could be improved by stratifying sampling by zone (marsh edge vs interior; low vs high marsh), thereby also providing more confidence that restoration is made truly compensatory.

4. Despite offering insight into specific functions of importance, production of MPB, cotton-strip assays of microbial degradation, tidal prism, summing production across multiple consumer trophic levels and below-ground biomass do not now represent viable single proxies of all ecosystem services of tidal marshes to replace the widely used stem
count/plant height metric. Nevertheless, assessing below-ground biomass of vascular plants better indicates resiliency and recovery potential, such that augmenting injury assessment with this additional metric has merit.

5. In tidal marshes known for specific ecosystem services of high value, additional metrics designed to quantify those particular high-value services are important. This includes not only the status and habitat needs of species listed as threatened or endangered but also such services as provision of invertebrate prey and small fishes for valued consumer species like some shorebirds or fishes.

6. In tidal marshes like those of the US west coast not dominated by single stands of grasses but including abundant sprawling or trailing vascular vegetation, plant height is not as meaningful a proxy for production and habitat structure. Plant cover and other proxies for production and habitat structure may need to be employed. For some avian species, plant structural layering and height distributions represent proxies for habitat value.

7. In botanically diverse marshes, indices of vascular plant richness, diversity and compositional similarity to reference marshes are important metrics of resilience and operation of many critical functions.

8. Non-indigenous species are substantially modifying some tidal marshes across the US and elsewhere, posing a special challenge to injury assessment and restoration. Even highly invasive species can enhance some ecosystem services and degrade others. Because the intense perturbation of an oil or chemical spill may open opportunities for invasion and spread of non-indigenous species and because restoration may offer opportunities to respond to past invasions, injury assessments and restoration plans should explicitly consider the role of non-indigenous species in the delivery of ecosystem services of tidal marshes.

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