Global Loss of Coastal Habitats
Rates, Causes and Consequences

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Offprint of Chapter

4. GLOBAL LOSSES OF MANGROVES AND SALT MARSHES

by

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4.1. INTRODUCTION

THE WORLD'S ENVIRONMENTS are undergoing remarkable changes, and the rate of change appears to be accelerating. Perhaps we are simply more aware of such alterations, but the reality is that if we measure almost any environmental quantity today, change is taking place, often at surprising rates. There is little doubt as to the root causes underlying the ever more evident environmental alterations: human-related influences far outweigh variations owing to sidereal or geological forcings (Valiela 2006).

The powerful anthropogenic changes derive basically from the unprecedented rise in human numbers through the 20th century, from perhaps 1.5 billion people to about 6 billion in 2000. Human populations are forecast to increase by another 30% or so by 2050. Of course, the demands for energy, food, water, and other resources have increased disproportionately in certain regions of the world, and such life-style disparities have added social, economic, and political complications. The importance of rising human numbers and the effects of uneven consumption are well known (Food and Agriculture Organization, http://www.fao.org; Population Reference Bureau, http://www.prb.org; United Nations, http://www.un.org/popin/wdtrends.html). Perhaps less common is awareness of two other aspects that are relevant to the loss of coastal wetlands, the topic of this contribution.

First, we are at a momentous stage in human history: we have just passed the point where fully 50% of us live in urbanized settings (Food and Agriculture Organization, http://www.fao.org). The proliferation of urban areas is unmistakably evident in an enhanced nocturnal composite image taken from orbit (photo 4.2). Humans living in aggregated fashion make greater demands on resources, consume proportionately greater amounts of energy (because of the

◀ **Photo 4.1: Salt marshes form complex networks of tidal channels.** Water circulates during the tidal cycle and small topographic differences result in important changes in vegetation and biodiversity.

Photo 4.2: Europe from orbit. Mosaic of enhanced nocturnal images of Europe taken from orbit. *Source*: http://www.gsfc.nasa.gov/topstony/2003/0815citylights.html.

extra demand for transportation of goods and people, heating and cooling, water supply, and so on), as well as occupying what might previously have been productive agricultural areas with valuable soils (Dow and DeWalle 2000; Van Breemen et al. 2002). In certain parts of the world, rather large proportions of the land have been urbanized (table 4.1). Expanding urban areas also eliminate natural areas that provide ecological subsidies such as nutrient retention and atmospheric cooling, and in general intensify issues of disposal

Table 4.1: Percentage of the area of states in four U.S. regions converted to urban sprawl; defined as "wildland-urban interface", the area where residences intermingle with native vegetation.

States located on the	% area of the state converted to the wildland-urban interface
Atlantic coast	38.6
Gulf of Mexico coast	10.8
Pacific coast	6.5
Interior	3.6

Source: Data from Radeloff et al. 2005.

of waste water, solid waste, industrial effluents, and vehicular and commercial exhausts. All in all, urbanization of landscapes presses intensification of all environmental management issues. As it turns out, major cities of the world have developed at critical transport nexus, often estuaries. Environments in the interface between land and sea—mangroves and salt marshes prominent among them—have therefore borne much of the brunt of urbanization.

Second, human beings have a propensity to accumulate near shore, as is also evident in the nocturnal image of the European region (photo 4.2). Regardless of the spatial scale—global (figure 4.1.A) or local (figure 4.1.B)—we build

Figure 4.1.A: Estimated number of people at different distances from the shore, worldwide

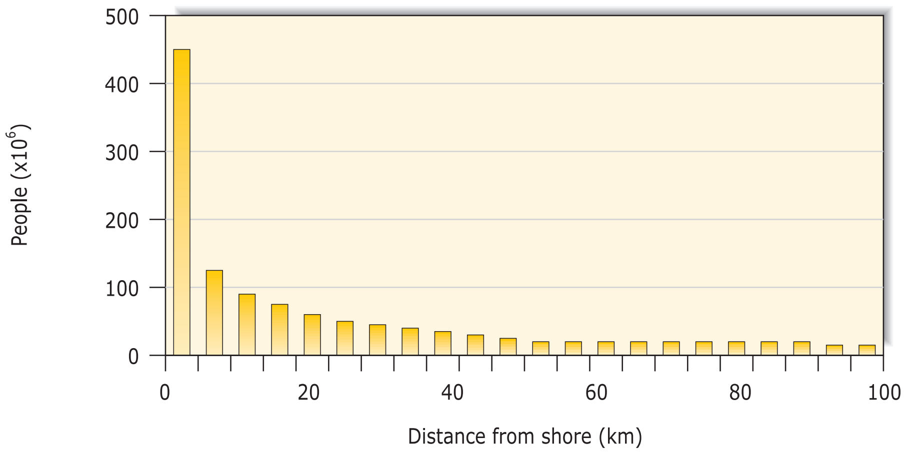
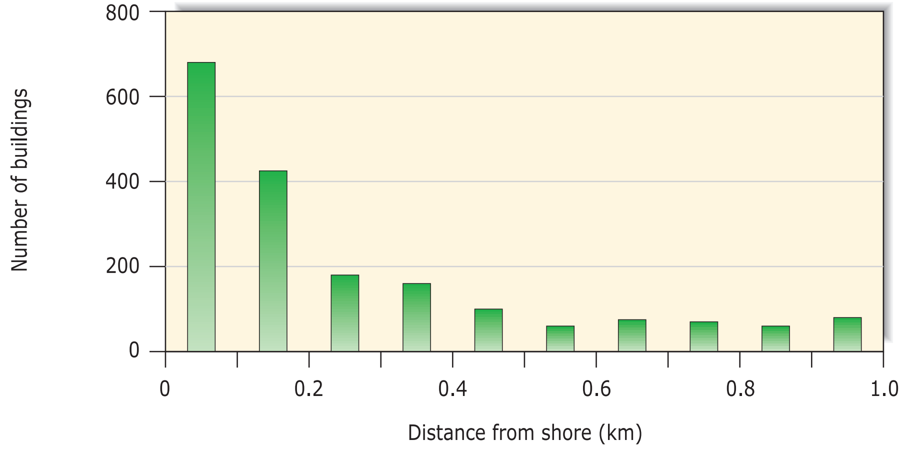


Figure 4.1.B: **Estimated number of buildings at different distances from the shore, in Waquoit Bay**, a small, local estuarine system in Cape Cod, MA, United States.



Source: Adapted from Valiela 2006.

structures as near to water as seems possible. This fractal tendency exacerbates the effects of increasing urbanization. Whatever the impacts of more people in denser population centers, coastal environments seem likely to suffer greater pressures. In the U.S., for example, the greatest degree of urban sprawl has taken place in coastal areas of the Atlantic and Gulf of Mexico (table 4.1), which happen to be where the majority of the coastal wetlands are found.

Coastal mangroves and salt marshes—along with most other coastal wetland environments—have to some degree been altered by changes brought about by increasing human activity. There are large discrepancies from place to place, but, globally, there have been substantial losses in area of both habitats, as well as degradation of considerable parts of surviving salt marshes and mangroves.

4.2. THE MAGNITUDE OF WETLAND LOSSES

Historically, wetlands were considered bad places for people, daunting environments where a person would be exposed to unhealthful miasmas. The term “malaria” referred to the bad airs thought to emanate from wet places where one might catch a fatal disease. There is, of course, some truth to such concerns, and the adversarial view is reflected in many different ways: we often refer to “reclamation” of mangroves and marshes, a term which implicitly suggests that by draining and filling we might bring these habitats back to a better state. People saw, and in many places on earth, still see few reasons for the preservation of marshes or mangroves. Wholesale filling, diking, draining, and conversion for agricultural and residential purposes have been the historical consequence of increased population densities near wetland-fringed estuaries, whether in the North Sea, Mondego River, Bangkok, Puerto Rico, Bangladesh, Iraq, Ebro Delta, Llobregat Delta, Boston Harbor, Hackensack River, or outer Cape Cod.

Speculation varies as to the worldwide fate of coastal wetlands. Nicholls et al. (1999) used modeling approaches to calculate losses in the range of 13-31%, of which 0-2% would plausibly be related to sea level rise. More recently, the IPCC (2007) issued a somewhat more pessimistic estimate of about a 30% loss of coastal wetlands worldwide. These are educated guesses, based on incomplete data. What we can be sure of is that future losses of coastal wetlands are inexorable, and that most losses will be directly or indirectly linked to human activity. In the sections that follow, we discuss the specific situations of mangrove forests and salt marshes.

4.2.1. Magnitude of mangrove forest losses

There has been much professional and press interest in the substantial ecological changes taking place in tropical latitudes. Such interest was the result of reports that about 30% of the area of global tropical forests, including rainforests, would be lost by the year 2000 (IPCC 1996). As regards coral reefs, alarms are being raised about a 10% loss of the habitat area, with perhaps an additional 30% degraded by midway through the 20th century (Wilkinson 1999); these statistics do not include the coral bleaching experienced worldwide late in the century (Baker et al. 2008). From such reports, we can safely conclude that there have been considerable recent alterations to significant habitats in the tropics.

The loss of area has been even more marked in the case of mangrove forests. From a meta-analysis of available data, we found that globally about 35% of the area of mangrove forests has disappeared since 1980 (Valiela, Bowen, and York 2001a). The loss of mangrove area averages about 2.1% per year, with greater annual losses of up to 3.6% per year in the Americas (table 4.2). Such estimates are confirmed by regional studies (Honculada-Primavera 1995; Blasco, Aizpuru, and Gers 2001). High recent loss rates make mangrove forests the most threatened major coastal habitat in the world.

Photo 4.3: Mangrove forests grow along the intertidal area of tropical and subtropical deltas. Glades like these support important ecosystem functions.

Table 4.2: Current mangrove swamp areas, percent loss, annual loss rate, and percent of original area lost per year, for the mangroves of the continents and the world

	Current mangrove area (km^2)	% loss of mangrove forest area	Annual rate of loss ($km^2\ y^{-1}$)	% of original area lost per year
Asia	77,169	36	628	1.52
Africa	36,529	32	274	1.25
Australasia	10,287	14	231	1.99
Americas	43,161	38	2,251	3.62
World	166,876	35	2,834	2.07

Source: Data from Valiela et al. 2001.

4.2.2. Magnitude of salt marsh losses

There are regional-scale assessments of salt marsh areas affected by human pressure. San Francisco Bay has seen a 79% reduction in area of salt marshes (figure 4.2), as well as a 9.932% increase in human-altered or constructed habitats (lagoons, salt ponds, etc.) (table 4.3). Some restoration efforts are underway to re-create native environments in South San Francisco Bay. In Chesapeake and Delaware bays, U.S., 10-20% were near lost in 1993 (table 4.4). There are some regional reconstructions of historical trajectories: about 50% of the salt marsh area in New England had been lost by the mid-1970s (figure 4.3). More recently, salt marsh loss rates have remained low in the U.S. (table 4.5), because of public awareness of the importance of these habitats, in particular the role of the main salt marsh grass in the region, the cordgrass *Spartina alterniflora*, and the ensuing enacting of restrictive protective legislation (Valiela 2006; Bromberg and Bertness 2005).

Figure 4.2: Changes in salt marsh area around San Francisco Bay, California. Dark blue represents salt marsh.

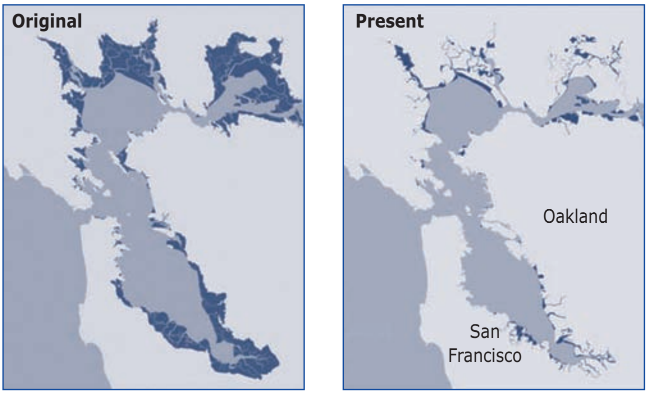


Table 4.3: Conversion of coastal wetland habitats in San Francisco Bay, across nearly two centuries, from natural systems to human-dominated land covers

Environments	% change
Native aquatic habitats:	
Open bay water	−7
Tidal flats	−42
Tidal marsh	−79
Human-dominated aquatic habitats:	
Lagoons	4,209
Salt ponds	2,062
Other altered areas	58,179
Total human-dominated aquatic habitats	9,932
Native coastal land habitats	−74

Source: Valiela 2006.

Table 4.4: Condition of estuarine marsh areas in Chesapeake and Delaware bays, 1993

	Condition (as % of the area of wetland)		
	Non-degraded	Slightly to moderately degraded	Severely to completely degraded
Chesapeake Bay	28-31	50-52	19-20
Delaware Bay	38-55	35-43	10-19

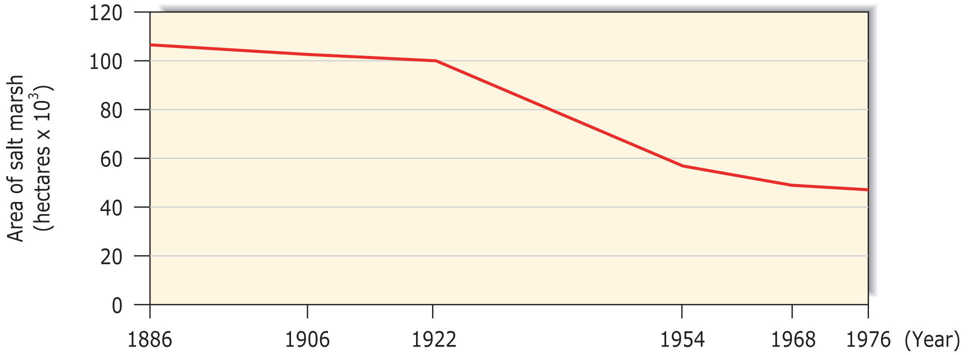
Source: Data from Kearney et al. 2002.

Table 4.5: Losses of coastal wetlands in the co-terminous U.S., 1920s-1980s

Years	% loss	% y^{-1}
1922-1954	6.5	0.2
1950s-1970s	-	-[1]
1970s-1980s	1.7	0.15
1975-1985	1.1	0.11
1982-1987	1.1	0.18

1 Annual losses were higher in certain places, such as coastal Louisiana, where rates reached 0.86 per year during 1958-1974.
Source: Adapted from data compiled from numerous sources (Valiela, Bowen, and York 2006).

Figure 4.3: Time course of area of salt marsh within states of the New England region, United States



Source: Adapted from Nixon 1982.

4.3. THE CAUSES OF WETLAND LOSSES

4.3.1. Salt marshes

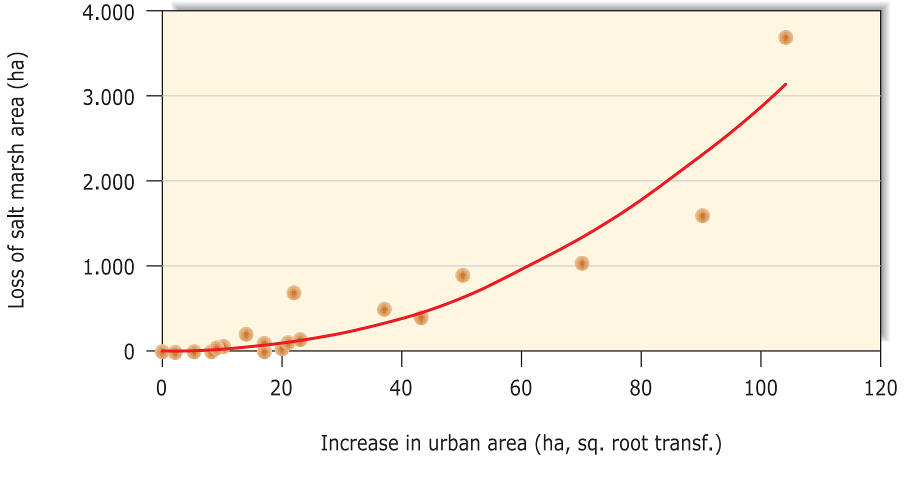
4.3.1.1. Losses from construction projects

By and large, in the United States at least, salt marsh losses before the 1970s were caused by some type of construction or civil engineering project. Coastal wetlands were, for one purpose or another, filled with imported sediment, drained of water, and diked to separate the wetland from tidal influences. The losses reported in tables 4.3-4.5 are largely a result of this sort of direct human intervention. It is no surprise, therefore, that reduction of salt marsh habitats was historically associated with increased urbanization of the adjoining watersheds (figure 4.4).

4.3.1.2. Losses from sea level rise

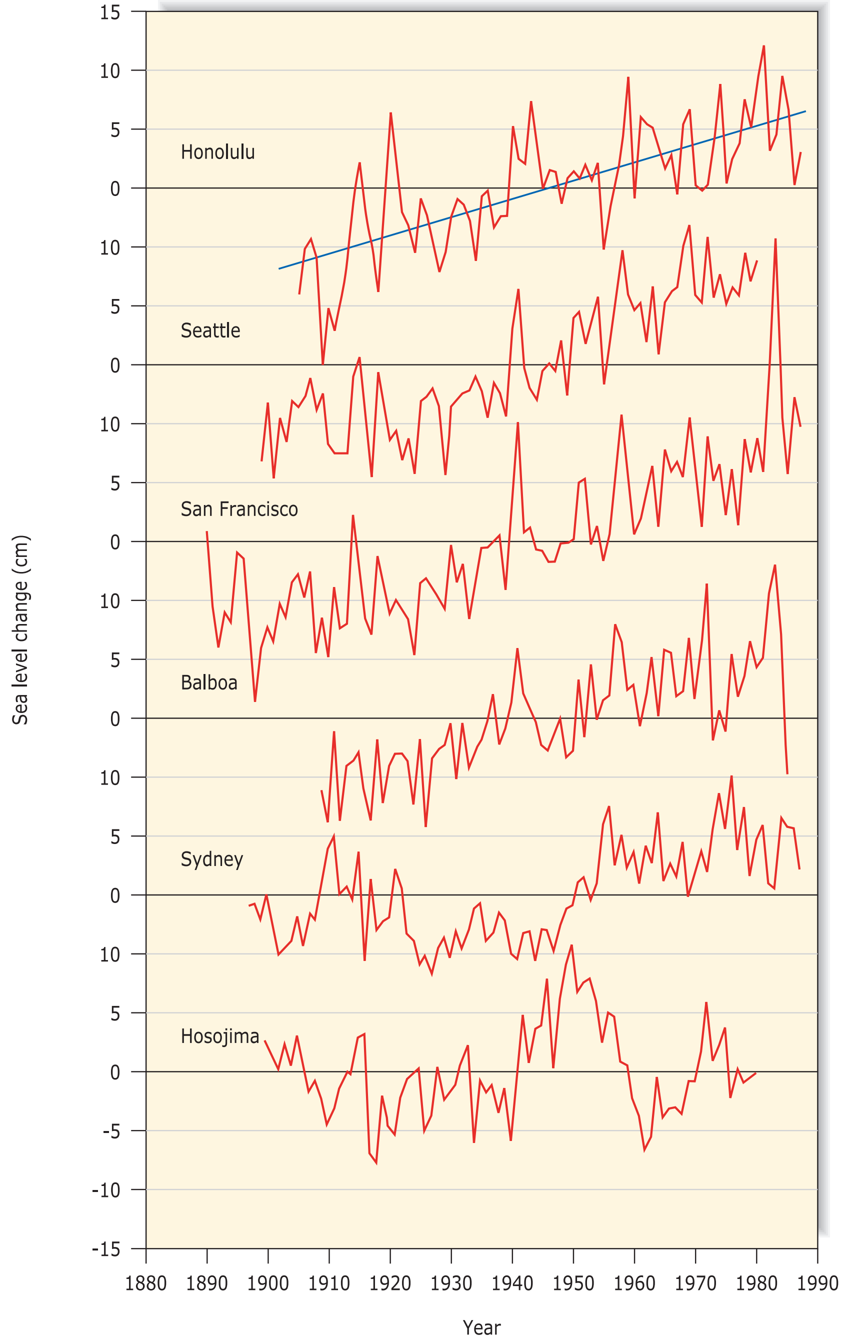
In certain places within the U.S. and other countries, evidence that salt marshes furnished important ecological and economic services useful to people led to laws being passed during the second half of the 20th century that restricted our historical imperative—and apparent license—to "reclaim" such land. These laws were later extended to cover the protection of mangroves. Hence the recent causes of loss of coastal wetlands are seldom filling, draining, and diking. Of course, there may be no such laws in many other parts of the

Figure 4.4: Loss of salt marsh area relative to increase in urbanized land area in southern New England, United States. Urban growth expressed as square root transformation of the values.



Source: Adapted from Bromberg and Bertness 2005.

Figure 4.5: Annual mean sea level for six Pacific stations. The straight line through the Honolulu data shows a 15 cm increase per century.

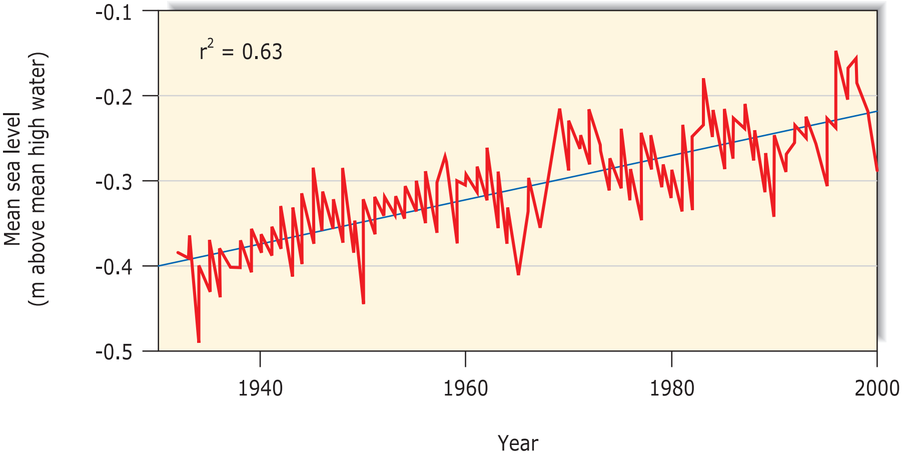


Source: Wyrtki 1990.

world, and the destruction of wetlands may at times take place even in areas under legal protection. In any case, direct human alteration is not currently a major cause of salt marsh and mangrove losses, at least within the U.S. Nonetheless, coastal wetlands are still being lost in the U.S. and the rest of the world. These current and future losses now primarily owe to an indirect result of human activities: increased sea level rise[1].

Sea level has been rising during recent decades across many of the world's shores (figure 4.6), although there is considerable local variation owing to geological processes. As sea level rises, wetland plants must respond, since the species involved are sensitively poised for best survival within certain limits of the tidal range. The physiological restrictions involved in submergence tolerance and redox regimes determine where wetland species will grow best. In general, salt marsh species will retreat landward as sea level rises and, if topography allows, will simultaneously extend further upslope (Wolters et al. 2005). Where salt marshes grow on low-lying islands—as occurs, for example, in many sites along the coast of Virginia (K. McGlathery, pers. comm.) or Maryland (Downs et al. 1994), sea level rise has more drastic effects, as there is no upland to offer a platform for marsh expansion.

Figure 4.6: Tide gauge measurements (m) of 6-month average sea level heights relative to mean high water level, 1932 to 2000



Source: Data from Dr. Richard Paine, Woods Hole Oceanographic Institution (NOAA/NOS).

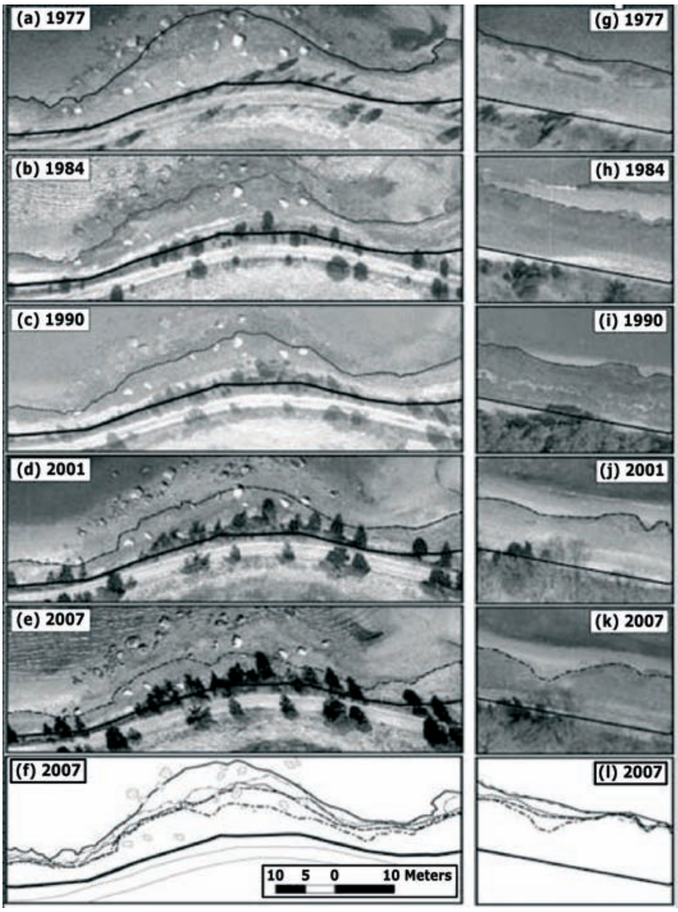
[1] We should note that coastal wetlands have been subject to fluctuations in sea level across geological time. Clear evidence of now submerged coastal wetlands is offered by the chunks of ancient salt marsh peat deposits that are not infrequently caught in bottom trawls towed over the seafloor of Georges Bank (Backus and Bourne 1991); relict mangrove sediments have been found at depth on the shelf of the Great Barrier Reef (Hull 2005).

Photo 4.4: Mangrove forests export carbon and contribute to recruit organisms to the adjacent coastal waters

Across most shorelines, spatial translations, depending on sea level, have been the necessary historical reality for salt marsh vegetation. With the increased urbanization of coastal areas described earlier, there are now people at the landward edge of many wetlands, and they very much prefer to keep marsh vegetation from taking over their land and constructed structures. This dilemma has been referred to as the "coastal squeeze" (Doody 2004), and although the extent of the problem has not been quantified, it may be more common than people realize (Wolters et al. 2005). Sea walls, road (figure 4.7) and rail beds, rip rap, and other erosion-control structures built at the landward edge of wetlands may well prevent the landward movement of salt marsh vegetation, and hence, in the face of sea level rise, lead to reduced salt marsh habitat areas. This possible mechanism of marsh loss needs to be quantified and tested under a variety of sea level rise scenarios.

Salt marshes may have seen the worst of their direct human threats, at least in the countries where protective legislation has been passed. Instead, the salient issue is how this coastal habitat will perform in the face of rising sea levels, and indirect human impact. Here again, urbanization and human construction structures come to bear, as salt marshes might be caught in a "coastal squeeze"

Figure 4.7: Vertical images of two Cape Cod salt marsh sites, taken during 1977-2007 (a) to (f) and (g) to (k). The broken lines show the position of the seaward marsh edge. The edges are composited in (f) and (l) to show the retreat of the marsh across the decades. Note that the marsh site on the left has a road bed on the upland margin which makes it impossible for marsh plants to migrate landward, forcing the loss of salt marsh area.



Source: Peacock 2007.

mediated by sea level and erosion-control structures. Assessments are needed of the relative importance of possible salt marsh habitat responses to faster-rising sea levels and the coastal squeeze.

4.3.1.3. Losses from salt marsh die-back

Recently, another kind of loss of salt marsh habitats has appeared along the east coast of the United States. Die-back describes the near-complete loss of vegetation in salt marsh parcels, with subsequent erosion and down-estuary transport of sediment away from the marsh platform. The lack of marsh plants drastically alters the ability of the habitat to provide the important ecological and biogeochemical services that are described below. Several causes of salt marsh die-back have been suggested. Possible mechanisms include submergence by sea level rise, erosion (Smith, in press), drought, warming, grazing, and fungal infection (Flory and Alber 2002; Alber et al. 2008). Possible causes appear to vary regionally, from drought in Louisiana and Georgia to fungal pathogens in Louisiana and Florida and grazers in parts of Cape Cod and Georgia, and it is likely that multiple control processes also play a part (Alber et al. 2008). In some Cape Cod marshes, grazing by the nocturnal purple marsh crab, *Sesarma reticulatum*, appears to cause low marsh die-back (Holdredge et al., in press; Bertness et al., in press). Due to the close correlation of high marsh die-back with elevation, it is thought that high marsh losses are a result of multiple factors, including herbivory and sea level rise (http://www.nps.gov/caco/naturescience/salt-marsh-dieback.htm; Smith 2008; Smith, in press)

In Georgia, 37 sites were affected by die-back between 2001 and 2003 (Flory and Alber 2002; GCRC 2004; Ogburn and Alber 2006), and the losses have progressed. Die-back has been reported on about 158,000 ha in Louisiana (Callahan and Schneider 2004; McKee, Mendelssohn, and Materne 2004; Edwards, Travis, and Proffitt 2005), and also in New York (Hartig et al. 2002) and South Carolina (J. Morris, unpublished data). In Massachusetts, die-back of salt marsh cordgrass and other plant species (Smith 2006) was reported throughout Cape Cod, and there are new reports from Maine, New Hampshire, New York, and Delaware. Die-back has therefore taken place across a wide range of U.S. coastal stretches. This may be a fairly recent phenomenon in the New World, but older reports describe similar events in European salt marshes (Goodman 1959; Sivanesan and Manners 1970), where die-back apparently came and went in recent decades.

Although the appearance of die-back in the U.S., and Cape Cod in particular, is widespread and losses in select marshes on Cape Cod have been quantified by Smith (in press), we lack enough survey data to determine the full extent of this sort of marsh loss. Loss of creek bank salt marsh plants by die-back may accelerate erosion of the bank habitat (Smith, in press) As yet, die-back affects a minor portion of salt marsh area, but it can be expected to spread further in North America, perhaps later diminishing, as it did after its heyday in Europe.

4.3.1.4. Losses from invasive reed expansion

Another as yet incompletely understood mechanism of salt marsh loss is the relatively recent proliferation of an invasive introduced genotype of the common reed, *Phragmites australis* (http://www.invasiveplants.net/phragmites/morphology.htm; Blossey 2002). The invasive growth usually occurs along the upper edges of salt marshes and extends seaward to increasing degrees. The invasive taxon appears more tolerant of salt (Vazquez et al. 2006), grows better in response to increased nutrients than the native genotype (Packett and Chambers 2006; Saltonstall and Stevenson 2007) and seems to be favored by the urbanization of the adjoining watersheds (King et al. 2007). It has been argued in a long list of papers (see review in Teal and Weistein 2002 and Hunter et al. 2006) that, at least in the U.S. sites, this vegetation type fails to contribute the ecological services (see below) provided by native salt marsh vegetation. Curiously, in China, *Spartina alterniflora* is an invader that is replacing native *P. australis* (Ma et al. 2007), and faunas diminished in invaded areas (Chen et al. 2007). The ongoing reed expansion has been reported widely in North America (Saltonstall 2002). So far there are no comprehensive data on its extent relative to the area of salt marsh, or estimates as to future trends.

Photo 4.5: Reedbeds of common reed (*Phragmites australis*). The common reed can be an aggressive invasive, especially when introduced. Its spread is favored by the urbanization of the areas adjoining salt marshes and its high saline tolerance.

4.3.2. Mangrove forests

4.3.2.1. Construction and exploitation effects

Mangroves have been subject to a variety of human uses, including the harvest of wood for fuel and the production of charcoal, the production of honey, medicinal purposes, and so forth (Saenger 2002). Most of these activities historically did not result in habitat destruction. In recent decades, however, mangrove use has intensified, and substantial loss has become evident (table 4.2, and Valiela et al. 2001b; Alongi 2002; Duke et al. 2007). Mariculture has been prominent among the activities that lead to loss: the construction of shrimp and fish ponds (photo 4.6) accounts for 52% of the world's loss of

Photo 4.6: Bornean mangrove forest. This aerial view shows dykes and enclosed shrimp ponds carved out of the mangrove habitat.

Table 4.6: Recent activities in mangrove forests that have led to loss of habitat

	% of total
Shrimp culture	38
Forestry uses	26
Fish culture	14
Diversion of fresh water	11
Land reclamation	5
Herbicides	3
Agriculture	1
Salt ponds	<1
Coastal development	<1

Source: Adapted from data compiled from numerous sources (Valiela, Bowen, and York 2001).

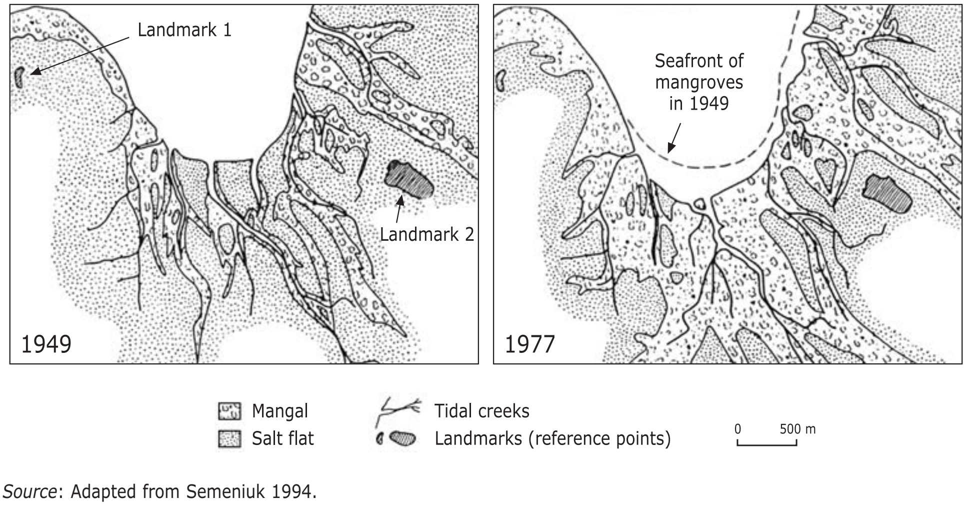
mangroves. A variety of other construction and exploitation activities add the remainder (table 4.6). The loss from herbicide use occurred during warfare in SE Asia.

4.3.2.2. Sea level effects

Sea level rise forces the retreat of the seaward margin of mangroves (Ellison 1993; Field 1995), much as is the case with salt marshes. Across most tropical shores, there is generally less of a built-up urbanized landscape, meaning the mangrove has sufficient space to expand landward (figure 4.8); mangrove sediment sources appear to be enough to support the accretion necessary (Field 1995; Alongi, in press). Different species of mangroves respond differently to experimental exposure to different sea levels (He et al. 2007). These results suggest that we can forecast that increased sea level will not only shift the position of mangrove forests landward, but will also alter the species composition of the forests.

It would be useful to ascertain the extent of the coming coastal squeeze for mangroves, since human populations and the development of urban centers may be increasing faster in low than in high latitudes. Taking the upper limit of the IPCC's sea level rise estimates (IPCC 2007), we might see a loss of 10-15% of current mangrove forest area by the year 2100 (Snedaker 1995; Gill-

Figure 4.8: Changes in the locations of mangrove estuarine habitats and locations of shoreline, 1949 and 1977, Fitzroy River, Australia



Source: Adapted from Semeniuk 1994.

man et al. 2006). Losses of mangrove forests associated with sea level rise are therefore considerably smaller than the ongoing losses generated by human conversion of mangroves to utilitarian purposes. If estimates of current total losses of 1-2% per year (Valiela, Bowen, and York 2001a; Alongi 2002; Duke et al. 2007) are correct, most of the world's mangroves might have gone before we see the impact of sea level-related losses. This being so, it appears sensible to direct management and restoration efforts toward prevention and remediation of direct mangrove deforestation.

4.4. THE CONSEQUENCES OF COASTAL WETLAND LOSS

So far we have established that, although comprehensive data may be scarce, there is compelling evidence that there have been substantial losses of salt marshes and mangrove forests, two widespread coastal habitats. We can also say that direct and indirect human effects are involved in the substantial ecological changes. The direct effects are via various construction-related activities, and the indirect effects are mediated through our warming of the atmosphere, and hence accelerated sea level rise, added to our possible involvement in other mechanisms. The question that arises at this point is whether or not all that matters.

Photo 4.7: View of a channel in a salt marsh of *Spartina alterniflora* in New Jersey, United States. The image shows the sharp edges of vegetation and the scattered algal cover often found in the channels.

To address that question, we need to first review the ecological functions played by coastal wetlands as part of the larger coastal zone, including people (Valiela 2006). Services provided by coastal wetlands include the following:

1. *Export of energy-rich materials important to food webs of deeper waters*

Most wetland ecosystems export energy-rich substances (reduced nitrogen compounds, dissolved and particulate organic matter) to adjoining deeper ecosystems (table 4.7). These subsidies can support the high rates of metabolism characteristic of the receiving near-shore waters (Hopkinson 1985). The subsidies in export of energy-containing materials from *Spartina alterniflora* salt marshes to adjoining waters were major arguments supporting the enactment of regulations protecting coastal wetlands in the U.S.

2. *Nurseries to many species of commercially important fisheries stocks*

Many commercially important species of shrimp and fish use wetlands as places where their young find cover and abundant food to support fast growth (Turner 1992; Werme 1981; Twilley 1998; Manson et al. 2005). In eastern North America, for example, menhaden, bluefish, winter flounder, and striped bass are among fish species fundamental to sport and commercial fisheries and are species that also use salt marsh estuaries as juvenile nurseries.

3. *Habitat for shell- and fin-fish stocks*

The rich waters of wetland-dominated estuaries support many commercially important shell- and fin-fish stocks. In temperate North America, for instance, oysters, quahogs, scallops, soft-shell clams, blue crabs, and winter

Table 4.7: Percentage of salt marshes (n=19) exporting materials out to deeper waters

Materials	Percentage of salt marshes studied that exported materials to deeper waters
Ammonium	64
Nitrate	36
Dissolved organic nitrogen	100
Particulate organic nitrogen	67
Total nitrogen	100
Dissolved organic carbon	91
Particulate organic carbon	59
Total carbon	82

Source: Adapted from data compiled from numerous sources (Valiela, Bowen, and York 2001).

Photo 4.8: Prop roots of mangrove trees. The roots form complex structures that serve as habitat for the recruitment of a broad range of species.

flounder—to name a few exploited stocks—are harvested from marsh-fringed estuaries. The values of such harvested crops are typically an order of magnitude larger, on a per unit area basis, than harvests from grains in terrestrial agriculture (Mackenzie 1989; Ver, Mackenzie, and Lerman 1999).

4. *Sites for aquaculture and other uses*

Phytoplankton-rich water within wetland-fringed estuaries are favored sites for mariculture practices, as there is protection from high seas, plentiful food, reasonable water exchanges, and good water quality to support high-density cultivation (Shumway et al. 2003). In Cuba, mangrove oysters are commonly harvested. High densities of suspension feeders may also be useful in clearing water columns, as a tool to improve or restore water quality (Cloern 1982; Ulanowicz and Tuttle 1992).

More intrusive modes of mariculture have been used to convert wetland areas into high-intensity shrimp and fish culture ponds, as noted above in the case of loss of mangrove forest area. In addition, large areas of coastal wetlands have in many places (western Australia, Portugal, San Francisco Bay, to name a few) been diked to create evaporative salt pans for the production of sea salt. Such practices, of course, destroy the wetland involved.

5. *Contaminant interception*

Salt marsh and mangrove sediments to a certain extent retain industrial contaminants, including metals, chlorinated hydrocarbons, and petroleum hydrocarbons (Twilley 1995). The biogeochemical mechanisms involved are complicated, as are the relative responses of the different parts of wetland ecosystems to exposure to these compounds. A summary of recent work in these very large fields of study is provided in Valiela (2006, chaps. 7-9).

6. *Shoreline and sediment stabilization*

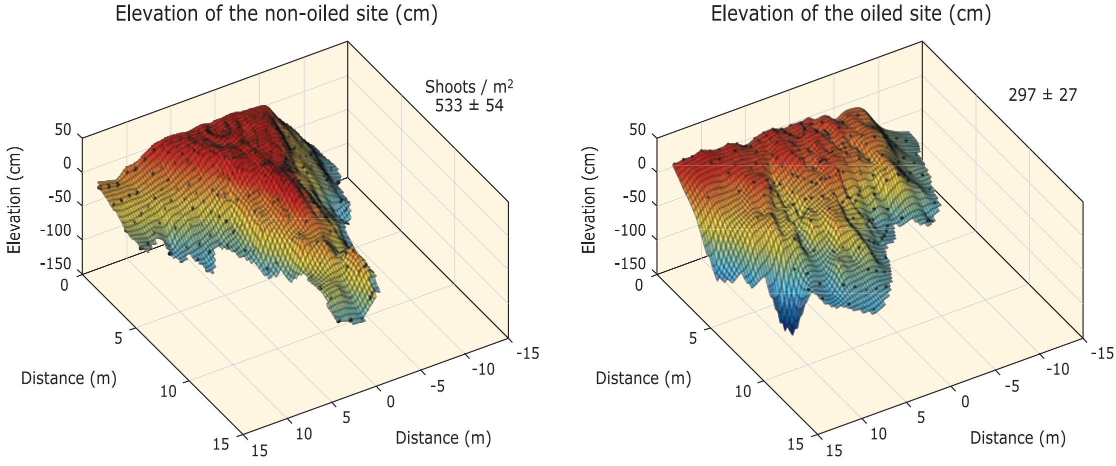
The presence of wetland vegetation conserves the stability of coastal sediments in at least two ways. First, marsh or mangrove vegetation dissipates the erosional power of storm waves (Alongi, in press): model studies show that there is a 50% decline in wave energy by 100-150 m into mangrove forests (Brinkman et al. 1997; Mazda, Wolanski, and Ridd 2006), and that there may be a 90% reduction of tsunami flow pressure within 100 m in dense mangrove stands (Harada and Imamura 2005; Tanaka et al. 2007). Such lowering of the motive force of water reduces the transport or erosion of sediments in vegetated wetlands and facilitates trapping of fine sediments within these ecosystems (Perry 2007).

Second, root rhizomes also add coherence to sediments (Alongi 2002). In a site where oil lies some 10-15 cm below the marsh surface, we found that the density of *Spartina alterniflora* shoots was considerable lower than in un-oiled marsh areas (Culbertson et al. 2008). Sediment loss has occurred in oiled sites with decreased plant densities (figure 4.9). Where oil is present, shoot density decreases and the characteristic flat, sloping marsh surface becomes pitted and dissected by gullies.

7. *Sources of forage and hay*

The use of salt marshes as places where livestock forage, or as sources of hay, is a venerable and widespread tradition. Grazing by livestock has been reported to have taken place by about 4000 BC in the Baltic and more recently elsewhere (Adam 2002). Indeed, the practice continues in many places. Visitors to Scotland will see sheep and highland cattle in most marshy areas, while cattle still regularly pasture on marshland in central Argentina and north Queensland. In northern North America, livestock pasturing and the harvest of hay began as early as 1650, and lasted until the late 1900s (figure 4.10). And there is a currently a modest market in marsh hay for horticultural uses.

Figure 4.9: Contours of the surface of salt marsh parcels supporting stands of *Spartina alterniflora* at higher (A) and lower (B) shoot densities. Note lower elevations on average, and dissected nature of the surface where shoot density was lowered.



Source: Adapted from Culbertson et al., in press.

Figure 4.10: *Hayfields: a clear day*, painted by Martin Johnson Heade, 1871-1880. This image portrays the harvesting of salt marsh grasses for feeding livestock in New England, United States.

8. *Waterfowl refuges and migratory stop-overs*

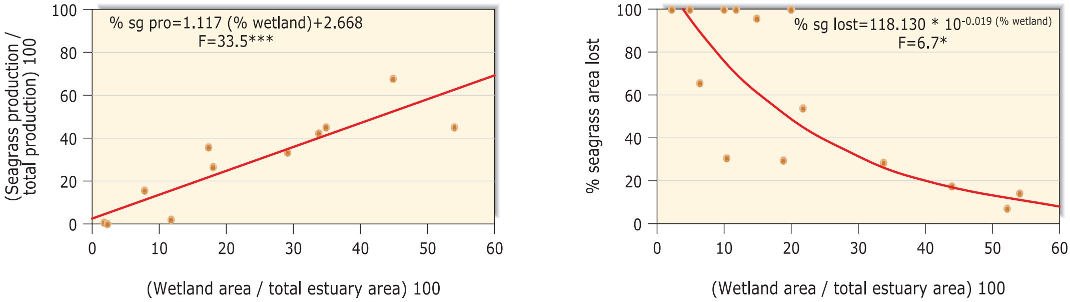
As humans have crowded coastal lands, there has been a sharp reduction in the areas where water-dependent birds can live, and which migrant species can use as stop-overs. These remnant habitats have become ever more critical for conserving the diversity of these water fowl, waders and other aquatic species.

Photo 4.9: Flock of flamingos in a salt marsh. The high production of invertebrates in salt marshes is a magnet for birdlife, contributing to their value for biodiversity conservation.

9. *Interception of land-derived nutrients*

Wetlands intercept certain materials being transported from land to sea. Of the compounds intercepted (not predominantly exported, unlike reduced compounds), one of the most important is nitrate (table 4.7), which powers the production of coastal plants and algae and hence fosters eutrophication. Interception of land-derived nitrate is possible thanks to the high rates of denitrification within salt marshes and mangroves and the burial of nitrogen in their sediments. Evidence of the powerful influence of such interception of land-derived nitrate is the relationship between salt marshes and seagrass meadows: the greater the area of wetland, the greater the production by seagrasses and the smaller the seagrass area lost (figure 4.11.A and B). These linkages occur because seagrasses are highly sensitive to increased nitrogen loads: the presence of a fringe of nitrogen-intercepting wetlands favors the survival of seagrass meadows. Where we see healthy seagrasses, we also often find a fringe of salt marsh interposed between land and sea.

Figure 4.11: Relationship between percent seagrass production (of total production) vs. wetland area of total estuary (A) and percent seagrass area lost vs. wetland area of total estuary (B)



10. *Values for ecotourism and other aesthetic purposes.*

Many of us share an appreciation for the aesthetic value of wetlands, as encapsulated in painterly images (figure 4.10). The development of public enjoyment of open space and interest in the fauna of wetlands—particularly birds—has opened up a nascent ecotourism industry involving visits to wetland sites. It is hard to know how to weigh these aspects, but in our urgency to make credible, concrete arguments we would be remiss to ignore the intangible attractiveness of coastal wetlands as additional reasons for their preservation and maintenance.

It would require far more space than we have here to detail the consequences of loss of coastal wetlands and the ecological services listed above. Moreover, there are surely considerable local differences from one part of the world to another. Here we limit our argument to saying, first, that it should be apparent from the preceding list of wetland services that these environments play multifaceted and important functions in the world's coastal regions. They also play fundamental roles in linkages among adjoining coastal ecosystems.

Second, the substantive ecological services provided by coastal wetlands are strongly correlated to wetland area (Turner 1992) or wetland fringe (Gosselink 1984; Brower et al. 1989). As we lose wetland area or fringe, we stand to lose the subsidies provided by these ecosystems.

Third, wetland losses ought to be of concern to people, because, as we argue above, the loss of wetland services matters ecologically and has economic implications. In fact, speculations on ecological valuation (Costanza et al. 1997) have concluded that coastal wetlands are among the most valuable parcels of the world's environments, owing to the many recognized ecological, conservation, water quality, and economic services they perform.

To sum up, the losses of coastal wetlands that are taking place worldwide are quantitatively significant, are apparently increasing and, more importantly, will have ecological and human impacts. We lack sufficient information with which to comprehensively and quantitatively assess the consequences of coastal wetland loss. Obtaining such relationships might be a good way to point the directions for future research in this study area. Efforts to define the functions linking wetland loss and services will require much interdisciplinary collaboration, and will have to cope with the likely spatial heterogeneity of the effects and possibly complex interactions.

We do know enough, however, to conclude that we have lost, globally and locally, a substantial part of the wetlands of the world, that these are key parcels of land- and seascapes, that the services these wetlands can furnish are of consequence ecologically, economically and socially, and that human activities, directly and indirectly, have been instrumental in their decline. It therefore seems imperative to plan concerted action to 1) prevent further losses, 2) preserve and maintain present habitats, and 3) foster efforts to restore lost habitats and create new wetlands.

4.5. THE RESTORATION OF COASTAL WETLANDS

In this essay we have focused on losses and services and said little about the very substantial efforts being made to restore wetland areas. The restoration or construction of coastal wetlands has a lengthy history, and reasonably feasible and economical techniques are available for such measures. Wetlands indeed have good regenerative abilities. One major effort that provides an example of salt marsh restoration is taking place on the Delaware River estuary, using innovative methods which have so far brought successful results (Teal and Weinstein 2002; Teal and Peterson 2005; Teal and Weishar 2005). Although the replanting of mangrove seedlings may fail on occasion, as happened in Samoa, there are many examples of successful mangrove forest restoration (Gilman and Ellison 2007): appropriate contour preparation to allow the recolonization of sediments by mangrove seedlings or the planting of mangrove seedlings has led to the recovery of Florida mangrove stands in the space of a few years.

Much has been done to evaluate whether or not reconstructions lead to the full restoration of services, and the evidence is uneven, though still coming in. But surely, reestablishing lost vegetative stands is a step in the right direction, building on the good start already made. Restoration planning must consider

Photo 4.10: Mangrove forests can be continuous habitats or form a patchy landscape with fringes and lagoons

the past conditions of sites and the causes of their decline, so remedial measures can avoid the conditions that led to the initial losses.

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