Estuarine Marsh: An Overview

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Abstract

Estuarine marshes commonly called “salt and brackish marshes” are tidal wetlands associated with the world’s estuaries where salinities range from well above sea strength to nearly freshwater. Subject to frequent tidal flooding, plant communities are dominated by halophytic (salt-tolerant) herbs, subshrubs, and/or succulent-leaved shrubs. Not uniformly distributed along the world’s sea coasts, tidal marshes tend to be the dominant plant community of the intertidal zone at middle and higher latitudes. The global extent of estuarine marshes is not well documented and this contributes to conservative estimates of their soil carbon stores. Most regions report significant historical and on-going loss of estuarine

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marshes by 1) human developments that in-part reflect a shift from an agrarian to industrial society and 2) natural events. Economic and cultural values set by society determine how estuarine marshes functions that yield many benefits to people and the estuarine aquatic ecosystem are valued. Estuarine marshes are increasingly being recognized among the world's most valuable ecosystems and, given their location between land and the sea, are especially vulnerable to human development and the effects of climate change.

Keywords
Brackish marsh · Climate change effect on estuarine marsh · Coastal wetland · Ecosystem services - estuarine marsh · Estuarine marsh · Plant diversity - estuarine marsh · Salt marsh · Tidal wetland · Wetland distribution - estuarine marsh · Wetland functions - estuarine marsh · Wetland threats - estuarine marsh · Wetland trends - estuarine marsh

Introduction

Estuarine marshes commonly called "salt and brackish marshes" are tidal wetlands associated with the world's estuaries where salinities range from well above sea strength to nearly freshwater (oligohaline brackish marshes). Dominated by halophytic (salt-tolerant) herbs, subshrubs, and/or succulent-leaved shrubs, these coastal wetlands are subject to frequent flooding by tides. These plant communities grow in the mid- to upper intertidal zone, generally above mean sea level and above tidal flats. They typically form in sheltered estuaries where currents and wave action are not strong enough to uproot seedlings and where ample sediments are deposited to support their growth and expansion. Such places include the mainland side of barrier islands, deltas, and shorelines of semi-enclosed bays and coastal rivers. Estuarine wetlands can also form in open shallow seas where tides are minimal, e.g., along the northeastern shore of the Gulf of Mexico (USA).

Within estuaries, salt marsh (dominated by the most salt-tolerant plants) occurs closer to the ocean than brackish marsh occupying the intertidal zone along coastal rivers whose salinity decreases with distance from the sea. While they are most characteristic of temperate and polar regions, salt marshes also occur in subtropical arid regions and in tropical climates often on the landward side of mangroves. They may include patches of and sometimes large nonvegetated or sparsely vegetated areas (salinas or salt flats), especially in arid and tropical climates. They also may include numerous shallow pools of open water. Figure 1 shows some examples around the world. This article provides an introduction to the world's estuarine marshes. More detailed information can be gathered from three publications (i.e., Chapman 1977; Adam 1990; Tiner 2013). See the senior author's contribution on "Hydrology of Coastal Wetlands" for a discussion of the hydrology of salt and brackish marshes.

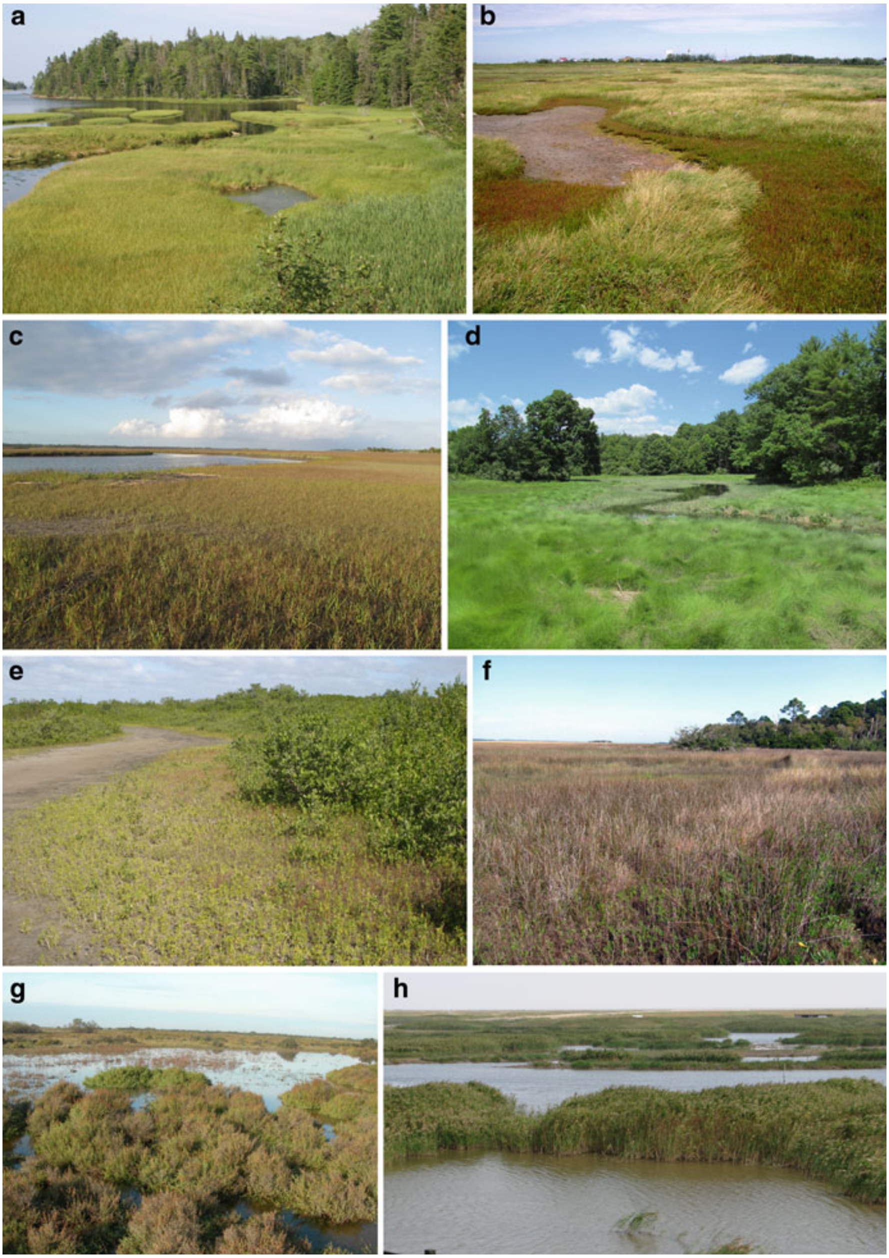

Fig. 1 Examples of estuarine marshes: (**a**) Salt marsh at the head of St. Ann's Bay, Nova Scotia (Canada); (**b**) salt panne in the high marsh along St. Lawrence estuary, Quebec (Canada); (**c**) *Spartina alterniflora* low salt marsh, South Carolina (USA); (**d**) strongly brackish marsh dominated by *S. patens* with *S. alterniflora* along creekbank, New Hampshire (USA);

Estuarine Marsh Formation

Many of today's estuarine marshes are established in river valleys that have been submerged by rising sea levels since the last glacial epoch. The majority likely began forming around 6,000 years ago when the rate of sea-level rise became more gradual (Tiner 2013). As sea level continues to rise, estuarine marsh vegetation eventually colonizes coastal plain lowlands, replacing maritime forests that have succumbed to increased salt stress – a process called marine transgression or more commonly salt marsh migration. Humans have also played an important role in the formation of tidal marshes. Salt marshes have formed in front of diked marshes or on the more sheltered side of riprap piers where tides and currents combine to deposit sufficient sediments for marsh colonization. In fact, many present-day marshes in parts of Europe (e.g., Netherlands, Denmark, and Germany) are the by-product of land reclamation of former tidal marshes and shallow embayments, forming in front of embankments constructed to create land for grazing and agriculture (Davy et al. 2009). Deforestation of coastal watersheds and poor agricultural practices have also aided tidal marsh formation by introducing more sediments into coastal waters that eventually settle out, thus raising estuarine substrates to levels suitable for colonization by hydrophytes. Any process, whether natural or human induced, that increases sedimentation in coastal waters may eventually promote estuarine marsh formation.

Geographic Distribution and Extent

Tidal marshes are not uniformly distributed along the world's sea coasts. They tend to be the dominant plant community of the intertidal zone at middle and higher latitudes (in temperate and polar regions), with the tropics dominated by various species of mangroves (Fig. 2). In tropical regions, however, tidal marshes may be found either in front of the mangals (e.g., Brazil; West 1977) or more typically on less frequently flooded more saline soils behind them (e.g., salinas or salt flats, Saenger et al. 1977).

Although salt marsh can be relatively easily delineated using remote-sensing imagery, the global extent of estuarine marshes is not well documented for many regions of the world (Adam 2002). Estimates ranging from 0.14 million km^2 (Duarte et al. 2008), to 0.22 million km^2 (Laffoley and Grimsditch 2009), and 0.4 million km^2 (Woodwell et al. 1973 cited in Duarte et al. 2005) are developed from a limited database. While acknowledging their estimates are very conservative, Schuyt and

Fig. 1 (continued) (**e**) salina with *Batis maritima* behind black mangrove swamp, Florida (USA); (**f**) *Juncus roemerianus* brackish marsh, Georgia (USA); (**g**) *Salicornia* flats Camargue (France); (**h**) *Phragmites australis* with invasive *Spartina alterniflora*, Chongming Dongtan Ramsar Site (China) (Photo credits: (**a–f**) R.W. Tiner ©; (**g**) C.M. Finlayson ©; (**h**) L. Young ©. Rights remain with the author)

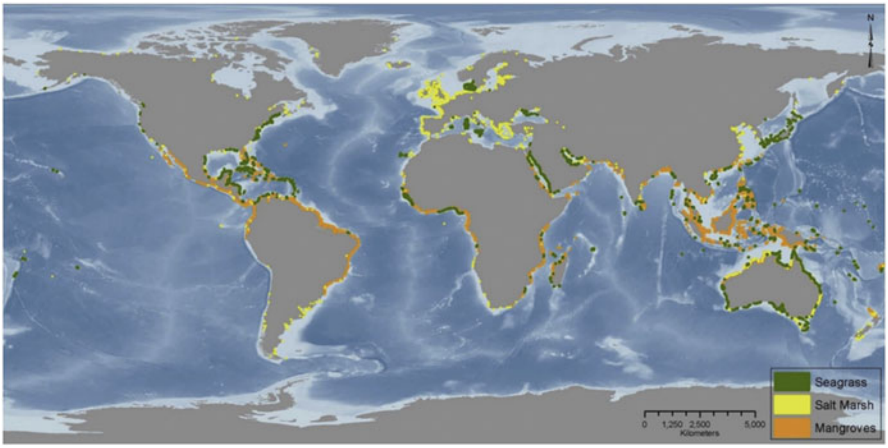

Fig. 2 Global distribution of tidal marshes, mangroves, and sea grasses (From: Pendleton et al. 2012; Fig. 1. https://doi.org/10.1371/journal.pone.0043542.goo1 licensed under Creative Commons CCO public domain dedication)

Table 1 Estimated tidal wetland area by continent. Unvegetated sediment wetlands are mostly from the coastal zone

Continent	Salt/brackish marsh (hectares)	Unvegetated sediment (hectares)	Mangrove (hectares)
North America	2,575,000	16,906,000	510,000
Latin America	1,707,000	9,223,000	4,224,000
Europe	500,000	2,374,000	Not present
Asia	1,027,000	8,011,000	1,439,000
Africa	487,000	4,632,000	3,686,000
Australasia	461,000	4,641,000	2,253,000
Total	6,758,000	45,788,000	12,112,000

Sources: Schuyt and Brander 2004: Table 9, © 2004 Living Water: the economic values of the world's wetlands, with permission WWF - World Wide Fund For Nature

Brander (2004) estimated tidal wetland area by continent using a database of nearly 3,800 wetland sites from around the world. They predicted that salt and brackish marshes minimally cover 67,580 km^2 (Table 1).

Information on the historic extent and losses of tidal marshes is extremely limited even in countries where wetlands have received much attention. Estimates of global declines in coastal wetland area do not differentiate between wetland types and are reported to be 46–50% since the beginning of the eighteenth century and 62–63% through the twentieth century (Davidson 2014). The relative rate of loss has accelerated in the twentieth and twenty-first centuries (Davidson 2014), and the Global Wetland Extent Index estimates an almost 50% decline between 1970 and 2008 (Leadley et al. 2014).

Although there are considerable regional differences, most regions report significant historical losses that are continuing due to both human and natural events. In their examination of North American wetlands, Bridgham et al. (2006) reported that the best estimate of "original" tidal wetlands in the USA was one for the 1950s and Valiela et al. (2009) provide a brief review of salt marsh loss in the contiguous United States. Various regions of North America have experienced different degrees of marsh loss in part related to their extent and the intensity and nature of development: Hudson Bay 63% (high uncertainty), Canadian Maritimes 64%, US North Atlantic 38%, US South Atlantic 12% (high uncertainty), Gulf of Mexico 18%, and Pacific Coast 93% (Gedan and Silliman 2009). In southern Sinaloa (Mexico), Camacho-Valdes et al. (2014) reported a 10–14% loss between 2000 and 2010. A study of changes in 12 of the world's largest estuaries reported a 67% loss since the onset of human settlement (Lotze et al. 2006), while Bridgham et al. (2006) arbitrarily used a 25% loss estimate for the world's tidal marshes outside of North America. Bailey and Pearson (2007) reported rapid declines of over 50% for some areas of salt marsh along the central southern British coast between 1971 and 2001, while Burd (1992) estimated losses of between 10–44% between 1973 and 1988 in 11 southeast England estuaries. An excess of 708,000 ha of land reclaimed from Chinese salt marshes (Yang and Chen 1995) and major rapid losses are reported for East and Southeast Asia (Mackinnon et al. 2012 and references within).

Plant Species Diversity

While climate is a major factor affecting plant distribution globally in tidal marshes and other habitats, many site-specific factors affect vegetation patterns within individual salt marshes (Fig. 3; see Tiner 2013 for details). Physical factors such as

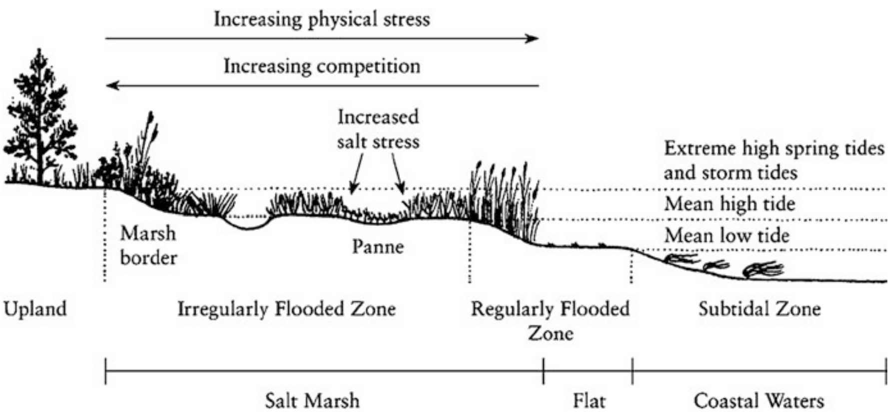

Fig. 3 In the salt marsh, increased physical stress occurs from the upland border to the water's edge, while biological competition increases in the opposite direction (From Tiner 2013; Fig. 4.15 copyrighted, permission from author)

salinity, inundation, soil saturation, and anaerobic soil conditions are more limiting in the marsh proper, while biological competition is greatest at the marsh-upland border where stress from the physical factors is low. The greatest salt stress in these marshes is in salt pannes – slight depressions where salinities can exceed 100 ppt. Here the most salt-tolerant species are found and are reduced in stature while in places even they are eliminated from growing due to the extreme salinity (i.e., salt barrens). Within the marshes, two general zones have been identified based on the frequency and duration of tidal inundation: low marsh (a zone that is flooded at least once daily for most of the year) and the high marsh (a zone that is flooded less often by the tides). A third zone – the upper marsh border – represents the highest elevations of the high marsh that, of course, are flooded less often and for shorter durations than the rest of the high marsh. Plant diversity is typically highest in this zone where salt water stress is much less than in the rest of the marsh. Where they occur in the tropics, the more extensive salt marshes (salinas) appear to be inland of the mangroves where more saline soils limit species diversity.

Species diversity is low in the Arctic, where *Puccinellia* and *Carex* are the predominant genera. Some common genera found in salt marshes elsewhere around the world include *Carex*, *Triglochin*, *Plantago*, *Glaux*, and *Hordeum* (boreal); *Spartina*, *Distichlis*, *Juncus*, and *Limonium* (temperate); and *Batis*, *Sesuvium*, *Cressa*, *Paspalum*, and *Sporobolus* (tropical) (see Chapman 1960, 1977; Beeftink 1977; Vierick et al. 1992; Thannheiser and Holland 1994; Adam 2002; Bortolus et al. 2009; Saintilan 2009; Tiner 1999, 2009, 2013 for more details). Members of the goosefoot family (Chenopodiaceae; especially *Sarcocornia*, *Salicornia*, *Suaeda*, and *Atriplex*) are also among other prominent halophytes characterizing the world's salt marshes.

Salinity in the intertidal zone along coastal rivers decreases with distance from the sea. Decreased salt stress allows more opportunities for colonization by plants with intermediate and low salt tolerances as opposed to the salt marsh proper where plants are exposed to the highest salinities. Interestingly, many plants restricted to the upland border in temperate salt marshes often become dominant species in brackish marshes further upriver. Consequently, some folks might consider the upper salt marsh border to be a brackish meadow, especially when it encompasses more than a narrow band.

Within salt marshes, especially in arid or tropical regions, there may be places where extreme salinities occur, in some cases more than three times that of sea water. The more extensive of these areas may be called salinas, salt barrens, or salt flats as they are often sparsely vegetated. It is here where the most salt-tolerant plants live: *Salicornia* spp., *Suaeda* spp., *Sagina maritima*, *Parapholis strigosa*, *Plantago coronopus*, and *Pottia heimii*, among others (Beeftink 1977; Tiner 1999, 2009, 2013).

Ecosystem Services

Historically tidal marshes have been filled for ports, and commercial, industrial, and residential development, and diked and drained for agriculture the world over (e.g., Gedan et al. 2009; Valiela et al. 2009; Silliman et al. 2009; Tiner 2013). Salt marshes

Table 2 Ecosystem services provided by estuarine marsh

Type of service	Examples
Supporting	Nutrient cycling, soil formation, primary production (photosynthesis), water cycling through wetlands
Provisioning	Food (e.g., fish, shellfish, plants), livestock grazing, aquaculture/fishing, fiber, genetic material for plant breeding, plants for natural medicines, ornamental products, animal products for fashion, etc.
Regulating	Flood regulation, coastal storm surge mitigation, climate regulation (carbon sequestration), erosion control, water quality
Cultural	Aesthetics, spiritual, educational, recreational/ecotourism, inspiration, sense of place

were highly valued by the agrarian societies since their livelihood largely depended on wetlands, and the lack of woody vegetation in salt marshes facilitated their conversion for agricultural uses. At the time of the European settlement of North America, salt marshes were arguably the most valuable natural resource in the colonies. Land prices in coastal agrarian communities were affected by the availability of salt marshes which was recognized as prized land for grazing and harvesting salt hay (an acre of salt marsh could produce enough hay to get one cow through the winter), as well as flat non-forested land that could be cultivated after diking and drainage (Hatvany 2001). However, with a change in culture to an industrial society that needed to support an ever-increasing population, values changed, technology facilitated conversion of forests to agriculture land, and it became easier to fill these areas for ports and other developments. Salt marshes became viewed by the societal leaders and the public at large as worthless lands, even a public nuisance in some regions as they produced hordes of mosquitoes that carried malaria and other life-threatening diseases. Consequently, tidal wetlands were ditched, drained, filled, or manipulated for a wide range of purposes.

While wetland functions continue to operate whether or not they are valued by society, economic and cultural values are set by society, and they may change as society changes. Tidal salt marshes provide many functions that yield many benefits to people and the estuarine aquatic ecosystem. The functions and values that they and other wetlands offer have been referred to as “ecosystem services” with the emphasis, often, on the ones of value to people (Reid et al. 2005). Table 2 lists some of the ecosystem services attributed to estuarine marsh. According to commonly used measures, the human well-being of coastal inhabitants is on average much higher than that of inland communities (Reid et al. 2005). The connection between people and the coastal waters and their wetlands is and has been an essential ingredient of this well-being.

In recognizing the ecosystem services provided by coastal wetlands in general, Laffoley and Grimsditch (2009) highlight the significant role of coastal wetlands including salt marsh in national and international climate change mitigation. Uncertainties in the global extent of salt marsh resulted in a conservative estimate by Chmura et al. (2003) of at least 430 Tg of carbon stores in the upper 50 cm of tidal salt marsh soils. Recent studies on carbon sequestration in tidal salt marsh have reported mean carbon burial rates that are probably an order of magnitude higher than terrestrial forests (Chmura 2013) but which can range from less than 20 to more than 1,700 g C $m^{-2}years^{-1}$ (McLeod et al. 2011). In October 2013, the Intergovernmental Panel on Climate Change (IPCC) adopted the *2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories*: *Wetlands* (*Wetlands Supplement*) of standards to assess and report on emissions from organic soils and wetlands including tidal marshes (IPCC 2014a). Moreover, salt marsh restoration activities are eligible for certification as greenhouse gas emission reduction projects in the voluntary carbon markets using existing standards, e.g., the Verified Carbon Standard VM0033 (http://database.v-c-s.org/methodologies/methodology-tidal-wetland-and-seagrass-restoration-v10).

The attribution of these ecosystem services to salt marsh is changing how they are valued by society. Formerly the value of a good or service was based on what someone might pay for a physical marketable product harvested from the wetland or, in terms of land, what one could sell it for or earn from it by growing crops, raising livestock, harvesting timber, or extracting minerals. Conventional valuation approaches undervalue natural resources that are not harvested and sold for profit, ignoring functions that benefit society at large (e.g., shoreline and flood protection, water quality renovation, recreation, and aesthetics), and help maintain a healthy estuarine ecosystem.

The conventional approach began to change in the 1970s with development of an economic valuation system that included an analysis of the life support role that tidal wetlands play (Gosselink et al. 1973, 1974). This was perhaps the beginning of what eventually emerged as the discipline of ecological economics that attempts to value the nonmarket values of natural resources – “natural capital” and “environmental services.” An American Northeast example of the use of these modern assessment techniques valued New Jersey’s estuarine wetlands at over $6,000 per acre annually, for a total resource value between $1.1 and $1.2 billion (Costanza et al. 2006; Mates 2007), and storm protection by US tidal wetlands alone produce benefits worth $23.2 billion per year (Costanza et al. 2008). Using more sophisticated methods than previously available to estimate the global economic value of tidal wetlands (Costanza et al. 1997), resource economists have determined that the world’s tidal wetlands (marsh and mangroves) may produce environmental services worth about $24.8 trillion annually which recognizes the immense storm protection, erosion control, and waste treatment values of these systems (Costanza et al. 2014).

Costanza et al. (2014) comment on how the valuation of ecosystem services can be used for a diverse group of purposes over multiple time and spatial scales including raising awareness and policy analyses. They caution against perceiving the valuations as exchange values rather than use or nonuse values associated with nonmarketable public goods or common pool resources. Valuation of ecosystem services is rather an approach to “…build a more comprehensive and balanced picture of the assets that support human well-being and human’s interdependence with the well-being of all life on the planet.” It is another “tool” to inform more balanced decision-making in achieving a healthy, productive ecosystem that supports human well-being and self-sustaining coastal fisheries and provides the vital links for migratory waterfowl, wading birds, and shorebirds moving between breeding grounds and winter habitat, without putting any species at risk of extinction.

Threats and Future Challenges

Their location at the interface of land and sea and the fact that the most populated areas of the world tend to be concentrated along the world's oceans have rendered tidal marshes especially vulnerable to the development and to the effect of climate change on sea level. Salt marshes are subjected to both natural and often intense human disturbances that affect their extent and quality (see Table 3). Their topographical position and features in close proximity to areas favored by human settlement and industrial patterns are a key determinant in the threats and challenges faced by salt marsh (Gedan et al. 2009; Adam 2016). Population pressure on coastal resources continues and in many developing regions is increasing. Nearly half of the world's major cities (having more than 500,000 people) are located within 50 km of a coastline, and more than a third of the global population resides coastally on approximately 4% of the land surface at densities 2.6 times larger than the density of inland areas (Reid et al. 2005). Despite environmental regulations and recognition/valuation of the ecosystem services, processes and functions provided by salt marsh, these systems remain under threat of loss or environmental degradation due to infrastructure development to provide for a growing and more affluent global population and accidental or purposeful discharges of industrial and domestic wastes (Adam 2016).

The introduction of new species to an ecosystem, whether by accident or deliberate, that become invasive is seen as a major threat to biodiversity and especially those species that are transformative in changing the ecological character of the ecosystem over substantive areas (Richardson et al. 2000). Estuaries and thus salt marshes are particularly exposed to invasive introductions by marine shipping from ballast release or as fouling organisms on ships' hulls (Adam 2016), e.g., the burrows of the Australian burrowing isopod *Sphaeroma quoyanum* introduced by ships to California in the mid-nineteenth century have altered sediment shear strength and increased erosion rates of US west coast salt marsh (Adam et al. 2008). Large numbers of introduced plants have been recorded in salt marsh (Adam 2002), but a smaller number of perennial species have major impacts. *Spartina* species and hybrids have been deliberately introduced to stabilize mudflats and create new marsh on North America's west coast, England, Europe, Australasia, and China with unintended results including loss of habitat for wading birds, outcompeting native plant species and displacing infauna through alteration of the physical structure of the marsh environment (Adam et al. 2008; Gedan et al. 2009; Adam 2016). *Juncus acutus*, native to the Mediterranean, is aggressively colonizing and displacing the native *J. kraussii* in eastern Australia (Adam 2002), and a number of species of *Tamarix* (native to Asia and Africa) introduced to North America are invading and converting herbaceous salt marsh to woodland (Adam 2002, 2016;

Table 3 Some impacts to tidal wetlands from (A) natural processes or activities and (B) human-induced disturbances (Source: Tiner 2013)

(A) **Natural processes or activities**	**Possible impacts**
Sea level rise and coastal plain subsidence	Submergence (loss) of wetland, change from vegetated wetland to tidal flat/open water, change from tidal flat to open water, change in shorelines, landward migration of marshes if suitable space is available, increase in salinity with changes in plant communities
Coastal processes (wave action, currents, and tides)	Erosion, sedimentation, wetland loss or gain, smothering of vegetation (e.g., from deposition of tidal wrack or overwash sediments), and changing shorelines
Deltaic soil compaction	Same as for sea-level rise and coastal plain subsidence, except migration and salinity changes
Hurricanes and other storms	Sedimentation (including overwash deposits), erosion, vegetation impacts, wetland loss or gain, saltwater intrusion, and changing shorelines
Ice scour	Erosion, vegetation removal, creation of open water in marsh
Grazing by animals (e.g., waterfowl, fur-bearers, and invertebrates)	Loss of vegetation (denuded areas) and vegetation changes
Insect infestations	Loss of vegetation and vegetation changes
Disease outbreaks	Loss of vegetation and vegetation changes
Beaver dams	Reduce tidal flowage to tidal freshwater wetlands, and vegetation changes
Fire from lightning	Vegetation impacts
Droughts	Brown marsh syndrome, vegetation changes
(B) **Human-induced disturbances**	**Possible impacts**
Filling for development (port, industrial, commercial, etc.)	Loss of wetland
Disposal of dredged material or garbage	Loss of wetland or change in plant community depending on amount of spoil
Construction of jetties and groins	Loss of wetland, changes in wetland type, altered hydrology, shoreline changes, and changes in wildlife use
Armoring shorelines	Loss of wetland and stops landward migration of tidal wetland
Construction of docks	Shading of vegetation and disturbance to wildlife
Dredging for marinas and residential development (canal development)	Loss of wetland and degraded water quality
Drainage for mosquito control	Altered hydrology, increased salinity, vegetation changes, and local subsidence
Diking (for many purposes)	Altered hydrology, vegetation changes, localized subsidence, loss or diminished estuarine exchange, and loss of wetland
Road and railroad crossings	Loss of wetland, altered hydrology, and vegetation changes
Installation of tide gates	Altered hydrology, salinity changes, and changes in vegetation and aquatic life

(*continued*)

Table 3 (continued)

Nonpoint source pollution from farms, lawns, etc.	Eutrophication vegetation changes, and changes in aquatic life
Discharge of industrial or municipal wastewater	Water pollution, fish kills, degraded water quality, increased algal blooms, hypoxia, and changes in vegetation and aquatic life
Oil spills	Vegetation die-off, changes in aquatic life, substrate contamination, death for oiled wildlife, fish kills, and water pollution
Deepening channels and dredging canals for navigation	Increased salt water intrusion, altered hydrology, shoreline erosion, vegetation changes, and change in aquatic life
Damming of tidal rivers for various purposes	Reduction in sediment load, loss of wetland, altered hydrology, altered salinity regimes, vegetation changes, and changes in aquatic life (e.g., fish migration)
Water withdrawals	Altered hydrology, possible subsidence, altered salinity regimes, and corresponding changes in vegetation and aquatic life
Diversion of river flows	Altered hydrology, increased salinity and corresponding changes in aquatic life
Groundwater withdrawals	Subsidence and changes in vegetation
Oil and gas withdrawals	Possible subsidence, corresponding changes in vegetation and aquatic life, and pollution from spills and leaks (see oil spills)
Prescribed burning for wildlife	Loss of soil organic matter and vegetation changes management
Timber harvest	Vegetation changes, may facilitate conversion to other uses
Log storage	Topographic changes, vegetation changes, habitat degradation
Marine aquaculture	Change in current patterns, disturbance to water birds, possible loss of wetland (via conversion to open water)
Harvest of baitworms	Disturbance to water birds and changes in invertebrate density
Plant introductions	Invasive species replacement of native flora and altered hydrology
Animal introductions	Replacement of native fauna
Grazing by livestock	Soil compaction and changes in vegetation
All-terrain vehicle traffic	Vegetation impacts, disturbance and destruction of nests and young birds
Beach renourishment	Change in sand composition and changes in invertebrate usage
Noise and light pollution (nighttime)	Unknown effect on wildlife, probable displacement of sensitive species; latter disturbance disorients nesting sea turtles
Plant collection	Loss or reduction of local populations (overharvest, e.g., sea lavender)
Nitrogen inputs from runoff	Change in vegetation, plant productivity, and aquatic life
Spraying of pesticides	Aquatic organism kills

Notes: With human impacts, changes are mostly one-directional (i.e., losses). Note that where a significant change in vegetation occurs, a change in wildlife use will likely occur

Gedan et al. 2009). *Phragmites australis* is indigenous but rarely dominant in North America's upper salt marsh of North America, but an introduced European strain that is more salt tolerant now forms extensive near monocultures, displacing other native species (Adam et al. 2008; Tiner 2013; Adam 2016).

The IPCC's 5th Assessment Report (2014b) is unequivocal that warming of the global climate system is occurring and primarily human induced and that climate changes are already underway and projected to grow (e.g., sea-level rise, changing precipitation patterns, longer growing season, rise in temperature, longer ice-free season for oceans and fresh water bodies, earlier snow melt, and changes in river flows). Changes in temperature and precipitation patterns will significantly affect the life cycles of many plants and animals worldwide. Examples of these changes have already been observed such as earlier spring migrations and northward range expansions of many North American birds (Hitch and Leberg 2007; McDonald et al. 2012; Auer and King 2014), and mangrove species have expanded their range poleward on at least five continents by replacing salt marsh (Saintilan et al. 2014). Although temperature is the key delimiting factor that predicates comprehensive mangrove replacement of salt marsh-dominated ecosystems, mangrove will be favored by environmental factors associated with global climate change including elevated sea level, elevated CO_2, and higher temperatures (Saintilan et al. 2014).

Temperature changes will also affect plant community composition. As an example, while rising sea levels may create more panne habitat (water-retaining depressions) in New England (USA) high marshes (Warren and Niering 1993), panne forbs may be replaced by salt hay grass *Spartina patens* prior to the formation of new pannes, thereby precluding forb colonization of the new pannes (Gedan and Bertness 2009). Warming might tend to favor C4 plant species, but C3 plants because of differences at the cellular level have been shown to respond more positively to elevated CO_2 (Ainsworth and Long 2005). Salt marshes contain a mixture of C3 and C4, and this differential response to elevated CO_2 may favor compositional shifts to C3 plants (Gedan et al. 2009) although other ecological factors can influence the ratio of C3–C4 plants (Adam 2002). Lengthening of the growing season in middle and northern latitudes will likely increase productivity of plants and greater incorporation of organic material into salt marsh soils (Kirwan et al. 2009; Langley et al. 2009).

The effect of global warming on rising sea level has enormous consequences and poses the greatest risks to the physical integrity of tidal wetlands as well as to coastal communities and Pacific island nations and territories. Thermal expansion of the ocean in combination with accelerated melting polar and glacial ice causes a rise in sea level referred to as "eustatic sea-level rise." Local and regional conditions (e.g., subsidence and tectonic activity) may affect the position of the land relative to sea level. The combined effects of eustatic sea-level rise and local land elevation changes produce what is called "relative sea-level rise". Relative sea-level rise is greater than eustatic sea-level rise where land subsides and is less where land rises (uplifts) (e.g., Hudson Bay Lowlands, Riley 2011). The latter situation often results in “negative relative sea-level rise.” Today, sea-level rise poses the greatest threat to the tidal marshes worldwide (e.g., Valiela et al. 2009; Tiner 2013).

The long-term stability of coastal wetlands in response to sea-level rise depends upon maintaining their position relative to the tidal frame by either horizontal migration landward and/or vertical migration through sedimentation (McFadden et al. 2007). A potential consequence of sea-level rise will be “drowning” of salt marsh and “coastal squeeze” where landward margins affected by steep topographical gradients or coastal defense structures prevent their horizontal migration (Adam 2016). Hoozemans et al. (1993) and Nicholls et al. (1999) using a similar scenario of a 1-m global sea-level rise in combination with human activities estimated coastal wetland (salt marsh, mangrove, intertidal areas) losses of 55% and 46%, respectively, based upon a limited 1990 dataset (~300,000 km^2) of coastal Ramsar Wetlands of International Importance. Nicholls et al.’s (1999) additional analyses of this dataset employing scenarios with a 38-cm global sea-level rise by the 2080s estimated global cumulative coastal wetland loss of 36–70% partitioned between human (25–57%) and relative sea-level rise (6–22%) impacts. Spencer et al. (2016) reevaluated these earlier broad-scale assessments of coastal wetland vulnerability to sea-level rise by incorporating improved data on global coastal wetland stocks, greater understanding of the main drivers of change, and further development of the Dynamic Interactive Vulnerability Assessment Wetland Change Model. The model’s algorithm follows MacFadden et al.’s (2007) consideration of three key drivers that control wetland-type response over different time horizons to (1) local sea-level rise relative to tidal range, (2) opportunity to horizontal migration, and (3) sediment supply. Their results are however consistent with the earlier studies. Evaluating the effects of restrictions to horizontal migration capacity (dike construction) and sediment supply, comparable sea-level rise scenarios of 29 and 110 cm give coastal wetland loss estimates of 32–40% and 53–60%, respectively, by the 2080s. Since coastal wetlands are dynamic resources that move both landward and seaward in response to long-term changes in sea level, the development of low-lying areas adjacent to tidal wetlands and construction of hardened shoreline (bulkheads, seawalls, and riprap) to protect those properties prevents the natural landward migration of salt marshes accompanying rising sea level. Its impact will undoubtedly be exacerbated by the likely societal response of shoreline armoring to protect private property. This has serious implications for the future of today’s tidal marsh.

The passage of environmental laws and policies has greatly improved the status of coastal wetlands in many countries (Tiner 2013). Moreover there are increasing numbers of examples at local and estuary scales of activities to restore salt marsh functions where there has been historical loss (Balletto et al. 2005; Adam et al. 2008; Tiner 2013). Nonetheless, even with existing regulations, policies and international agreements (e.g., Ramsar Convention on Wetlands) in effect, there remain serious threats to coastal wetlands particularly in developing tropical countries. In all countries, laws can be changed by legislative bodies, and the effectiveness of regulations in protecting wetlands can be weakened by the courts, lack of enforcement, or “flexibly” applied to permit further loss of salt marsh to human developments (Adam 2002; Tiner 2013).

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