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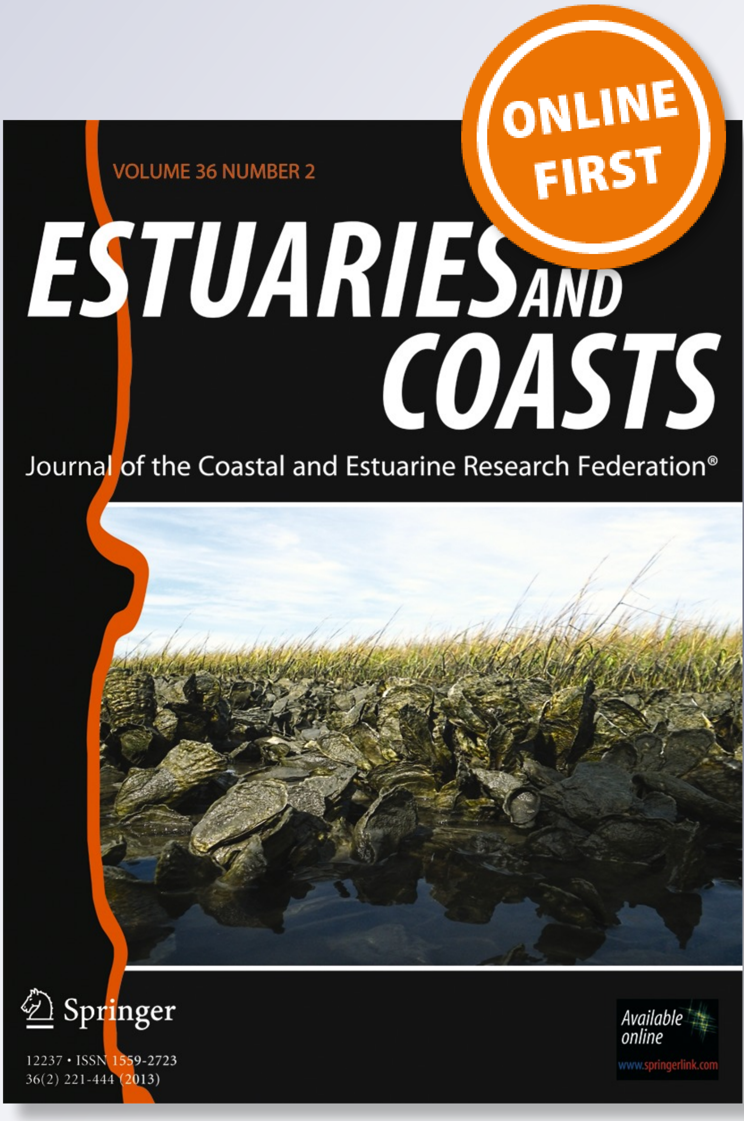
Estuaries and Coasts
Journal of the Coastal and Estuarine Research Federation

ISSN 1559-2723

Estuaries and Coasts
DOI 10.1007/s12237-013-9626-z



Springer

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Received: 5 December 2012 / Revised: 27 March 2013 / Accepted: 1 April 2013

Abstract Tidal freshwater wetlands (TFW) are situated in the upper estuary in a zone bordered upstream by the nontidal river and downstream by the oligohaline region. Here, discharge of freshwater from the river and the daily tidal pulse from the sea combine to create conditions where TFW develop. TFW are often located where human population density is high, which has led to wetland degradation or destruction. Globally, TFW are largely restricted to the temperate zone where the magnitude of annual river discharge prevents saline waters from penetrating too far inland. The constant input of river water delivers high loads of sediments, dissolved nutrients, and other suspended matter leading to high sedimentation rates and high nutrient levels. Prominent biogeochemical processes include the transformation of nitrogen by bacteria and immobilization of phosphate. A diverse, characteristic vegetation community develops which supports a rich fauna. Biotic diversity is highest in the high marsh areas and decreases in the lower levels where tidal inundation is greatest. Benthic fauna is rather poor in diversity but high in biomass compared to other regions of the estuary. Global climate change is a threat for this system directly by sea level rise, which will cause brackish water to intrude into the fresh system, and indirectly during droughts, which reduce river discharge. Salinity will affect the presence of flora and fauna and facilitates sulfate reduction of organic matter in the soil. Increased decomposition of organic matter following saltwater intrusion can result in a lowering of wetland surface elevation. The papers assembled in this issue focus on how these tidal freshwater wetlands have changed over recent time and how they may respond to new impacts in the future.

Keywords Estuary · River · Fresh water · Processes · Hydrology · Distribution · History · Human impact · Diversity · Global change

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Introduction

This special journal feature was developed from papers delivered at a session on tidal freshwater wetlands (TFW) organized by Patricia Delgado and Christopher Swarth that was held at the CERF conference in Portland, OR, USA in November 2009; three additional papers on microbial soil processes were added later. Presentations at the Portland conference addressed environmental issues impacting tidal freshwater wetlands and their associated flora and fauna, while providing new information on their status, restoration, protection, and management efforts in the USA.

This introduction describes some major physical and ecological features of TFW and the environmental impacts they face. We outline the history and distribution of TFW, the differences with brackish regions, their physical and chemical processes, and biotic diversity. Another section considers human impacts and global change, indicating the set of problems that TFW have experienced during recent decades. We conclude with brief summaries of the papers that are included in this issue.

Published online: 17 April 2013

Tidal freshwater wetlands are often near dense population centers and as a result are subjected to numerous environmental stressors. Intense human development has reduced many tidal freshwater wetlands to scattered remnants. Mounting pressure from land use practices leading to outcomes such as increased sediment and nutrient loads, and to hydrological alterations in addition to invasive species and potential impacts from climate change (particularly salt water intrusion and sea level rise), continue to threaten these productive ecosystems. On the other hand, TFW provide important services to society, ranging from hydrological processes (e.g., flood water retention and groundwater recharge) to sediment accretion and many chemical and bacterial processes that reduce concentrations of dissolved carbon, nitrogen, and phosphorus (Arrigoni et al. 2008; Ensign et al. 2008; Hopfensperger et al. 2009; Megonigal and Neubauer 2009; Loomis and Craft 2011).

The TFW domain occupies the floodplain space between the upstream nontidal river and the downstream saline estuary. These wetlands are at the upper end of the estuarine gradient where salinity does not generally exceed 0.5; the tidal pulse is a dominant feature of the ecosystem. Discharging rivers supply the TFW with freshwater but a river sensu stricto lacks tides; thus, TFW exhibit bidirectional current flow and high sedimentation compared with rivers and even with other sections of the estuary (Craft 2007). Compared with the lower regions of an estuary, measurable salinity is largely absent in TFW, resulting in fundamentally different chemical and biological processes. In common, however, are physical processes linked to the tidal amplitude because the tides are not restricted to saline waters; it is the tidal energy that creates the flow upstream into the river. Between the brackish section in the estuary and the upstream limit of the tidal wave is the tidal freshwater section that, depending on the geomorphology, extends for 30–100 km, or in the most extreme case of the Amazon, up to 800 km.

Estuarine researchers tended to concentrate on the more saline portions of coastal systems (McLusky 1993), whereas river ecologists avoided regions where rivers experiences tidal fluctuations. As a result, little attention was devoted to the "hybrid" ecosystem in the middle. This focus is now changing as more researchers investigate the biogeochemical processes, ecological relationships, and ecosystem responses to global climate change occurring within these wetlands.

The major differences with the more saline parts of the estuary can be appreciated by (1) the different species assemblages in the freshwater region including high avian diversity, as well as increased prevalence of shrubs and trees; (2) chemical processes such as the oxidation of organic matter by methanogenesis rather than sulfate reduction; (3) the prominent human impacts; and (4) the sensitivity of the TFW to future increases in salinity that will result from global climate change.

In estuaries, two major ecological axes predominate: from the fresh environment to the saline sea and from the upland terrestrial environment to deep water. Both axes change gradually, yet completely, creating conditions for the potential variety in biodiversity. The estuary, therefore, is "a habitat, which is a complex dynamic mixture of transitional situations and is almost never static and where physical and chemical factors show marked variations" (McLusky and Elliott 2004). A number of other definitions of the estuary have been put forth (Davidson et al. 1991); most have in common a river that discharges water into the estuary resulting in a salinity gradient. In TFW, this salt stress is absent, but flooding by the tides causes physical stress that selects for the presence of species and dominates the ecological processes.

The controversies in the definition of an estuary have been discussed by Elliott and McLusky (2002); McLusky and Elliott (2007). The definition by Pritchard (1967) used the boundary of the saline water intrusion as the upper limit of the estuary. Fairbridge (1980) incorporated the freshwater sections in the estuary in his definition, describing it as "an inlet of the sea reaching into the river valley as far as the upstream limit of the tidal rise." This discussion about definitions is not just a game with words. For example, a legal consequence in Europe is that protection by the Water Framework Directive of "transitional waters" in estuaries is valid but the Directive does not specify that tidal freshwater wetlands are an integral part of the estuary, resulting in heated discussions about the status (Elliott and McLusky 2002; Van den Bergh et al. 2009).

History and Distribution

Humans have used European TFW at least since the Neolithic Period (5000–4000 BP). In the UK (Severn and Humber Rivers; Van de Noort 2004) and the Netherlands (Meuse River; Van Regteren Altena et al. 1962), hunters lived in the tidal plains and had temporary settlements. These early locations are long buried beneath sediments because sea level rose for meters after that period, but humans have been present for most of the time (Zonneveld and Barendregt 2009). Little information is available from North America (Schneider 1996), but dated archeological remains document the continual presence of Native Americans (e.g., at Jug Bay, MD, USA) for 12,000 years (Dent 1995; Al Luckenback, personal communication). During those early periods, the impact of humans would have been localized and relatively minor, although sedimentation was an issue in some areas (Stinchcomb et al. 2011). Sea level, of course, was many meters lower at that period.

In Europe, the clearing of woodlands for agriculture during the Neolithic Period caused erosion in the watersheds of major rivers, which resulted in the transportation of enormous sediment loads into estuaries (e.g., Erkens 2010). During the period 5000–1000 BP, the geomorphology of modern European estuaries developed. In North America, the same geomorphological changes are reported (Fletcher et al. 1993) and major landscape changes began with the arrival of European colonists 350 years ago. In the eastern USA, erosion increased owing to forest clearing for agriculture; water mills with their ponds trapped sediments (Walter and Merrits 2008), which went into the coastal estuaries after the ponds were abandoned and breached. As a result of all these activities, sedimentation rates in TFW increased during the last three centuries (e.g., Orson et al. 1990; Pasternack et al. 2001).

The previous 200 years of modifications have impacted many European TFW, just as in North America. This includes the reclamation of wetlands for agriculture and for built-up areas and prominent changes in hydrology caused by closing rivers from the estuary (e.g., Somme in France), damming the entire estuary (e.g., Rhine–Meuse in The Netherlands), and by deepening channels (e.g., Elbe in Germany). In addition to these physical changes, chemical pollution and eutrophication must also be considered (e.g., Riedel-Lorjé and Gaument 1982). As result, many TFW have become degraded and reduced in area. However, when the connection with the tides is maintained or restored, TFW are able to persist. Some TFW possess many of their original values and functions and there are regions such as in Alaska, with pristine TFW (Hall 2009).

The conclusion is that for many estuaries, the natural conditions in the freshwater sections have been replaced following human occupation and development and, as a result, the original ecosystem is mostly unfamiliar even to ecologists. Even basic knowledge on the global distribution of the TFW is lacking. However, a growing body of knowledge is beginning to accumulate: in North America (east and west coasts), including the Mississippi Delta (Sasser et al. 1995), and in Europe (Barendregt et al. 2009a); in China and Japan (Baldwin et al. 2009); and in the Southern hemisphere along the Rio de Plata estuary in Argentina (Kandus and Malvárez 2004). The relative lack of information about this ecosystem, the tremendous productivity, and the many aspects in the estuarine functions (e.g., fisheries) are important arguments for summarizing recent knowledge.

The global distribution of TFW appears to be related to the constancy of river discharges. By using the average monthly discharge (in cubic meter per second) of rivers and selecting the maximum and minimum values, we calculated an index for a selection of rivers (Table 1, data from www.sage.wisc.edu/riverdata). The rivers in Table 1 from the temperate zone are reported (in literature or communication) for their presence of TFW. When the minimum discharge is greater than 10–15 % of the maximum, the fresh conditions

Table 1 Discharge data from temperate, tropical, and Mediterranean climate region rivers. Indicated are: river, country, mean maximum, and mean minimum monthly discharge (in cubic meter per second) and the percent that the minimum is of the maximum. Selected is the most downstream discharge gauge of the river in database; in case of multiple monitoring locations, the selected entry in the database is mentioned after the name of the river

	Mean maximum	Mean minimum	%Min/max
TFW in temperate climate—Northern and Southern hemisphere			
Yukon, USA	16,714	1,382	8.2
Copper, USA	5,350	239	4.5
St Lawrence, Canada	8,080	6,689	82.8
Hudson (2884), USA	885	163	18.4
Delaware, USA	651	155	23.8
Potomac, USA	645	120	18.6
James (2902), USA	356	91	25.6
Connecticut, USA	1,243	173	13.9
Mississippi (3456), USA	22,125	6,325	28.6
Sacramento, USA	387	87	22.5
Columbia (3845), USA	9,340	3,675	39.3
Changjang, China	41,425	9,258	22.3
HuangHe, China	2,858	543	29.0
Elbe, Germany	1,072	463	43.2
Weser, Germany	460	192	41.7
Rhine, the Netherlands	2,998	1,728	57.6
Thames, UK	138	34	24.6
Trent (Humber), UK	151	45	29.8
Seine, France	560	101	18.0
Loire, France	1,519	256	16.8
Negro, Uruguay	850	239	28.1
Rio Uruguay, Uruguay	9,203	4,089	44.4
No reported TFW in (sub-)tropical and Mediterranean climate			
Amazon, Brasil	239,302	113,602	47.5
Zaire, Congo	56,042	31,065	55.4
Orinoco, Venezuela	46,200	7,520	16.3
Marowijne, Surinam	1,178	50	4.0
Fritzroy, Australia	942	8	0.1
Ganges, Bangladesh	26,307	1,386	5.3
Mekong, Thailand	21,872	1,505	6.8
Indus, Pakistan	10,128	189	1.9
Tapi, India	1,941	58	3.0
Buzi, Mozambique	800	54	6.7
Save, Mozambique	1,468	14	1.0
Sanaga, Cameroon	5,357	529	9.8
Gambie, Senegal	552	10	1.8
Juba, Somalia	457	31	6.8
Dowga, Nigeria	1,490	109	7.3
Comoe, Ivory Coast	370	0.8	0.2
Mondego, Portugal	410	11	2.7

for the occurrence of TFW exist (in Alaska, many rivers are frozen in winter, with limited discharge). When discharge falls below this 10–15 % value, excessive saline water temporarily enters the system and TFW cannot develop or persist. Such conditions prevail in Africa, Australia, and Southern Asia, where, instead of TFW, mangroves dominate the coasts and estuaries. Extremely large rivers in tropical regions, such as the Amazon, have no TFW in our information.

The first synthetic studies of North American TFW were made by Good et al. (1978), Simpson et al. (1983), and Odum et al. (1984). Mitsch and Gosselink (2007) summarized the general characteristics of TFW, Yozzo et al. (1994) prepared a bibliography of studies, and, recently, Conner at al. (2007) summarized the forested TFW of the US East Coast. In European TFW, integrated research on physical processes, soil development, vegetation, and hydrology was initiated in the Rhine–Meuse (Zonneveld 1960) and Elbe estuaries (Kötter 1961) in the 1950s. Over the next 25 years, many publications on fauna and hydrology came from the same regions. A synthesis of European research is found in the special issue by Meire and Vincx (1993) and in Meire and Van Damme (2005) on the Scheldt estuary. A worldwide review of many aspects of TFW is in Barendregt et al. (2009a).

Differences with the Brackish Region of the Estuary

The dynamic nature of estuaries makes them difficult to characterize. Many review papers describe characteristics and differences among US estuaries (e.g., Roman et al. 2000; Dame et al. 2000; Emmett et al. 2000) and European estuaries (e.g., McLusky and Elliott 2007), but few devote attention to the freshwater tidal regions. For example, Roman et al. (2000) state that the physiography of the drainage basin and suspended sediment load are key characteristics that define the variability of salt marshes across regions, but not for TFW.

Due to physiological processes, most plants and animals found in TFW cannot survive a pulse in salinity, even for short periods (Edmiston et al. 2008). The constant input of freshwater is a basic life requirement; however, this can be disturbed in many ways. River discharge is affected by water regulations (77 % of world rivers are regulated; Dynesius and Nilsson 1994). Many rivers are blocked off from the estuary by dams and entire estuaries may be closed from the sea (Roman et al. 2000; Barendregt et al. 2009c), such that the freshwater regions are cut off from the tides and isolated from the estuary. The opposite conditions can develop when shipping lanes are dredged in the estuary and saline water enters the TFW (Kerner 2007). The rise in tidal amplitude (1 m) in Delaware River at Trenton is attributed at least in part to dredging for shipping (M. Leck, personal communication).

The most prominent chemical differentiation in the estuary is the mineralization of organic matter (Odum 1988). The fresh regions are characterized by methanogenesis as in other freshwater systems; whereas in the brackish and saline parts, the oxidation of organic matter is often coupled with sulfate reduction (Weston et al. 2006, 2011). This is a fundamental difference between TFW and the brackish regions of the estuary. However, locally, Fe(III) reduction can be the dominant anaerobic mineralization process in TFW and salt marshes (Megonigal and Neubauer 2009). The accumulation of organic carbon and nitrogen in the sediments appears to be greater in the fresh parts compared with the brackish or saltier regions (Loomis and Craft 2011). The saline parts of the estuary are mainly nitrogen limited, whereas the fresh parts are mostly co-limited by nitrogen and phosphorus (Crain 2007). However, recent research indicates that some TFW marshes are also nitrogen limited (Ket et al. 2011). More study on this subject is needed as some researchers suggest that the TFW swamps are phosphorus limited (Bedford et al. 1999; Baldwin 2007).

The diversity of flora and fauna species in tidal freshwater marshes is greater than in salt marshes. Benthic diversity in the estuary decreases from the river to the tidal fresh parts and further to the brackish parts, and increases again with higher salinity (Remane 1934; Remane and Schlieper 1971; McLusky and Elliott 2007); at salinities of 5–10, diversity is at a minimum. Seasonal variation in salinity is more important in causing low diversity than salinity concentration itself (Wolff 1973; Attrill 2002). This is in line with the characteristics of TFW, where permanent freshwater conditions should be present. Macrobenthos diversity and relative species abundance in the subtidal fresh habitats is comparable with that of the rivers, with high biomass in Oligochaeta (especially *Tubifex* species), Diptera (chironomids), and Mollusca (Wolff 1973; Swarth and Kiviat 2009; Barendregt et al. 2009b). The brackish (mesohaline) region is characterized by polychaetes and amphipods, whereas higher salinity regions are characterized by polychaetes and Mollusca (Ysebaert et al. 1998). The estuarine distribution of shorebirds (waders) and waterfowl (particularly diving ducks) is related in large part to this gradient in their macrobenthos prey resource (Ysebaert et al. 2003).

Researchers often describe general TFW “zones”, such as the high marsh, the (intertidal) low marsh, and subtidal habitats. The high fresh marsh has a wealth of vegetation (e.g., *Bidens*, *Typha*, and *Sagittaria* in North America; *Valeriana* and *Symphytum* in Europe); grasses dominate the high brackish marsh. The TFW low marsh, where inundation is prolonged, is species poor (e.g., with *Nuphar* or *Zizania* in North America; *Schoenoplectus* or *Caltha* in Europe). This is comparable to the low brackish marsh communities that are typically dominated by a few species (e.g., S*partina* species). Many subtidal areas lack emergent plants due to turbidity and wind- or current-induced dynamics in the water; but these areas may have a number of submergent species, e.g., *Vallisneria americana*, *Hydrilla verticillata*, and *Elodea* spp. Phytoplankton production is very high in the freshwater part of the estuary compared with the brackish parts (Heip et al. 1995; McLusky and Elliott 2007; Van Damme et al. 2009), apparently due to high nutrient availability.

Physical and Biogeochemical Processes

The constant input of fresh river water in the TFW results in two main depositional processes or conditions. First, most materials (i.e., sediments, nutrients, and suspended particulate matter) that are discharged into the river catchment basin or watershed will eventually enter the estuary. The tidal freshwater region of the estuary, except blackwater systems (Kerr et al. 2013), is rich in these substances. Second, the interface of fresh and brackish water is the location where large amounts of suspended matter are concentrated (e.g., Grabemann and Krause 2001; Fain et al. 2001). This section is called the estuarine turbidity maximum or ETM. Suspended particulate matter develops where high-density brackish water moved upstream by the tides meets low density freshwater, often as a salt wedge (Meade 1972). High turbidity results where these fresh and brackish waters meet (Barendregt et al. 2006).

Three conditions can explain these sedimentary processes. First, the upstream flow of brackish bottom water and the downstream flow of fresh river water on the surface meet at a tangential plane, where velocity is near zero and suspended matter concentrations appear to be highest (Officer 1981). Second, physical–chemical processes occur with the load of chloride ions and organic particles, resulting in flocculation at these low salinities (Eisma 1986). Flocculation results in the production of high concentrations of suspended matter that accumulates and creates mudflats and consequently layers of clay. The third condition, explained by Verney et al. (2009), stresses the importance of diatom blooms near the concentrations of suspended particulate matter; salinity does not appear to be an explanatory factor.

A consequence of the suspended particulate matter is high sedimentation rates in TFW. Deltas grow by vertical accretion and this process is described for TFW by Kahn and Brush (1994), Pasternack and Brush (1998, 2001), Neubauer et al. (2002), and Craft (2007). Pasternack (2009) reviews the different scales in geography and time over which this occurs. Wetland plants cause vertical accretion directly by trapping sediment on leaves and culms and among roots, but prominently by the production of organic matter that becomes buried in the sediments (Darke and Megonigal 2003). Neubauer (2008) stated that organic compounds contribute four times as much material to accretionary buildup as do the mineral components, indicating that there are prominent local feedback mechanisms between the biotic and physical processes that impact this accretion. Moreover, accretion rates vary seasonally (Pasternack and Brush 2001) such that the vertical accretion in these dynamic tidal areas is a balance between erosion and sedimentation. Spatial and temporal variation can result in source-sink conditions at the same location in TFW (Lehman et al. 2010).

The chemistry of the sediments is influenced by the mineral components in the suspended material and ions in solution in the tidal waters. Land use, human waste, and treated wastewaters result in the discharge of high concentrations of nutrients and suspended particulate matter (Alberts and Takács 1999). Additionally, the biological processes of uptake, digestion, or oxidation by bacteria, plants, and animals directly impact this chemical pollution. To review the sources of mineral and chemical contributions, three types of loads will be discussed.

Sediments—sand and clay from the river is deposited in the estuary resulting in accretion.

Suspended matter—suspended loads of organic and inorganic matter in the river water enter the TFW and via precipitation and deposition augment the creation of flats and marshes. Pesticides, heavy metals, and other toxic substances are also stored in the soil.

Dissolved matter—nutrients and dissolved organic matter in the river water are subjected to microbial and chemical processes. Owing to the shallow water and large surface area, nutrients stimulate bacterial growth, and the tidal dynamics lead to changeable aerobic and anaerobic conditions, which stimulate nitrification and denitrification. Additionally, phosphate can precipitate with iron or calcium. The organic matter (waste) in the water is removed by bacteria and leaves the system as CO_2.

To illustrate the capacity of TFW to transform nutrients, Table 2 compares the output of freshwater from a TFW in The Netherlands (Tiengemeten) with the input in a 12.5-h tidal cycle in September and April (Barendregt, unpublished data). By measuring the quantity (ca. 15,000 m^3) and quality of the surface water at the beginning of a tidal creek below the wetlands each 30 min, it was found that major quantities of nutrients were removed in the TFW in only a few hours. Polluted waters entering the TFW at high tide were cleansed and flushed back into the region of the estuary with much lower concentrations in the waters that drained off at low tide. Similar processes (Fig. 1) were observed with NO_3 concentrations at Jug Bay in Maryland (Greene 2005).

Table 2 Percent reductions within 12.5 h in concentrations of chemicals in ebbing tidal waters compared with concentrations in flooding waters. Measurements made in fall and spring in a tidal freshwater wetland in Tiengemeten, the Netherlands (Barendregt, unpublished data)

Elements in surface water	NH_4	NO_3	P	Si	SO_4	Ca	Fe	K
% Removed (Sept 2008)	25.5	8.1	25.5	8.6	0.1	1.6	41.0	1.2
% Removed (Apr 2009)	79.1	11.7	24.5	12.0	0.9	6.2	99.0	0.1

Methanogenesis is an important microbially mediated process in TFW whereas sulfate reduction of organic matter predominates in brackish regions (Conner et al. 2007; Weston et al. 2006, 2011). The reduction of Fe(III) is another mineralization process (Megonigal and Neubauer 2009). Increasing salinity caused by global climate change or man-made control of river flow can change biogeochemical processes from methanogenesis to sulfate reduction. Coincident with these changes, efflux of NH_4^+ from the sediments is stimulated at higher salinity (Laverman et al. 2007), resulting in another important change in the ecosystem. Denitrification can be influenced by higher salinity, but with either negative or positive effects (compare Rysgaard et al. (1999) and Marton et al. (2012)).

Biotic Variation

The rich assortment of plant and animal species found in TFW are adapted to environmental conditions that fluctuate on hourly, daily, and seasonal time scales. Odum et al. (1995) found in TFW a perfect example of a "pulsed" environment and they described how these pulses contribute to the diversity and biomass productivity in the estuary. When compared with other ecosystems, the productivity of wetlands (Costanza et al. 1997) and especially TFW is very high (Whigham 2009). High species diversity can be explained by the near absence of limiting factors such as water, sunlight, nutrients, and minerals. These are mostly available in great quantities. Sunlight, however, can be limiting to low-growing plants, and the lack of oxygen in the sediments is a stress factor which wetland plants are adapted to tolerate. Most important for the biota is that TFW lack salinity, the major physiological stressor in the lower part of the estuary.

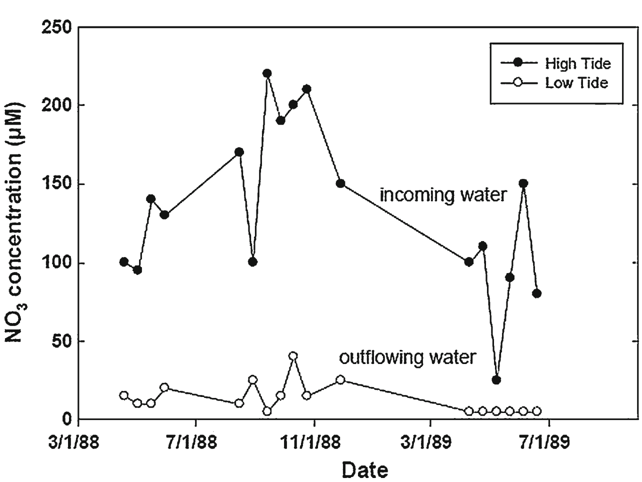

Fig. 1 Nitrate concentrations in tidal waters draining versus flooding the north marsh in Jug Bay on the Patuxent River (figure from Greene (2005), data from Swarth and Peters (1993))

Spatial and biotic variation within the TFW can be driven by the vertical elevation, resulting in a gradation of habitats from tidal flats and channels, low marshes, high marshes, and finally swamps. Many plant species are impacted by the flooding frequency and flooding duration that can restrict their occurrence to certain "zones" (Odum et al. 1984; Baldwin et al. 2001); the distribution of animal species is also arranged in zones that are related to the vertical elevation (Barendregt 2005). Below the low water level, the aquatic component of the TFW supports a different community of algae, submersed aquatic plants, and animals (e.g., Findlay et al. 2006; Van Damme et al. 2005, 2009).

In the lower parts of the elevation gradient, perennial species dominate; whereas at higher elevations, annual species increase in diversity and density (Hopfensperger and Engelhardt 2008). The variation in terrestrial vegetation is prominent and is differentiated by region and continent, e.g., reviewed by Leck et al. (2009) and Struyf et al. (2009). Seed dispersal is primarily by water (Neff and Baldwin 2005) and the seeds of many other terrestrial species, unable to germinate in saturated soils, are also found in the sediments (Leck 2003).

Vertebrate animal diversity is high compared with high salinity regions. Swarth and Kiviat (2009) and Barendregt et al. (2009b) summarize the variation for North America and Europe. Reptiles and amphibians are especially abundant in the USA, and avian diversity on an annual basis is orders of magnitude higher than in salt marshes. The tidal creeks in TFW are inhabited by many resident and migratory fish species and a variety of benthic species. Terrestrial invertebrate richness, especially that of insects, is quite high in the marshes and swamps; some of the species are characteristic for this ecosystem. Mammals, birds, reptiles, and amphibians move back and forth between upland habitats, TFW, and fully aquatic habitats and they require this habitat variation in the ecosystem.

The concentration of all nutrients (including potassium and silica) is high compared with other systems, explaining the overall high biomass production; production with dry weight of 2 kg/m^2/year is normal (Whigham 2009). Many authors have explored the relation between high productivity and nutrient cycling processes in TFW; only a few studies will be mentioned here. Eckard et al. (2007) discuss the input of dissolved carbon. Arrigoni et al. (2008) review the transformation of carbon and nitrogen. Neubauer et al. (2005) suggest a model for nitrogen cycling and ecosystem exchanges in TFW. Morse et al. (2004) used nutrient additions and conclude that the N/P ratios indicate that nitrogen might limit primary production although experiments could not confirm this. Other studies find that nitrogen is more limiting than phosphorus (Frost et al. 2009); these authors indicate that benthic invertebrates density, especially that of oligochaete worms, increases with additional nitrogen.

Human Impacts

Historically, the tidal freshwater part of the estuary is the region where ocean-going ships reach the upstream limit of navigation, and where small riverboats ended their downstream journey. This location, where goods were transferred near the limit of tidal action, was an important reason why harbors and cities such as Hamburg, Rotterdam, Antwerp, London, and Bordeaux in Europe, and Philadelphia, Richmond, Washington DC, and Portland in North America became established. Moreover, the fresh and fertile sediments adjacent to the lowland rivers in the estuary created optimal conditions for agricultural reclamation (e.g., Nordstrom and Roman 1996; Petzelberger 2000; Verger 2005), which led to serious reductions in the spatial extent of TFW.

At many locations, the TFW ecosystem suffers from chronic and long-term habitat degradation and pollution. Indirectly, degradation comes from nutrients and pesticides from throughout the watershed, and directly by waste from the industry and housing in the fresh parts of the estuary. Conversion of wetlands for housing, roads, and industry leads to the loss of these marshes. Many are not generally aware that formerly there was a rich, characteristic ecosystem present, whereas today pristine reference areas are rare.

The environment of the TFW is more exposed to disturbance compared with impacts that could disturb the higher salinity regions of the lower estuary. The relatively restricted spatial extent of TFW compared to the more widespread and geographically extensive saline parts of the estuary, combined with the characteristic species assemblage of the TFW, and important ecosystem services (e.g., water purification), underscores the need to safeguard these wetlands as a special ecosystem. Positive change, however, is evident near some cities (e.g., the Anacostia River in Washington, DC, USA) where wetlands are being restored or recreated to stimulate their original functions, processes, and biodiversity (Baldwin 2004).

Global Change

The position of the TFW in the upper part of the estuary makes them sensitive to climate change in three ways: sea level rise, air and water temperature rise, and increased salinity (Barendregt et al. 2006; Neubauer and Craft 2009; Craft et al. 2009). Unknown are the impacts of changes in concentration of greenhouse gasses (e.g., CO_2) and increases in storm intensity. The relative rate in sea level rise might not be a problem if accretion is able to keep pace with increased water depth; however, accretion varies greatly in time and space. A number of studies in TFW suggest that vertical accretion may not be sufficient (Khan and Brush 1994; Pasternack and Brush 2001; Neubauer et al. 2002; Neubauer 2008) to keep pace with increasing water levels (Vermeer and Rahmstorf 2009) so that the TFW may get flooded at increasing frequencies. For instance, in the Delaware River estuary, a conversion from high marsh to low marsh is reported in downstream areas to a greater extent than in upstream parts (Field and Philipp 2000). The geographical migration of the TFW upstream in the estuary might seem a partial solution. However, many river valleys become narrow in the upstream direction leaving little space for wetland expansion. In many cases, the TFW already butt up against hardened shorelines and other elements of human occupation making it impossible for new wetland development.

The effect of warming temperature is more difficult to evaluate. The rates of microbial processes in sediments and the water column will increase with increased temperature and the mineralization of organic matter will be stimulated, with the consequence that marsh elevation levels may fall. The effect on seed germination rates is unknown. TFW plants and animals are generally found in a variety of aquatic and terrestrial habitats and only a few are endemic to TFW, so widespread population declines of these organisms will probably not result; southern species (for example, fish and submersed aquatic plants) may shift northward.

Salinity may increase directly by the inflow of saline water from sea level rise or indirectly by droughts in summer and fall that result in reduced river discharge. Under either scenario, there is a direct impact on the vegetation (Howard and Mendelssohn 2000; Crain et al. 2004; Baldwin 2007; Krauss et al. 2009; Sharpe and Baldwin 2012). Far more consequential are impacts on biogeochemical processes. Saltwater intrusion has major stimulating effects on the microbial mineralization of organic matter, creating conditions where more carbon is released from the sediments that are flooded at a high frequency (Weston et al. 2006, 2011).

Contributions in this Issue

The papers in this issue present new topics on geomorphology, physical, and microbial processes to the impacts of sea level rise and increased salinity on TFW. This collection complements work presented in Barendregt et al. (2009a) and extends our basic knowledge about TFW.

The tidal pulse is dominant in TFW and the question is whether the processes are equally distributed in the upper and lower freshwater section. Hydrological processes in TFW and spatial/temporal patterns in denitrification were the central topic in Ensign et al.; the majority of the N_2 efflux occurred in the upstream portion of tidal rivers. Two modes of efflux explain differences; the biogeochemical mode was more common in the upper regions, whereas the hydrologic mode was most common in the lower portion.

Accretion is an important aspect in TFW, but it is uncertain if this is constant in space and time. Delgado et al. used sedimentation elevation tables to measure sedimentation rates under different conditions in time. Two marshes in Jug Bay, MD, USA, were compared, with significant accretion during the growing season and elevation loss during the nongrowing season. A downstream marsh appeared to keep pace with sea level whereas an upstream marsh did not benefit from riverine sediments and it is losing elevation.

Do macroinvertebrates respond to the same sets of environmental conditions as the vegetation? Benthic macroinvertebrate abundance, taxonomic composition, and surface flooding dynamics were compared by Yozzo and Osgood among high- and low-elevation stands of cattail (*Typha*) and common reed (*Phragmites*). Macroinvertebrate taxa richness was lowest in mesohaline *Phragmites*, but similar among *Phragmites* and *Typha* habitats in oligohaline wetlands. Total macroinvertebrate densities were greater at high-elevation *Phragmites* relative to low-elevation *Phragmites* at mesohaline sites.

Long-term studies of the stability of plant communities are often based on theory rather than on empirical measurements because of the large investment of time. Swarth et al. assessed vegetation community dynamics over four decades to determine if compositional trends could be detected in the dominant plant communities. They analyzed broad-scale spatial changes using aerial photographs combined with fine-scale studies of species richness and plant cover. Salinity events exceeding 0.5 may be increasing in the wetlands they studied, but no discernible changes to species composition were noted. Although shifts in the importance values of some species occurred through time, there were no temporal trends in community composition.

Many researchers have examined the responses of plant communities to changes in nutrient concentrations but little is known about plant responses in estuarine environments. Baldwin conducted in TFW a fertilization study and explains how annual and perennial plants responded to nitrogen and phosphorus additions, and how responses differed between marsh and swamp habitats. Annual cover decreased following nitrogen addition, possibly due to a decrease in the relative supply of phosphorus. His study demonstrates that eutrophication can alter plant species composition without causing detectable increases in aboveground biomass and it provides new insights into how wetland plant communities respond to excess nutrients and eutrophication.

A prominent discussion is developing in the literature about the consequences of climate change on TFW. Multidimensional changes predicted in the future for salinity, nutrients, and hydrology are considered by three contributions. Salinity and hydrology are the variables in the first paper. Neubauer used in situ manipulations in a *Zizaniopsis miliacea* (giant cutgrass)-dominated wetland to determine how the ecosystem responds to elevated salinity and altered hydrology. The major impact of elevated salinity was a decline in plant productivity, whereas increasing freshwater decreased the rates of ecosystem CO_2 emissions. The overall result was that net ecosystem production decreased due to elevated salinity, increased when hydrology was altered, and did not change when salinity and hydrology were both manipulated.

The consequences of changes in salinity and hydrology on TFW soils were tested in the laboratory by Jun and Craft. They investigated the effects of increasing salinity and inundation on inorganic nitrogen and phosphorus sorption in tidal forest soils. Soil cores were collected in healthy forests and in forests experiencing saltwater intrusion. In the lab, soils were exposed to three levels of salinity. Soils exposed to salinity sorbed more PO_4-P than those exposed to fresh water, soils lacking salinity sorbed NH_4-N, and soils exposed to salinity released NH_4-N. Their findings suggest that saltwater intrusion will promote nitrogen release into the water column and may exacerbate eutrophication of estuaries in the future.

The impact of salinity on the recycling in leaf litter fall was investigated by Cormier et al. They established forested study sites along a landscape transect representing fresh water, moderate salinity, and high salinity, and they monitored litter fall and made dendrometer band measurements. More nitrogen was returned to the forest floor from litter on freshwater sites compared with sites undergoing salt impact. They suggest that the decomposition and potential nitrogen mineralization on sites with salinity may be more important than loading via litter fall.

The chemical and microbial processes taking place in TFW soils are not fully understood. Methane plays a key role in the global carbon cycle and is a potent greenhouse gas. Keller et al. studied anaerobic decomposition by using a novel ecosystem-scale plant removal experiment. They explored the hypothesis that plants, which release oxygen into the rhizosphere and thus affect microbial competition, mediate competition between iron reduction and methanogenesis. Anaerobic microbial carbon mineralization was dominated by methanogenesis even in the presence of growing plants. Soil type and temperature, rather than simply the presence of plants, appear to be important in controlling pathways of anaerobic metabolism.

The composition and potential role of archaeal populations in tidal freshwater soils is largely unknown. Emerson et al. examined the archaeal community in a Patuxent River TFW to determine how the plant rhizosphere influences major microbial processes in wetland sediments. Using cultivation-independent, molecular methods, they found that archaea were abundant and the composition of this community was consistent with other saturated freshwater sediments studies elsewhere. The researchers could not detect significant variations between plots with plants and without plants during the growing season.

Understanding the processes that regulate the production and fate of methane (CH_4) in wetland soils is essential for forecasting CH_4 emissions. Bullock et al. investigated iron reduction in wetlands soils, an important carbon mineralization pathway that is capable of suppressing CH_4 production. They tested the hypothesis that temperature regulates iron reduction rates indirectly through differential effects on Fe(II) oxidation versus Fe(III) reduction. The rates of iron reduction appeared more sensitive to changes in temperature than rates of iron oxidation. Warmer temperatures can cause the Fe(III) oxide pool to decline, limiting the Fe(III) supply to iron reducers and relieving competition for organic carbon with methanogens.

Acknowledgments We thank Mary Leck, Carlton Hershner, and Iris Anderson for reviewing earlier drafts of our "Introduction" section and offering many constructive comments. We also thank the following individuals for reviewing the manuscripts in this issue: Carmen Aguilar, Linda Blum, Suzanna Brauer, John C. Callaway, Bob Christian, Robert J. Diaz, Heida Diefenderfer, Stuart Findlay, Marilyn Fogel, Carlton H. Hershner, Cheryl Kelley, Carla Koretsky, Adam Langley, Mary Leck, Shufen Ma, Robin Miller, Gregory Noe, Steven C. Pennings, Michael Piehler, Marty Rabenhorst, Lawrence P. Rozas, Lori Sutter, Christopher Swarzenski, Jenneke Visser, Nathaniel B. Weston, Kimberlyn Williams, Lisamarie Windham-Myers, Joseph Yavitt, and Susan Ziegler.

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