ELKHORN SLOUGH
TECHNICAL REPORT SERIES 2012: 4

Sponsored by the Elkhorn Slough National Estuarine Research Reserve
and the Elkhorn Slough Foundation

The significance of pickleweed-dominated tidal salt marsh in Elkhorn Slough, California: A literature review

Andrea Woolfolk and Quinn Labadie

June 2012

ABOUT THIS DOCUMENT

Andrea Woolfolk and Quinn Labadie were invited to prepare this document as a part of their duties for the Tidal Wetland Project at the Elkhorn Slough National Estuarine Research Reserve.

OBTAINING COPIES

This document is available in hard copy in the reference library maintained by the Elkhorn Slough Foundation and the Elkhorn Slough National Estuarine Research Reserve, 1700 Elkhorn Road, Watsonville, CA 95076, tel (831) 728-2822. The hard copy can be used on-site; the library does not lend materials.

This document is also available for downloading as a pdf at the Elkhorn Slough National Estuarine Research Reserve and the Elkhorn Slough Foundation: http://www.elkhornslough.org/research/bibliography_tr.htm

HOW TO CITE THIS DOCUMENT

The appropriate citation for this document is:

Woolfolk, A. and Labadie, Q. 2012. The significance of pickleweed-dominated tidal salt marsh in Elkhorn Slough, California. Elkhorn Slough Technical Report Series 2012:4.

AUTHOR AFFLIATION

At the time the report was prepared, Andrea Woolfolk was Stewardship Coordinator at the Elkhorn Slough National Estuarine Research Reserve and Quinn Labadie was the Communications Assistant for the Tidal Wetland Project.

DISCLAIMER

ABOUT THE ELKHORN SLOUGH TECHNICAL REPORT SERIES

The mission of the Elkhorn Slough Foundation and the Elkhorn Slough National Estuarine Research Reserve is conservation of estuarine ecosystems and watersheds, with particular emphasis on Elkhorn Slough, a small estuary in central California. Both organizations practice science-based management, and strongly support applied conservation research as a tool for improving coastal decision-making and management. The Elkhorn Slough Technical Report Series is a means for archiving and disseminating data sets, curricula, research findings or other information that would be useful to coastal managers, educators, and researchers, yet are unlikely to be published in the primary literature.

Contents

I. SUMMARY

Tidal salt marshes have become a rare habitat in recent history and the various laws in place protecting them are evidence of their value. Marshes perform many functions, and the *Salicornia pacifica*-dominated mashes of Elkhorn Slough exhibit these functions.

Tidal salt marshes undergo the processes of subsidence and accretion, which often allow them to maintain a stable elevation in pace with the natural rate of sea level rise. This ability to keep pace with sea level rise has been shown to reduce erosion and channel widening and increase sediment accretion while maintaining subtidal habitats. The process of accretion both traps and creates sediment, and this helps slow water velocity to control erosion and provide shoreline protection.

Marshes have also been shown to improve nutrient filtration, which provides a health benefit to the estuary's aquatic life forms and to humans by reducing eutrophication and the transmittal of pathogens.

Furthermore, the unique sediment conditions of salt marshes allow them to store disproportionate quantities of soil carbon and help them to remove nitrogen from the hydrosphere.

Finally, tidal marshes in Elkhorn Slough are home to dozens of native plant species, and are used by invertebrates, fish, reptiles, birds and mammals for resting, feeding, breeding and refuge. The dominant *Salicornia pacifica* may also play a role in the detrital food web, although its role in the overall food web has not been found to be significant.

II. INTRODUCTION

About 52% of the wetlands in the United States have disappeared. California's have disappeared for mostly anthropogenic reasons over the past 200 years, resulting in a more than 90% loss of total wetland habitat in California (from approximately 5 million to 450,000 acres) (Grewell et al 2007). Of those remaining today, few are not dominated by *Spartina* species.

In Elkhorn's tidal salt marshes, a single dominant plant, pickleweed (*Salicornia pacifica*, formerly *Salicornia virginica*) accounts for almost all the cover in the low to mid marsh (approximately mean high water to mean higher high water in areas open to full tidal exchange). Above mean higher high water, other marsh plants co-occur with pickleweed and also with upland plants in the salt marsh-upland ecotone. Like several other central California estuaries, Elkhorn Slough's low marshes lack cordgrass (*Spartina foliosa*).

This paper examines the value of the functions performed by the Elkhorn Slough's tidal salt marshes, which are some of the most extensive remaining tidal wetlands in California.

III. MORPHODYNAMIC FUNCTIONS

For decades, conceptual models of salt marsh evolution implied that tidal marshes steadily and inevitably filled in over time. However, research over the last 25 years has demonstrated dynamic processes in tidal marsh morphology, which often lead to a near equilibrium that can maintain marsh habitats over the long-term (Friedrichs and Perry 2001). Marsh plants themselves contribute to this equilibrium.

In their book Wetlands, Mitch and Gosselink (2000) explain:

> The long-term stability of a salt marsh is determined by the relative rates of two processes: 1) sediment accretion on the marsh (including the production and the deposition of peat by growing plants), which causes it to expand outward and grow upward in the intertidal zone; and 2) coastal submergence caused by rising sea level and marsh surface subsidence. These two processes are, to some extent, self-regulating; as a marsh subsides, it is inundated more frequently and, thus, receives more sediment and stores more peat. Conversely, if a marsh accretes faster than it is submerging, it gradually rises out of the intertidal zone, is flooded less frequently, receives less sediment, and oxidizes more peat.

This stability over time may influence more than just the marsh itself. Models indicate that in the face of sea-level rise, vegetated marshes may be critical for maintaining other associated intertidal surfaces as well. Model experiments conducted in systems with and without marsh vegetation found that 1) without marsh plants, sea-level rise resulted in the deepening and erosion of tidal channels, which led to the conversion of intertidal surfaces to completely subtidal surfaces; and 2) with marsh plants, sea-level rise resulted in increased sediment accretion, and the maintenance of intertidal habitats (Kirwan and Murray 2007). Marsh plants also appear to play a role in the formation and maintenance of tidal creeks and provide shoreline protection.

A. Sediment accretion and decreased water velocity/erosion control

Marsh plants can contribute to sediment accretion in two main ways: 1) the plants' physical structure can trap sediments and bind soils, and 2) plant growth, both above- and below-ground, can contribute organic sediment to the marsh plain (Allen 2000).

1. Sediment trapping and soil stability

Marsh plants' above-ground structure has been shown to significantly reduce tidal flow speed and turbulence relative to unvegetated areas, promoting sediment deposition and preventing sediment resuspension (Friedrichs and Perry 2001). Studies done across several U.S. estuaries found that mean flow speeds in marshes were 2.5 to 3 times lower than areas without marsh canopy (Leonard and Reed 2002), and even short marsh plants are effective and slowing water and increasing sedimentation (Boorman et al. 1998). Because marsh plants so efficiently dampen tidal flows, Friedrichs and Perry (2001) claim that "it is probably unlikely that water flow through healthy marsh grass ever results in long-term net erosion of sediment from the marsh surface."

The roots of marsh plants also promote stability, by binding deposited soils and adding strength through intertwined below-ground growth (Allen 2000). Microscopic algae and bacteria ("biofilms") found growing in salt marshes may also help to bind sediment grains, making the marsh surface more resistant to erosion (Allen 2000).

2. Sediment creation

In addition to trapping and binding sediments, marsh plants produce much of the organic component of marsh sediments. Aboveground growth contributes litter that accumulates on the marsh surface, but most plant production in coastal marshes occurs belowground as roots and rhizomes (Allen 2000, Turner et al. 2009). These organic contributions have been increasingly recognized as critical to marsh sustainability, even in marshes where the soil appears to be dominated by mineral sediments (Turner et al. 2004, Nyman et al. 2006). In a brackish San Francisco Bay marsh dominated by *Salicornia pacifica* and *Distichlis spicata*, researchers concluded that belowground productivity is a main driver in marsh elevation (Culberson et al. 2004), although another researcher found surface accumulation to be significant in the same region (Reed 2002).

Because plant productivity appears to play a significant role in tidal marsh sustainability, stressors to plant growth can trigger detrimental feedback loops. Too frequent or prolonged inundation can decrease marsh plant root growth, which in turn, decreases sediment elevation, further increasing the tidal flooding, which further reduces plant growth (Mitch and Gosselink 2000). This pattern of marsh drowning, seen in several estuaries including Elkhorn Slough, is characterized by plant loss in the central portions of the marsh (Friedrichs and Perry 2001). Recent research has implicated eutrophication in this pattern of marsh drowning. In long-term salt marsh experiments conducted on the east coast, nutrient enrichment reduced belowground organic matter, which in turn, can lead to significant elevation loss and increased inundation (Turner et al. 2009). These authors caution that salt marshes at the low end of their elevation range exposed to high nutrient loading are very vulnerable to relative elevation changes and in danger of irreversible marsh loss.

3. Formation of tidal channels and creeks

Tidal creeks may form before the emergence of vegetated marsh, arising from terrestrial drainages or previously incised mudflats (Friedrichs and Perry 2001), or may evolve partially as a result of water flows deflected from and concentrated between nearby dense marsh plant patches (Temmerman et al. 2007). While plants are effective at preventing erosion inside the marsh plain, salt marsh plants do not appear to reduce erosion along wetland edges (Feagin et al. 2009). In fact, marsh plants resist displacement, so direct erosion often occurs on tidal creek banks, which undermines marsh edges and creates slumps (Friedrichs and Perry 2001). Despite high rates of erosion, undercut edges, and slumping creek banks, salt marsh creeks are recognized as stable landscape features that can persist for many, many years. Work done in San Francisco Bay proposed that the discrepancy is due to the persistence of the failed bank material (Gabet 1998). The author explained that "when a [tidal creek] bank collapses, the slump block induces sedimentation behind it and buttresses the bank. Once buttressed, the bank is protected from attack until the slump block is eventually eroded away" (Figure 1).

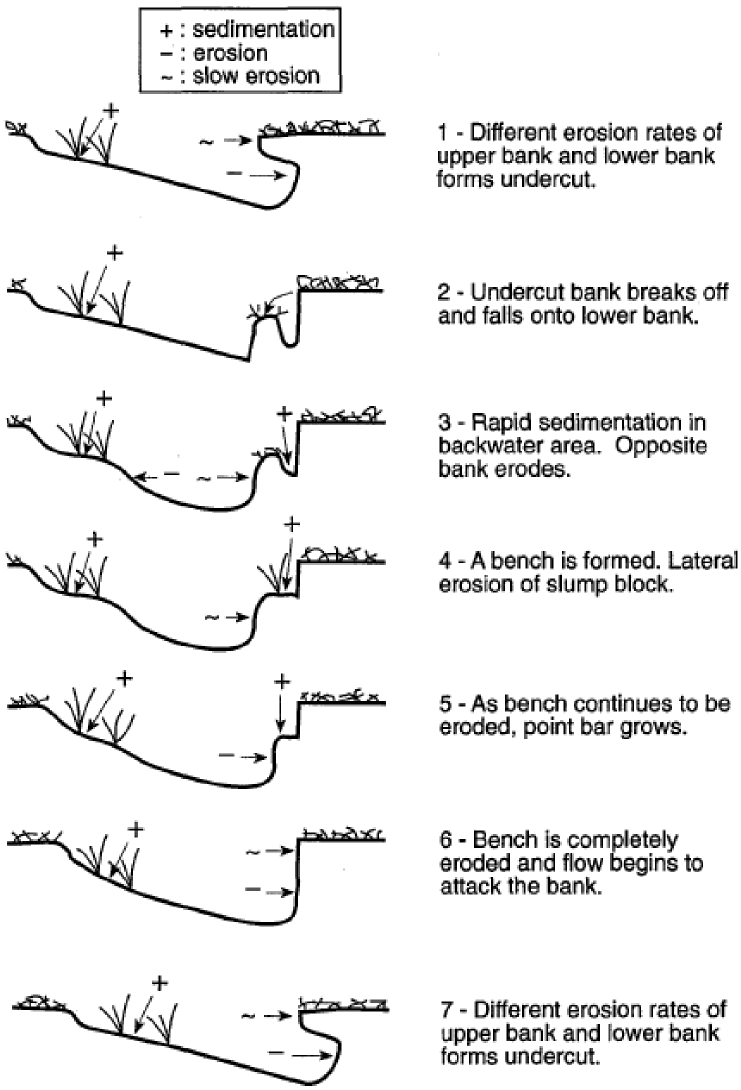

Figure 1. Illustration of the processes and events that occur in a tidal creek meander bend. From Gabet 1998.

B. Shoreline protection

As noted above, water flows are significantly dampened as they pass through salt marsh plants. Therefore marsh plains can provide adjacent uplands with protection against coast flooding and wave erosion (Allen 2000). However, fringing marshes do not appear to offer the same protection. Field and lab studies have shown that salt marsh plants do not significantly reduce erosion along wetlands edges, and therefore do not provide protection from breaking waves along its edges (Feagin et al. 2009). This is evident in Elkhorn Slough. Wind waves in areas with only a narrow fringing salt marsh, such as the Parsons Complex, can result in significant erosion of the upland edge.

C. Nutrient Uptake and Water Quality

Joana Nelson's field studies in Coyote Marsh in the Elkhorn Slough suggest that marsh plants have a significant ability to continue to take up excess nitrogen, and the capacity of salt marsh plants to take up experimentally-added nitrogen above and beyond the high background levels of nitrogen already found in Slough tidewater (2009).

Research by Karen Shapiro et al (2010) found that total degradation of wetlands may result in increased Toxoplasma transport of six orders of magnitude or more. This work indicates that destruction of wetland habitats along central California may thus facilitate pathogen pollution in coastal waters with detrimental health impacts to sea otters and other wild life, as well as to humans.

IV. BIOGEOCHEMICAL CYCLING

Tidal salt marshes have unique biogeochemical processes due to the anoxic conditions and high levels of sulfate that tend to be present in their soils.

A. Sulphur

Microbial sulfate reduction is a key process in marine environments (where sulfate is abundant), but it is usually limited in freshwater wetlands by low levels of sulfate and takes place only under anaerobic conditions (U.S.G.S. 2004). The high sulfate levels in tidal salt marshes, combined with organic matter burial through sea-level driven sediment accretion, help them store carbon as shown in Figure 2 (Chmura 2003; DeLaune 2003).

B. Carbon

Wetlands as a whole store a disproportionate amount of soil carbon, perhaps as much as one third of the world’s total soil pool (Wolf 2007), and are widely recognized as a natural sink for carbon dioxide, yet this sink is offset by the emission of a large percentage of the total global flux of methane (Chmura 2003; Bridgham 2006).

Wetlands in general are widely recognized as the largest natural source of methane (Whiting 2001; Chmura 2003; Whalen 2005; Bridgham 2006; Altor 2008; Yu 2008); however, in tidal salt marshes high levels of sulfate limit methane production to such a degree that these marshes are considered negligible methane sources and in some cases methane sinks (Chmura 2003; IPCC 2007). Tidal salt marshes are also considered sinks for carbon dioxide (Mitsch 2000; Whiting 2001; Chmura 2003; Bridgham 2006).

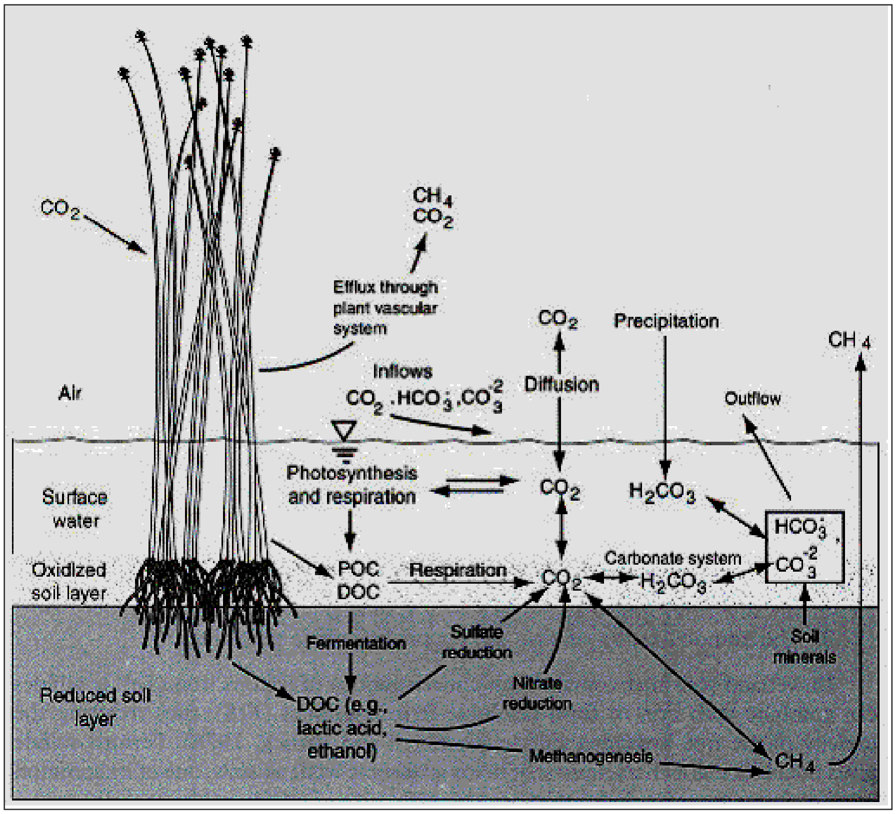

Figure 2. Carbon cycle in wetlands; POC indicates particulate organic carbon. DOC indicates dissolved organic carbon. From Mitsch 2000.

While in most wetland systems methane flux negates benefits from carbon sequestration, this is not the case with tidal salt marshes. These marshes have a high abundance of sulfate, which is a more thermodynamically favorable oxidizing agent than self-oxidation, and so methane production through self-oxidation is strongly inhibited. In fact, tidal salt marshes produce about one fifth of the methane than freshwater wetlands, 100mg C per day compared to 500 mg C per day, in large part due to their higher concentration of sulfate (Mitsch 2000).

The burial of organic matter in anaerobic marsh soil, which slows the decomposition process significantly, traps organic matter and prevents it from being quickly decomposed (Mitsch 2000; vanLoon 2005). However, a rapid increase in sea level or land development could cause those sediments to be eroded and allow aerobic microorganisms to break down organic matter much more rapidly, releasing long-sequestered carbon to the atmosphere by exposing anaerobic soils to aerobic conditions and transforming tidal salt marshes from methane sinks to methane sources (Callaway 2007). Because of this, wetland management may help reduce marsh degradation by anticipating a particular marsh's reaction to climate change and responding appropriately.

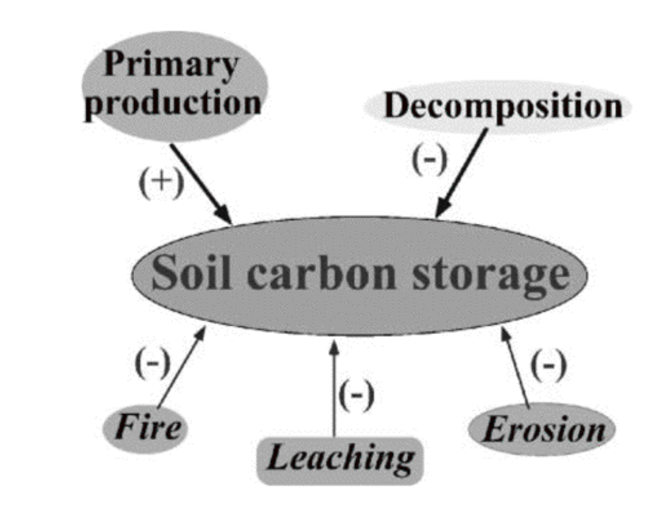

Figure 3. Major process controlling carbon storage. From Mitsch 2005.

C. Nitrogen

The anoxic conditions of tidal salt marshes make microbial denitrification a significant route for gaseous nitrogen to enter the atmosphere from soil and water (Mitsch and Gosselink, 2007). The thin aerobic layer of soil present in most marshes facilitates an upward diffusion of ammonium, which prevents a build-up of excessive levels in marsh soil. The transformation of organically bound nitrogen to ammonium nitrogen, or ammonification, is common in marshes with excessive algal blooms, like those in the Elkhorn Slough, as these marshes tend to have high a pH (Mitsch and Gosselink, 2007).

Created and restored wetlands may also decrease overall nitrous oxide emissions on a landscape scale when compared to the emissions stemming from denitrification in aerobic farm fields, ditches, and downstream coastal waters (Mitsch and Gosselink, 2007).

The ability of marshes to remove nitrogen from the hydrosphere is especially important in light of the excessive amounts of nitrogen that lead to eutrophication, which often stem from fertilizer use (Mitsch and Gosselink, 2007).

V. PRIMARY PRODUCTIVITY & THE FOOD WEB

Wetlands have been called "ecological supermarkets" because of the extensive food chain and rich biodiversity they support (Mitch and Gosselink, 2007). The Elkhorn Slough is no exception.

A. Primary Production

Measurements of standing biomass in the San Francisco Estuary marshes range from 270 to 690 g/m^2 for *Spartina foliosa* and 550-960 g/m^2 for *Salicornia pacifica*; multiple harvests in the pickleweed-dominated southern California Los Peñasquitos marsh yielded 1,200 to 2,860 g/m^2 of biomass (Grewell et al 2007). While Mitsch and Gosselink (2000) report that most vascular plant productivity is not directly consumed, it contributes significantly to the detrital food web.

Generally, primary productivity is considered to have a positive effect on community dynamics; however in eutrophic waters, like those of the Elkhorn Slough, it can reach a tipping point where too much productivity can lead to hypoxic conditions (Hughes 2009).

Nitrate is often a limiting factor in primary productivity, and can drive the process in saline environments where nitrogen is the limiting factor rather than phosphorus. When nutrients are no longer a limiting factor to primary productivity, the competitive hierarchy in the marsh shifts to one dominated by ephemeral algae and bacterial mats rather than marsh plants. "This overall increase in primary productivity can have profound effects on dissolved oxygen concentrations and biogeochemical pathways, especially in shallow waters, that can choke certain aerobic species with high oxygen demands" (Hughes 2010).

A lot of pickleweed drops to the marsh surface during and following the growing season, contributing dead material to the detrital carbon and nitrogen pool (Page 1997).

B. Food Web

Quammen and Onuf report that food availability, intra- and inter-specific competition, and predation all influence the abundance and rate of change of abundance of each component in the food web (1987).

Quammen and Onuf studied a pickleweed-dominated marsh in southern California and found that there is almost no direct consumption of living vascular salt marsh plants. Although macroinvertibrates played a major role in the breakdown of vascular material, most assimilation of organic plant matter is done through consumption by microbial decomposers on the surfaces of the detritus (Quammen and Onuf 1978). Furthermore, Kwak and Zedler (1997) traced isotopes to determine the base of the food web in California marshes and concluded that macroalgae, marsh microalgae and *Spartina* species play a much greater role than that of *Sarcicornia* species. These findings were supported by Page (1997). So while pickleweed may play a role for detritavores, its effects on the overall marsh food web are small.

VI. HABITAT AND SUPPORT OF SPECIES DIVERSITY

To a casual observer, the marsh appears to be almost homogenous, and it is often assumed to support fewer species than other habitat types (Grewell et al 2007). But, in truth, California's salt marshes are home to a surprising number of plants and animals.

A. Plants

In their review of California estuaries, Grewell et al. (2007) note that west coast salt marshes are "floristically diverse and support a high number of endemic species." These authors list 43 native vascular plant species in Elkhorn Slough's estuarine wetlands and salt marsh-upland ecotones.

Recent surveys conducted at a subset of Elkhorn Slough salt marshes documented seven native salt marsh plant species and 22 native upland species occupying the high marsh/ecotone zone. Non-native plants were also abundant in the higher elevation zones – two salt marsh non-native species and 34 non-native upland species were recorded (Wasson and Woolfolk 2011).

B. Animals

The plants growing in California salt marshes provide habitat for a wide variety of animals including both resident and migratory species. Invertebrates, fish, reptiles, birds, and mammals utilize local marshes for resting, feeding, breeding, and refuge from predators (Josselyn 1983, Zedler et al 1992, Williams and Desmond 2001).

1. Invertebrates

Marsh invertebrates are often inconspicuous, but they are a diverse group that includes benthic infauna and crustaceans in the lower marsh, and insects and spiders in the upper marsh (Josselyn 1983, Zedler et al. 1992). A recent settlement plate survey done in Elkhorn Slough salt marshes found 25 different species of invertebrates including crustaceans, insects, spiders, snails, bivalves, and polychaetes (Griffith pers. comm.).

Although not as species rich as adjacent tidal creeks, California salt marsh sediments can provide habitat for dense populations of oligochaetes and polychaete worms, while the lower elevation marsh surface is often dominated by gastropods, amphipods, isopods, and crabs (MacDonald 1969, Talley and Levin 1999, Williams and Desmond 2001). These species play important roles as detrital processors, algal grazers, and predators (Josselyn 1983).

The beach hopper *Traskorchestia traskiana* is reported to occur within the litter beneath pickleweed in San Francisco (Josselyn 1983). The small native snail, *Assiminea californica*, is reported to be common in other California salt marshes, often in dense pickleweed (MacDonald 1969, Josselyn 1983), but it appears to be rare or possibly absent at Elkhorn Slough (K. Wasson pers. comm.); and the once common native horn snail *Cerithidea californica*, which may have extended up into low marshes, has been replaced by the non-native Japanese mud snail (Byers 1999). The lined shore crab (*Pachygrapsus crassipes*) has been reported to be an occasional inhabitant of San Francisco marshes (Josselyn 1983), but surveys of its burrows in Elkhorn Slough reveal that it is locally very abundant in low marshes (Wasson and Woolfolk unpublished data). The lined shore crab is omnivorous, eating macroalgae and diatom films as well as small animals; and the crab itself is a important food source for some shorebirds in Elkhorn Slough (Ramer, Page, and Yoklavich 1991); locally it was a major prey item for the now-extirpated California clapper rail (Varoujean 1972); and the southern sea otter has been observed foraging for this species in local salt marshes (R. Eby, pers. comm.)

Higher in the marsh, insects and spiders are the dominant invertebrates, and in fact these species have been reported to be among the most abundant animals in all California salt marshes (Josselyn 1983, Talley and Levin 1999). Studies done in San Francisco and Elkhorn Slough found that Diptera (flies), Coleoptera (beetles), Hymenoptera (ants, bees, wasps), and Homoptera (true bugs) are the most common types insects inhabiting salt marshes (Cameron 1972, Woolfolk 1999). In San Francisco marshes, noteworthy insects include the inchworm moth (the high marsh specialist *Frankenia salina* is larval host), pygmy blue butterfly, and mosquitoes (Goals Project 2000)

2. Fish

Tidal salt marshes are only intermittently inundated, making this habitat available to fish only during high tides. Nonetheless, some fish species are known to utilize pickleweed marsh on high tides, using the habitat for refuge from predation and for food. In southern California, researchers estimated that a pickleweed marsh at their study site was accessible to fish less than 16% of the time. Nonetheless, four native fish species routinely utilized the marsh for foraging when it was accessible. The most common prey items were marsh invertebrates including ostracods, amphipods, snails, insects, and spiders. Polychaetes and detritus were not commonly consumed, however (West and Zelder 2000).

Fish known to use tidal salt marsh as habitat in northern California include the threespine stickleback, arrow gobies, and juvenile starry flounder (Goals Project 2000). Based on West and Zedler's work (2000), it is reasonable to assume that long-jawed mudsuckers, topsmelt, and mullet use in local marshes at high tide, as well.

3. Reptiles

In southern California high elevation marshes, fence lizards, California kingsnakes and gopher snakes are found in areas with relatively dry soils (Zedler et al. 1992). These same species are routinely found in Elkhorn Slough's muted marshes, and gopher snakes have been observed preying on small mammals in high marshes (A. Woolfolk, pers. obs.)

4. Birds

California salt marshes provide feeding, roosting, and breeding habitat for a number of bird species. Egrets, great blue herons, willets, marbled godwits, and long-billed curlews use Elkhorn Slough salt marshes to roost and forage for polychaete worms, crabs, and fish (Harvey and Connors 2002). Many shorebirds feed primarily on mudflats, but retreat to salt marshes when mudflats are inundated. It has been suggested that the protection provided by marsh vegetation may reduce metabolic losses due to wind chill and extreme high tide (Josselyn 1983). At Elkhorn Slough, Caspian terns occasionally nest on islands where salt marsh vegetation is low.

Sparrows, western meadowlarks, and killdeer are reported to use salt marshes for feeding and nesting. Raptors, including the northern harrier, American kestrel, white-tailed kite, red-tailed hawk, and red-shouldered hawk forage on small mammals living in the marsh (Zedler et al. 1992, Harding and Stevens 2001).

Loss of Elkhorn Slough salt marsh may have contributed to the local extinction of the federally endangered California clapper rail. Historically, California clapper rails bred in the slough's high elevation salt marshes, using paths through dense pickleweed to travel between their high marsh nests and mudflat foraging areas (Varoujean 1972). Clapper rails were last seen in the slough in 1980. The exact cause of extirpation is unknown, but loss of salt marsh habitat is a likely factor (Harvey and Connors 2002). Deteriorating salt marsh in Elkhorn Slough may also affect prey abundance for willets, marbled godwits, and long-billed curlews. A Moss Landing Marine Labs study found that densities of these three bird species were lower in salt marsh areas characterized by lower percent cover of pickleweed (Benson 1994).

5. Mammals

Although Elkhorn Slough lacks mammals that are dependent on pickleweed marshes for survival, a number of mammals, ranging from small voles to large marine mammals, do utilize the habitat. Common upland species that are known to rest, breed, and/or feed in local high salt marshes include vagrant shrews, deer mice, brush and black-tailed rabbits, and California ground squirrels (Josselyn 1983, Zedler et al. 1992). The California vole feeds extensively on pickleweed (Goals Project 2000), and in the summer and fall months, when upland vegetation is dry and sparse, high marsh habitat provides voles with food and cover from predatory birds (Harding 2000). The Salinas harvest mouse, described by the California Department of Fish and Game as being on its "watch list" (Bolster 1998) was once thought to be closely associated with local pickleweed and salt grass marshes (Von Bloeker 1937). More recent surveys have found that this species is frequently found in local uplands as well (Jeskova, unpublished data). Another "watch list" mammal, the Salinas ornate shrew, was also originally described as being restricted to Monterey County salt marshes and sandhills (Von Bloeker 1937), but it, too, appears to be common in upland habitats, and its status as a true subspecies in need of protection is under review (Bolster 1998).

Harbor seals occasionally use low salt marshes in Elkhorn Slough as haul-out habitat, although mudflats are also used (McCarthy 2010). Recently, researchers have observed the federally threatened southern sea otter using Elkhorn Slough's marshes as haul-out sites, particularly at low tide (Fig. 1), and otters have been observed foraging for lined shore crabs in pickleweed (Maldini et al. 2010)

Figure 4. Sea otter resting in pickleweed, Elkhorn Slough, CA. (Credit – Ron Eby, Okeanis)

VII. SUMMARY & CONCLUSIONS

Elkhorn Slough hosts one of the largest tracts of salt marsh in California outside of San Francisco Bay, and thus is important for regional representation of this rare habitat type. Marshes at Elkhorn Slough are ancient and important from the perspective of historical integrity, but also provide a variety of useful functions to the Elkhorn Watershed.

Salt marshes have been shown to improve estuarine water quality, increase nutrient cycling, provide habitat for many species, and support estuarine food webs and productivity (Griffith 2010). The tidal salt marsh habitat in the Elkhorn Slough watershed provides refuge for a variety of plants and animals and undergoes unique biogeochemical processes to filter nutrients, which improves water quality and provides a protective buffer to wildlife from land borne pathogens. Furthermore, the vegetated marsh helps to create land through accretion, aids in the protection of shorelines, sequesters carbon, and aids in the denitrification process to combat eutrophic conditions.

VIII. REFERENCES

Allen, J.R.L. (2000). Morphodynamics of Holocene salt marshes: a review sketch from the Atlantic and Southern North Sea coasts of Europe. Quaternary Science Reviews 19:1155-1231.

Altor, A. E., William J. Mitsch (2008). "Methane and carbon dioxide dynamics in wetland mesocosms: effects of hydrology and soils." Ecological Applications **18**(5): 1307-1320.

Benson, Scott (1994). The effect of deteriorated salt marsh in Elkhorn Slough on shorebird densities and foraging behavior. Student report. Moss Landing Marine Laboratories, CA.

Bolster, Betsy C., ed. (1998). Terrestrial Mammal Species of Special Concern in California. California Department of Fish and Game, CA.

Boorman, L.A., A. Garbutt, and D. Barratt (1998). The role of vegetation in determining patterns of the accretion of salt marsh sediment. *In* Black, K.S., D.M. Patterson, and A. Cramp, eds. Sedimentary Processes in the Intertidal Zone. Geological Society, London. Special Publications 139:389-399.

Bridgham, S. D., Megonigal, J. Patrick ,Keller, Jason K., Bliss, Norman B., Trettin, Carl (2006). "The carbon balance of North American wetlands." Wetlands **26**(4): 889-916.

Byers, James E. (1999). The distribution of an introduced mollusc and its role in the long-term demise of a native confamilial species. Biological Invasions 1:339-352.

Callaway, J. C., V. Thomas Parker, Michael C. Vasey (2007). "Emerging issues for the restoration of tidal marsh ecosystems in the context of predicted climate change." Madroño **54**(3): 234-248.

Cameron, G. N. (1972). Analysis of insect trophic diversity in two salt marsh communities. Ecology 53:58-73.

Chmura, G. L., Shimon C. Anisfeld, Ronald R. Cahoon and James C. Lynch (2003). "Global carbon sequestration in saline wetland soils." Global Biogeochemical Cycles **17**(4): 22.1-22.12.

Culberson, Steven D., Theodore C. Foin, and Joshua N. Collins (2004). The Role of Sedimentation in Estuarine Marsh Development within the San Francisco Estuary, California, USA. Journal of Coastal Research 20: 970–979.

DeLaune, R., SR Pezeshki (2003). "The role of soil organic carbon in maintaining surface elevation in rapidly subsiding US Gulf of Mexico coastal marshes." Water, Air, & Soil Polution: Focus 3(1): 167-179.

Feagin, R. A., S. M. Lozada-Bernard, T. M. Ravens, I. Möller, K. M. Yeager, and A. H. Baird (2009). Does vegetation prevent wave erosion of salt marsh edges? PNAS 106: 10109–10113.

Friedrichs, Carl T., and James E. Perry (2001). Tidal salt marsh morphodynamics: a synthesis. Journal of Coastal Research SI 27:7-37.

Gabet, Emmanuel J. (1998). Lateral migration and bank erosion in a saltmarsh tidal channel in San Francisco Bay, California. Estuaries 21:745-753.

Goals Project (2000). Baylands Ecosystem Species and Community Profiles: Life histories and environmental requirements of key plants, fish and wildlife. Prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project. P.R. Olofson, editor. San Francisco Bay Regional Water Quality Control Board, Oakland, Calif.

Grewell, Brenda J., John C. Callaway, and Wayne R. Ferren, Jr. (2007). Estuarine wetlands. Pages 124-154 in Barbour, Michael G., Todd Keeler-Wolf, and Allan A. Schoenherr eds. Terrestrial Vegetation of California, Third Edition. University of California Press, CA.

Griffith, K. A. (2010). Pickleweed: factors that control distribution and abundance in Pacific Coast estuaries and a case study of Elkhorn Slough, California. Elkhorn Slough Technical Report Series 2010:9.

Harding, Elaine Kathleen (2000). Landscape heterogeneity and its importance for community dynamics and conservation of a marsh-grassland system. PhD dissertation, UC Santa Cruz, CA.

Harding, Elaine K., and Emiko Stevens (2001). Using stable isotopes to assess seasonal patterns of avian predation across a terrestrial-marine landscape. Oecologia 129:436–444

Harvey, James T, and Sarah Connors. Birds & Mammals. Pages 187-214 in Jane Caffrey, Martha Brown, W. Breck Tyler, and Mark Silberstein, eds. Changes in a California Estuary: A Profile of Elkhorn Slough. Elkhorn Slough Foundation, Moss Landing, CA.

Hughes, B. 2009. Synthesis for management of eutrophication issues in Elkhorn Slough. Elkhorn Slough Technical Report Series 2009:1.

IPCC (2007). "Fact Sheet 4.18: Restoration of Former Wetlands. IPCC Special Report on Land Use, Land-use Change and Forestry." Retrieved March 18, 2009, from http://www.grida.no/climate/ipcc/land_use/241.htm.

Jeskova, Tereza (2003). Elkhorn Slough mammal survey. Unpublished data.

Josselyn, Michael (1983). The Ecology of San Francisco Bay Tidal Marshes: A Community Profile. U.S. Fish and Wildlife Service, Division of Biological Services, Washington, D.C. FWS/OBS-83/23.

Kirwan, Matthew L., and A. Brad Murray (2007). A coupled geomorphic and ecological model of tidal marsh evolution. PNAS 104:6118-6122.

Kwak, Thomas J. and Joy B. Zedler (1997). Food web analysis of southern California coastal wetlands using multiple satable isotopes. Oecological 110:262-277.

Maldini, Daniela, Ron Eby, and Robert Scoles (2010). Impact of proposed alterations of tidal flow on sea otters and harbor seals using Elkhorn Slough and the Parsons Slough Complex. Report to the Elkhorn Slough NERR. Okeanis, Moss Landing, CA.

MacDonald, Keith B. (1969). Quantitative studies of salt marsh mollusc faunas from the North American Pacific Coast. Ecological Monographs 39:33-60.

McCarthy, Erin (2010). Harbor seals: factors that control distribution and abundance in Pacific Coast estuaries and a case study of Elkhorn Slough, California. Elkhorn Slough Technical Report Series 2010:8. Available online at http://library.elkhornslough.org/research/bibliography/McCarthy_Seals_technicalreport_2010.pdf

Mitsch, W. J., James G. Gosselink (2000). Wetlands, 3rd Edition. New York, John Wiley & Sons, Inc.

Mitch, W. J., James G. Gosselink. (2007). Wetlands, 4th Edition. New York, John Wiley & Sons, Inc. Hoboken.

Mitsch, W. J., Li Zhang, Christopher J. Anderson, Anne E. Altor, Maria E. Hernandez (2005). "Creating riverine wetlands: Ecological succession, nutrient retention, and pulsing effects." Ecological Enginering **25**: 510-527.

Nelson, Joanna L. (2009). Does salt marsh function as a coastal filter for nutrient additions from land? Available online at http://www.elkhornslough.org/tidalwetland/downloads/JNelson_saltmarshfilter_ESNERR_FINALDec09.pdf

Nyman, John A., Russel J. Walters, Ronald D. Delaune, and William H. Patrick Jr. (2006). Marsh vertical accretion via vegetative growth. Estuarine, Coastal and Shelf Science 69: 370-380.

Onuf, C. P. 1987 *The Ecology of Mugu Lagoon, California: An Estuarine Profile. US Fish and Wildlife Report* 85, 122 pp.

Page, H. M. (1997). Importance of Vascular Plant and Algal Production to Macro-invertebrate Consumers in a Southern California Salt Marsh. Estuarine, Coastal and Shelf Science (1997) 45, 823–834.

Quammen, M.L. and C.P. Onuf (1987). Chapter 5: The Biota: Dynamics and Interactions. Pages 70-99 *in* C.P. Onuf. The Ecology of Mugu Lagoon, California: An Estuarine Profile. U.S. Fish and Wildl. Serv. Biol. Rep. 85 (7.15). 122 pp.

Ramer, B.A., G.W. Page, and M.M. Yoklavich (1991). Seasonal abundance, habitat use, and diet of shorebirds in Elkhorn Slough, California. Western Birds 22:157-174.

Reed, Denise J. Understanding tidal marsh sedimentation in the Sacramento-San Joaquin Delta, California. Journal of Coastal Research 36: 605-611.

Shapiro K., Conrad P.A., Mazet J.A., Wallender W.W., Miller W.A., Largier J. L. (2010). Effect of estuarine wetland degradation on the transport of Toxoplasma gondii surrogates from land to sea. Appl Environ Microbiol. [Epub ahead of print], from http://www.ncbi.nlm.nih.gov/pubmed/20802072?dopt=Abstract

Talley, T.S. and L. A. Levin (1999). Macrofaunal succession and community structure in Salicornia marshes of southern California. Estuarine, Coastal and Shelf Science 49:713-731.

Temmerman, S., T.J. Bouma, J. Van de Koppel, D. Van der Wal, M.B. De Vries, and P.M.J. Herman (2007). Vegetation causes channel erosion in a tidal landscape. Geology 7:631-634.

Turner, R. Eugene , Brian L. Howes, John M. Teal, Charles S. Milan, Erick M. Swenson, and Dale D. Goehringer-Toner (2009). Salt marshes and eutrophication: An unsustainable outcome. Limnology and Oceanography 54:1634-1642.

Turner, R. Eugene, Erick M. Swenson, Charles S. Milan, James M. Lee and Thomas A. Oswald (2004). Below-ground biomass in healthy and impaired salt marshes. Ecological Research 19: 29–35.

U.S.G.S. (2004). "Impacts of Sulfate Contamination on the Florida Everglades Ecosystem." Retrieved May 15, 2009, from http://pubs.usgs.gov/fs/fs109-03/fs109-03.html.

vanLoon, G. W., Stephen J. Duffy (2005). Environmental Chemistry: A Global Perspective, 2nd Edition. New York, Oxford University Press, Inc.

Varoujean, Daniel H. (1972). A study of the California clapper rail in Elkhorn Slough. Department of Fish and Game, CA.

Von Bloeker, Jack C. (1937). Four new rodents from Monterey County, California. Proceedings of the Biological Society of Washington 50:153-158.

Wasson, Kerstin, James Nybakken, Rikk Kvitek, Caren Braby, and Mark Silberstein (2002). Invertebrates. Pages 135-161 in Jane Caffrey, Martha Brown, W. Breck Tyler, and Mark Silberstein, eds. Changes in a California Estuary: A Profile of Elkhorn Slough. Elkhorn Slough Foundation, Moss Landing, CA.

Wasson, K., and A. M. Woolfolk. 2011. Salt marsh – upland ecotones in central California: vulnerability to invasions and anthropogenic stressors. Wetlands 31:389-402

West, Janelle M., and Joy B. Zedler (2000). Marsh–creek connectivity: fish use of a tidal salt marsh in southern California. Estuaries 23:699–710.

Whalen, S. C. (2005). "Biogeochemistry of methane exchange between natural wetlands and the atmosphere." Environmental Engineering Science **22**(1): 73-94.

Whiting, G. J., J. P. Chanton (2001). "Greenhouse carbon balance of wetlands: methane emission versus carbon sequestration." Tellus **53**(5): 521-528.

Williams, Gregory D., and Julie S. Desmond (2001). Restoring assemblages of invertebrates and fishes. Pages 235-269 in Zedler, Joy B., ed. Handbook for Restoring Tidal Wetlands. CRC Press, Boca Raton, FL.

Woolfolk, A. M. (1999). Effects of human trampling and cattle grazing on salt marsh assemblages in Elkhorn Slough, CA. M.S. Thesis. Moss Landing Marine Laboratories, CA.

Yu, K., Faulkner, Stephen P. , Baldwin, Michael J. (2008). "Effect of hydrological conditions on nitrous oxide, methane, and carbon dioxide dynamics in a bottomland hardwood forest and its implication for soil carbon sequestration." Global Change Biology **14**(4): 798-812.

Zedler, Joy B., Christopher S. Nordby, and Barbara E. Kus (1992). The Ecology of Tijuana Estuary: A National Estuarine Research Reserve. NOAA Office of Coastal Resource Management, Sanctuaries and Reserves Division, Washington, D.C.