ELKHORN SLOUGH
TECHNICAL REPORT SERIES 2010: 9

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Pickleweed: factors that control distribution and abundance in Pacific Coast estuaries and a case study of Elkhorn Slough, California

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June 2010

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ABOUT THIS DOCUMENT

This document was written by Katie Alt Griffith, University of California, Santa Cruz, as a part of her work as a Graduate Research Fellow at the Elkhorn Slough National Estuarine Research Reserve. The following experts have generously reviewed and greatly improved this document.

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This document is part of a series of reports on key species that use estuarine habitats on the Pacific Coast. Coastal decision-makers are setting habitat and water quality goals for estuaries worldwide and exploring restoration projects to mitigate the major degradation estuarine ecosystems have undergone in the past century. These goals can be informed by an understanding of the needs of key species that use estuarine habitats. To inform on-going restoration planning as a part of ecosystem-based management at Elkhorn Slough, an estuary in central California, we have selected eight species / groups of organisms that are ecologically or economically important to estuaries on the Pacific coast of the United States. The first five sections of each review contain information that should be broadly relevant to coastal managers at Pacific coast estuaries. The final sections of each review focus on Elkhorn Slough.

Kerstin Wasson served as Editor-in-Chief for this series of reports, with editorial and production assistance from Erin McCarthy and Quinn Labadie. They conducted this work as staff of the Elkhorn Slough National Estuarine Research Reserve, owned and managed by the California Department of Fish and Game in partnership with the National Oceanic and Atmospheric Administration (NOAA). Grants from the Packard Foundation, Resources Legacy Fund Foundation, and the Estuarine Reserves Division of NOAA supported this project.

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.

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A. Background

Pickleweed (*Sarcocornia pacifica*) is a common, succulent plant of Pacific coast salt marshes, which often forms extensive monospecific stands (Fig. 1). Pickleweed is ecologically important to a variety of other species. For example, the benthic algal and mudflat invertebrate community is directly affected by the shade pickleweed provides (Whitcraft and Levin 2007), while crabs (Willason 1981) and the native California hornsnail (Josselyn 1983) rely on habitat structure provided by pickleweed. Insects and spiders utilize picklweed as habitat (de Szalay and Resh 1996, Woolfolk 1999), as do mammals such as the salt marsh harvest mouse (Bias and Morrison 2006). Pickleweed marshes are especially well known as important foraging, nesting, and cover habitat for birds (Harvey and Connors 2002). The black rail in particular requires at least 90-97% pickleweed cover (Evens and Page 1983), usually located in the upper intertidal (Crooks, Pers. Comm.) for adequate refugia. During high tides when shorebirds are unable to forage in mudflats, they congregate in the lower vegetated marsh to resume foraging for prey such as worms and crabs. Some animals also rely on pickleweed as a food source in itself. Certain insects have been reported to feed on living plants (Cameron 1972, Zedler 1982) and once decomposed, several marsh detritovores rely on it for nutrition (Page 1997).

In addition to serving as a habitat and food source, pickleweed ecosystems also provides many important services including sediment trapping, nutrient retention, and denitrification. By effectively trapping sediments that wash into the slough's waters during winter floods, pickleweed not only improves water quality by decreasing turbidity (which benefits eelgrass) but also stabilizes the marsh by maintaining an appropriate elevation for vegetation growth (Lewis 2000). Primary productivity is boosted by the nutrients carried by runoff that is retained in the marsh (Cahoon et al. 1996). Denitrification is also an important service provided by pickleweed marsh, which helps prevent eutrophication of the estuarine and coastal waters (Caffrey et al. 2002).

B. Trends in distribution and abundance

Pickleweed has recently undergone a taxonomic revision. Formerly, pickleweed on the Pacific coast of North America was identified as *Salicornia virginica*, but it has now been assigned to a different genus, *Sarcocornia*. *Sarcocornia* is separated from *Salicornia* by its perennial habit (Davy et al. 2006), although the Jepson Interchange for California Floristics still recognizes *Salicornia virginica* as the accepted name for this species (http://ucjeps.berkeley.edu/cgi-bin/get_cpn.pl?42662andexpand=1). This genus is widely distributed throughout the world and has two species in North America's coastal wetlands. *Sarcocornia perennis* (Miller) A.J. Scott is located on the US west coast in Alaska, Oregon and Washington while *Sarcocornia pacifica* (Standley) A.J. Scott grows on the US west coast from California to Baja Mexico and on the US east coast from New England down to Florida (Peinado et al. 1994). Within its range on this coast, pickleweed is found almost exclusively in coastal habitats, although there are records of the species growing in other saline habitats such as inland salt pans (Ungar et al. 1979).

Although pickleweed as a species is not endangered, the marshes it inhabits (and essentially creates) are in decline. Only 46% of the more than 87 million ha of wetlands estimated to exist in the contiguous United States when Europeans arrived remain (Interagency Workgroup on Wetland Restoration). Of California's 36,000 ha of coastal salt marshes, 2/3 have been diked or filled in the past century (Lewis 2000). In San Francisco Bay, 80% of tidal marshes have been similarly lost

(Goals Project 1999). San Francisco Bay and Morro Bay contain the largest tracts of salt marsh in California, due to Pacific coastal marshes being small and relatively isolated compared to those on the Atlantic coast.

C. Factors affecting estuarine abundance

Physical Factors

The biomass of pickleweed is mostly affected by salinity, flooding, and nutrients. The role of salinity has been examined extensively in halophyte biology (Barbour and Davis 1970). Although many halophytes grow faster and attain a higher biomass when freshwater is available (Barbour and Davis 1970, Snow and Vince 1984), pickleweed requires some salt for optimum growth (Barbour and Davis 1970, Griffith Unpublished data). Salinities of 10 ppt typically yield optimum growth (Josselyn 1983). In freshwater, plants often accumulate less biomass, are less succulent with weakened re-rooting capabilities (Griffith Unpublished data), and are easily outcompeted (Zedler 1982, Allison 1992). Thus, while reducing salt stress can lead to rapid establishment and growth (Allison 1996), prolonged periods of growth in freshwater can stunt growth (Allison 1992) and ultimately kill the plant (Zedler 1982). Regardless of the salinity of flooded water, inundation itself can have negative effects on pickleweed growth. Mahall and Park (1976c) observed thicker, more erect growth forms in lower elevations in San Francisco Bay. More frequent tidal immersion at lower elevations is likely the direct cause of lateral branching inhibition as well as the inhibition of vegetative propagation by re-rooting along the sediment. In an experiment exposing pickleweed to artificial tides of different heights, growth of both seedlings and older plants was reduced by 30-40% by tides reaching 8cm higher than the control (Mahall and Park 1976c). In an Oregon salt marsh, pickleweed biomass was unaffected by elevation, although plant height and number of internodes were greater at higher elevations (Seliskar 1985). Other work suggests that elevation may not be as important as local conditions, where cases of saline flooding can diminish plant growth (Schile et al. In Prep). Biomass is also affected by nitrogen in the sediments. Boyer et al. (2001) demonstrated that nitrogen additions to field plots increased succulent tissue biomass and branching. They concluded that pickleweed is limited by sediment nitrogen concentrations, even in eutrophic Pacific estuaries (Boyer et al. 2001, Traut 2005). However, over-enrichment of sediments with nitrogen can lead to decreased allocation to below-ground biomass in *Spartina* marshes, and resultant decreased organic accretion rates (Turner et al. 2009); such potential negative responses to high nutrient levels have yet to be examined in *Sarcocornia*.

These physical factors can all be affected by alterations to tidal exchange (Zedler 1982, Josselyn 1983). Depending on seasonal precipitation and evaporation patterns, tidally restricted salt marshes can become either hypersaline or hyposaline, and flooded or parched (Zedler et al. 1980, Josselyn 1983, St. Omer 1994). Although pickleweed is often the dominant halophyte in marshes with restricted tidal exchange (Josselyn 1983, St. Omer 1994), multiple studies report a wide range of responses by pickleweed to such conditions. Some researchers in Northern California observed these plants to be less “vigorous” than pickleweed grown in sites with full tide exchange - as defined by several morphological parameters (Seliskar 1985, St. Omer 1994). Others have found higher primary productivity of pickleweed in restricted, southern California marshes due to impounded water that reduced salinity stress (Zedler et al. 1980), and pickleweed dominance associated with higher salinities and lower sediment moisture (Ibarra-Obando and Poumian-Tapia 1991). At Elkhorn Slough in central California, pickleweed has a higher percent cover in fully tidal marshes, yet greater biomass in restricted marshes (Parravano 2004). However, in certain areas of San Francisco Bay, pickleweed is the only plant to grow (albeit poorly) in low salinity diked wetlands (E. Watson, pers. com.). The widely variable climate, seasonal growth patterns, and extreme edaphic tolerance of pickleweed are likely explanations for the large range of responses reported.

Biological Factors

Pickleweed density is also affected by biotic factors including parasitism, herbivory, competition and recruitment rates. Parasitism is the least studied mechanism. The presence of mite galls (Chevalier 1922) and up to 32 species of endophytic fungi (Petrini and Fisher 1986) have been reported on pickleweed, although their effect on density remains to be quantified. The conspicuous parasitic plant, salt marsh dodder, has also been observed to decrease pickleweed biomass during periods of heavy infection in southern California (Pennings and Callaway 1996).

Herbivory on related species by terrestrial species is well-documented. The growth rate of one species of pickleweed (*Salicornia europaea*) on the US east coast is affected by beetle grazing while Coleophorid moths reduced fecundity but not plant size (Ellison 1987). Heavy grazing of other plants by sheep can increase densities of pickleweed in a European study (Kiehl et al. 1996). Here, grazing and trampling can cause an increase in salinity and soil compaction, thereby promoting lower marsh species to move up to higher elevations (Bakker 1985, Kiehl et al. 1996). Similarly, herbivory by geese in Europe may maintain high densities of *Salicornia europaea* by reducing the abundance of its competitor, *Puccinellia maritima* (Rowcliffe et al. 1998). Insect herbivores have also been reported to feed on pickleweed in California (Zedler 1982). There are seasonal patterns to insect herbivory: although a scale insect (*Pseudococcus sp*.) is the most abundant year-round, stem boring insects are only present during the winter months when they feed on the woody stem tissue (Cameron 1972). In central California, light trampling by both cattle and humans can lead to a reduction in plant height and flowering, whereas heavy or active trampling often converts pickleweed beds to bare ground (Woolfolk 1999, Wasson and Woolfolk, in prep). Trampling and feeding by coots can also cause pickleweed mortality (Zedler et al. 2003). Finally, voles are known to feed extensively on pickleweed in San Francisco Bay (Lidicker 2000).

Fewer studies have examined the effects of herbivory by marine species. In southern California, the combined presence of snails and crabs reduced the pickleweed canopy index (incorporating measures of branch length and number of branches) of young transplants by 95% at low elevations (Boyer and Fong 2005a), although it is possible that burrowing and bioturbation are beneficial to well-established plants (K. Boyer, pers. comm.). Algal mat deposition can also promote the growth of *Salicornia europaea* by creating gaps in the *Spartina* zone free of competition (van Hulzen et al. 2006), and providing an additional source of nitrogen (Boyer and Fong 2005b).

Competition with other plants is another important factor determining pickleweed density. In southern California, competition between pickleweed and other marsh plants results in low pickleweed densities in drier and more saline marsh sediments. Because pickleweed has a higher tolerance for tidal flooding, it is found in high densities in the lower marsh zone where plants other than *Spartina* cannot survive (Pennings and Callaway 1992). Competition between pickleweed and other marsh plants can also be affected by salt marsh dodder, which suppresses pickleweed enough to permit weaker competitors to colonize (Callaway and Pennings 1998).

Successful recruitment has a large impact on pickleweed density. Pickleweed will rapidly colonize suitable sediment with either vegetative growth from nearby adult plants or by seeds carried with the tides. In San Francisco Bay, copious amounts of seeds (2100-3175 m^2) are set in October and November (Josselyn 1983), and germination peaks in early April. A 1987 study suggests that at Elkhorn Slough germination occurs between January and March (Mayer 1987). In suitable habitats, seedling density may exceed 100,000 seeds per square meter (Davy et al. 2001), although in Elkhorn Slough's Parson Complex seedling density averaged between 0 and >200 seedlings/m^2 at marsh elevations fifteen months after a restoration project returned tidal flow to this reclaimed wetland (Mayer 1987) In Parsons, seedling mortality was high between April and June. Hairy seed coats attach to wrack and are deposited with it on the high marsh. Seedling density increases in disturbance areas caused by wrack deposition (Ellison 1987).

D. Factors affecting estuarine distribution

Elevation and Submergence

In areas with full tidal exchange, pickleweed usually occupies a zone from mean high water to the highest high tides (Mahall and Park 1976a, Josselyn 1983). The lower limit of its distribution is set by submergence time. Since prolonged flooding can kill pickleweed (Zedler 1982), it grows best when the emergence period is greater than or equal to the period of submergence and dies when the submergence period is four times greater than the emergence time (Josselyn 1983). Pickleweed in southern California occupies a zone that is inundated 13% of the time (Sadro et al. 2007). Which factors associated with tidal immersion actually limit pickleweed is unclear, but Mahall and Park (1976c) have concluded that soil aeration is not important in setting the lower limit.

Submergence time sets pickleweed's upper limit by serving as a source of sediment moisture. Pickleweed is often found in saturated but well-drained sediments (Josselyn 1983). However, submergence time also acts indirectly to limit pickleweed. Although pickleweed can tolerate a wide range of salinities (Zedler 1982, Josselyn 1983), it exhibits maximum growth at sediment salinities of 10 ppt (Josselyn 1983), and becomes outcompeted in sediments without salt (Zedler 1982, Allison 1992). In sites with restricted tidal exchange, these same factors may set distributional limits, although the elevation range will likely differ due to marsh subsidence. Changes to inundation and salinity regimes are also important consequences of global climate change (Callaway et al. 2007).

Salinity

Pickleweed is typically present in sediments with a salinity range of 10 ppt (Josselyn 1983) to 90 ppt (Lewis 2000). However, in San Francisco Bay, it has been found in sediments with salinities ranging from 3.4 ppt to 1966 ppt, with a median salinity of 28.5 ppt (Watson 2006a). Although pickleweed can survive in freshwater sediments (Griffith Unpublished data), it is easily outcompeted in such habitats by plants better adapted to such conditions (Mahall and Park 1976b, Allison 1992). As the most salt tolerant plant, pickleweed dominates areas with high sediment salinities (Zedler 1982). Aside from its effects on established plants, salinity can also affect germination. Prolonged periods of rainfall may lead to increased germination events in the upper intertidal (Noe and Zedler 2001).

Sediment type

Although there is little published information on the sediment quality that pickleweed specifically is associated with, in California marshes where it is naturally found, sediments generally contain less than 30% sand (Byrd and Kelly 2006), contain between 10-40% organic matter (Zedler 1982, Callaway 2001, Watson and Byrne 2009), and are made up of fine, clay-rich soils (Callaway 2001). However, in a restored southern California salt marsh, sediments with as much as 60% sand supported pickleweed transplants, and natural recruitment even occurred on sediments with 75% sand (Zedler et al. 2003). In Europe, the same species of pickleweed has been found growing on gravelly and sandy beaches (Davy et al. 2006). Thus, a wide range of substrates appear to be suitable for pickleweed growth.

Sediment supply

In order for the existing marsh plain in an estuary to keep pace with sea level rise, an adequate sediment supply is necessary to allow the marsh platform to increase in elevation. The paleoecological record for San Francisco Bay suggests that at least one natural tidal marsh (China Camp), sea level rise outpaced sediment accumulation during the recent past, causing tidal marsh to convert to inter-tidal mudflat (Malamud-Roam and Ingram 2004). Furthermore, rates of exogenous sediment accumulation measured in Northern San Francisco Bay in most cases did not meet or exceed current rates of sea level rise in San Francisco Bay (Culberson et al. 2004). However, in South San Francisco Bay, high turbidity has allowed tidal marshes to not only keep pace with accelerated sea level rise caused by subsidence due to groundwater pumping (RSLR of >1cm yr^{-1} in some cases), but also to expand (Patrick and Delaune 1990, Watson 2004, Watson In Press). Salt marshes may keep pace with future accelerated sea level rise associated with global warming if they have an ample supply of suspended sediment; projections for San Francisco Bay suggest concentrations above 100 mg/L are needed if sea level rise proceeds at a rate equal or less than 3-5 mm/yr (Orr et al. 2003). Pickleweed is considered relatively tolerant of turbid waters with high rates of sedimentation compared to other marsh plants (Allison 1996, Zedler et al. 2003).

In additional to external sediment supply, marsh sustainability may be a function of rate of below-ground organic accumulation. One study in Louisiana found evidence that below ground root biomass was highly correlated with organic accumulation rates below ground, and that both of these were stronger predictors of marsh dieback than was inorganic sediment supply to the marsh (Turner et al. 2004).

Biological factors

In addition to tidal inundation and sediment accumulation rates as limiting factors in pickleweed distribution (Mahall and Park 1976c), there is also evidence in *Salicornia europaea* that the lower limit is set by amphipod bioturbation when the animal buries and/or disturbs seeds which limits establishment (Gerdol and Hughes 1993). The lower edge of *Sarcocornia pacifica* marshes can also be reinforced by bioturbating species such as crabs and snails that work the channel edges (Boyer and Fong 2005a). This lower bound is also more susceptible to algal mat deposition which may smother and kill young plants (Zedler et al. 2003), or release the plants from competition with *Spartina* (van Hulzen et al. 2006). Heavy, frequent, trampling by humans and/or cattle at the upper bound can completely exclude pickleweed from an area (Woolfolk 1999).

Finally, competition is a critical factor determining the distributions of many halophytes in salt marshes (Ungar 1998). Species interactions are especially affected by salinity levels of the sediments. In freshwater sediments, pickleweed growth is often inhibited (Griffith Unpublished data) and it can be outcompeted by plants that grow better in such soils (Allison 1992). Pickleweed is often the most tolerant of high salinities and therefore dominates sediments with high salt content (Zedler 1982, Josselyn 1983). In a southern California salt marsh, Pennings and Callaway (1992) concluded that competition was the factor limiting pickleweed establishment in the drier and more saline *Arthrocnemum* zone. In a central California salt marsh, pickleweed was observed competing with non-native upland plants near the upper limits of its distribution (Wasson and Woolfolk, in prep.). It is possible that as invasive plants become more dominant, they could further limit the distribution of pickleweed in the marsh, proper, as appears to be occurring as a result of *Lepidium latifolium* invasion in San Francisco Bay (Reynolds and Boyer, in prep.).

E. Predicted changes in estuary-wide abundance in response to estuarine restoration projects

Changes to water quality

Changes to water quality could potentially affect levels of nutrients, salinity, turbidity and contaminants. Since pickleweed growth is limited by nitrogen (Boyer et al. 2001, Siciliano et al. 2008, increasing nutrient levels would likely increase above ground biomass of pickleweed. Pickleweed may also acquire more nutrients with heavier algal mat deposition on the marsh, if algae species respond positively to higher nutrient levels (Boyer and Fong 2005b). However, an increase in the production of algae can also kill young pickleweed transplants by forming thick mats on the canopy (Zedler et al. 2003). It is also possible that increased nutrient levels would lead to decreased below ground biomass and organic accumulation, as has been observed for some *Spartina* marshes (Turner et al. 2009). Increasing contaminant levels, especially cadmium, would likely be detrimental to pickleweed beds by exerting negative effects on plant height, biomass, and CO_2 assimilation (Rosso et al. 2005). In the case of a major freshwater flooding event, pickleweed may become outcompeted by other marsh plants and perhaps even freshwater plants. Although pickleweed has been shown to grow better when freshwater is available (Barbour and Davis 1970, Barbour 1978), other marsh species are able to outcompete pickleweed during such times due to more rapid growth (Allison 1992). Increases in turbidity levels and associated sedimentation is not likely to have a large negative effect on pickleweed (Allison 1996), and indeed suspended sediments are vital for marsh sustainability (Orr et al. 2004).

Changes to habitat extent

If the extent of suitable estuarine habitat (i.e., tidal elevation of about MHW to MHHW in areas with soil salinities of at least 10 ppt) were to increase, the extent of pickleweed beds would similarly increase. Pickleweed will rapidly colonize suitable sediment with either vegetative growth or by seed. Because pickleweed seeds are dispersed by water, the proximity of existing populations to new areas is relatively unimportant as long as the seeds can travel there with the tides. Seeds are equipped with small hooks that readily attach to floating debris (K. Griffith, pers. obs.). Copious amounts of seeds (2100-3175 /m^2) are set in October and November (Josselyn 1983) and generally disperse in December and January when pickleweed stems decompose (K. Griffith, pers. obs.). Sampling done in the surface waters of Elkhorn Slough's main channel found an average of 4.7 *S. pacifica* seeds/m^3 (Mayer 1987). Germination occurs between January and April (Josselyn 1983, Mayer 1987). In suitable habitats, density may exceed 100,000 seeds per square meter (Davy et al. 2001). Seeds are not viable in the field for very long – by the middle of June 96% of seeds have died (Josselyn 1983, Hopkins and Parker 1984). Seed recruitment is so abundant that restoration experts recommend letting pickleweed "volunteer" to new sites as opposed to planting or seeding (Zedler et al. 2003).

F. Elkhorn Slough trends

Pickleweed covers a greater area than any other salt marsh plant in Northern California (Josselyn 1983). This competitive dominant marsh plant at Elkhorn Slough forms extensive monocultures throughout the Slough's marshes (Oliver and Mayer 1987), and is extremely important to the welfare of other marsh dwellers. Elkhorn Slough is one of the few estuaries that *Spartina* spp. have not colonized (Watson 2007).

Geomorphology and Paleoecological Trends

Elkhorn Slough was originally a freshwater river valley that delivered freshwater to the sea which was approximately 120 m lower than its current levels (Schwartz et al. 1986). When the glaciers began to melt, around 18,000 years ago, sea level rose to fill Elkhorn Slough with salt water. Regular and vigorous tidal action resulted in the colonization of marine organisms like oysters and clams (Schwartz et al. 1986, Hornberger 1991). Only when tidal forcing slowed (due to a decrease in sea level rise) did sediments begin to accumulate and form the beginnings of Elkhorn Slough's tidal marshes (Schwartz et al. 1986, West 1988, Hornberger 1991). Over time, freshwater inputs to the Slough has been variable due to a variety of factors including the gain and loss of large tributary rivers (the Salinas and Pajaro Rivers) due to inlet dynamics, input from freshwater springs, and variability in seasonal rain inputs due to natural climate variability. Paleoecological evidence suggests that Elkhorn Slough has had a dynamic history, with periods of varying amounts of freshwater and tidal influence, but saline conditions and dominance by pickleweed have been typical for most of the past five thousand years in most parts of the estuary (Schwartz et al. 1986, West 1988, Hornberger 1991, Watson 2006b, Watson et al. 2010). It is likely that variation in mouth configuration (size of sandbar) and location, and variation in Salinas river flow and location (sometimes but not always flowing into the estuary) contributed to the shifting conditions (West 1988, Watson et al. 2010).

The Last 150 Years

Elkhorn Slough's wetlands have undergone rapid change in the last 150 years (Van Dyke and Wasson 2001, Figure 2). Between 1870 and 1956, humans turned more than 60% of healthy salt marsh into a variety of other habitats including freshwater ponds and brackish marshes, unvegetated mud flats, and degraded salt marsh. Between 1931 and 1956, an additional 30% of salt marsh was reclaimed as agricultural land. By 2000, tidal flushing had been mostly returned to the marshes due to degraded levees. However, the decline in healthy marsh continued and by 2000 only 23% of the healthy marsh present 1900 remained. The total extent of marsh in the estuary is still within the natural range for the past thousands of years; there was an increase in extent likely associated with sediment deposition due to changed land uses in the early European American colonization period which preceded the declines summarized above. However, the rate of decline in past decades is high enough that if the trajectory continues, marsh extent will fall below natural range for the estuary within a few more decades. The following sections review causes of this decline.

Effects of Historic Tidal Restrictions

The main effect of these historic tidal restrictions was subsidence in the marsh as the sediments dried and compacted. Once tidal exchange was reintroduced, such as to the Parsons complex, much of the area previously suitable for pickleweed (in terms of elevation) was significantly lower and thus flooded. As a result, large areas of previous pickleweed marsh have been replaced by mudflats and channels. However, marsh does exist in areas where elevations are still appropriate for pickleweed growth (in narrow bands along the upper intertidal).

Effects of Existing Tidal Restrictions

Although existing water control structures such as flap gates, tide gates, and culverts permit some exchange (usually <50% of the tidal amplitude), pickleweed is still negatively affected by tidal restrictions. This is due to a variety of reasons including increased submergence time, decreased salinity, and marsh reclamation. A study comparing restricted marshes to flushed ones found that pickleweed has a higher percent cover in flushed marshes, yet greater above ground biomass in restricted marshes (Parravano 2004). Because some tidally restricted marshes are being managed as lagoons submergence time has increased, with standing water replacing former pickleweed habitat. In restricted marshes with no seawater exchange, freshwater ponds have formed, with associated vegetation such as cattails and tules. Finally, human land use in reclaimed areas have completely replaced pickleweed beds with agriculture or industry, thereby changing the marsh habitat completely.

Marsh Degradation in Fully Tidal Regions

Extensive deterioration of Elkhorn Slough wetlands is also evident in marshes that have never been subject to artificial tidal restriction. Vegetation cover has decreased from an average of 90% to 40% in the past seventy years. Additionally, tidal creeks have widened from an average of 2 to 12 meters (Van Dyke and Wasson 2005). The pattern of interior marsh loss and thinning is consistent with “marsh drowning” observed elsewhere, and suggests that marsh elevation has shifted downward in the tidal frame. There are numerous potential mechanisms that could have generated such a decreased elevation relative to tidal inundation. Regional rates of sea level rise may have increased, but water level measurements from Monterey and San Francisco indicate only slight changes over the past decades and these alone do not appear sufficient to explain the extensive marsh dieback. Local sea level may have increased as a result of the 1946 creation of an artificially deep and wide mouth to accommodate Moss Landing Harbor (Caffrey et al. 2002). In addition to the potential for increased water levels, the relative elevation loss of pickleweed marshes may also be driven by subsidence. A recent study of marsh plain elevations suggests that while accumulation at the surface may be relatively high (5 mm/year), subsidence rates may be almost as high (4 mm/year), leading to a net marsh accretion rate which is insufficient to keep up even with current rates of sea level rise, let alone future predicted levels (Spear 2010). Causes of marsh plain subsidence are not well understood, but may be at least partly the result of human perturbations. High nutrient loading can lead to decreased organic accretion and root decomposition or plant death due to smothering by algal mats (Zedler et al. 2003, Turner et al. 2009) and thus shallow subsidence, while groundwater overdraft can lead to deep subsidence. In addition to anthropogenic disturbances, tectonics may play a significant role in deep subsidence.

In sediment-rich estuaries, relative loss of elevation of the marsh plain (due to increased sea level or marsh plain subsidence) can be offset by increased marsh accretion rates. Indeed, shallow cores corresponding to the most recent 50 years indicate that sediment accumulation rates have increased in a manner consistent with decreased elevation of the marsh plain in the tidal frame (Watson et al. 2010). However, these observed increases in sediment accumulation rates have apparently not been sufficient to prevent marsh drowning. Sediment supply to the marshes has likely decreased over the past century due to the 1909 diversion of the Salinas river (Caffrey et al. 2002) and the 1946 opening of the harbor mouth, which resulted in increased rates of sediment export (Malzone 1999). The lack of sufficient sediment has thus contributed to marsh dieback by preventing sufficient rates of sediment accumulation to offset local sea level rise and/or marsh plain subsidence.

G. Predictions for Elkhorn Slough

Overview

Four large-scale management alternatives for Elkhorn Slough were developed with the goal of decreasing rapid rates of subtidal channel scour and salt marsh conversion to mudflat habitat that have been documented over the past decades (Largay and McCarthy, 2009; Williams et al., 2008). Changes to physical processes and water quality in response to these management alternatives vs. a "no action" alternative have been modeled and summarized (Williams et al. 2008, Largay and McCarthy 2009). To determine which management alternative best optimizes estuarine ecosystem health, the coastal decision-makers involved in this process of wetland restoration planning require at minimum some basic information about how species that play major ecological or economic roles are likely to respond to the different management alternatives. In the absence of detailed demographic data and rigorous quantitative modeling, it is impossible to obtain robust quantitative predictions about response of these key species. Instead, the goal of the preceding review of factors affecting density and distribution of the species across their range and the evaluation of trends at Elkhorn Slough is to provide sufficient information to support qualitative predictions based on professional judgment of experts. These predictions represent informed guesses and involve a high degree of uncertainty. Nevertheless, for these species the consensus of an expert panel constitutes the best information available for decision-making.

Predictions under management alternatives

Williams et al. (2008) predicted extent of salt marsh in their assessment of the five management alternatives. Since Elkhorn Slough salt marshes are dominated by pickleweed, the predictions for salt marsh and pickleweed extent should be virtually identical. The predictions were based on evidence of current elevational distribution of salt marsh in the tidal frame, with tidal frame changes under alternatives made using hydrodynamic modeling; at year 50, a 30 cm increase in sea level due to global climate change was assumed for all alternatives (Williams et al. 2008). For these predictions, the geographic boundaries are all the fully tidal estuarine habitats of Elkhorn Slough excluding the Parsons complex (predictions do not include tidally restricted areas). The predictions for acreage changes in marsh habitat extent have been modified somewhat since this report was prepared and the most recent numbers are provided by Table 1 below (B. Largay, pers. com.).

Table 1 - Predicted changes to salt marsh extent under management alternatives.

	yr 0	yr 10	yr 50
Alternative 1. No action	0%	-7%	-65%
Alternative 2. Mouth re-route	18%	6%	-40%
Alternative 3a. Low sill	9%	0%	-55%
Alternative 3b. High sill	22%	18%	-36%
Alternative 4. Parsons restoration	-1%	-6%	-61%

Alternatives 1 and 4 show similar patterns. By definition, there is no change in salt marsh at Year 0 in Alternative 1 (this is the baseline to which all other alternatives and periods are compared). Likewise, there is no significant change for Alternative 4. At Year 10, some loss of salt marsh has occurred due to anticipated sea level rise included in the modeling. By Year 50, this loss has become extremely substantial, with the majority of today's marshes being drowned due to sea level rise.

Alternatives 2 and 3b also show similar patterns. At Year 0, an approximately 20% increase in salt marsh extent is predicted due to truncation of the tidal frame, leading to conversion of current mudflat habitat to marsh (note that this is modeled for Year 0, but might take a few years to occur as marsh colonizes mudflats). However, this gain is relatively short-lived and salt marsh extent is predicted to decrease somewhat by Year 10, and substantially by Year 50, as a result of the sea level rise incorporated in the model. While losses to salt marsh are major in these alternatives, they are considerably lower than in the other alternatives.

Alternative 3a shows intermediate patterns. A modest gain in marsh is predicted for Year 0, by Year 10 these gains have been offset by sea level rise, and by Year 50, substantial losses of salt marsh extent are predicted, at levels between those between the first and second sets of alternatives described above.

The rank order of these alternatives from the perspective of maximizing pickleweed in the longer term is thus Alternative 3b > 2 > 3a > 4 > 1, but given the projected sea level rise, none of them are predicted to avoid major losses.

Other factors besides those modeled might lead to differences between alternatives. For instance, the alternatives could affect nutrient concentrations which in turn might affect shallow subsidence rates. However changes to nutrient concentrations have not been modeled and are uncertain (e.g., they might increase under Alternative 2, the mouth re-route, due to greater residence time, or decrease due to lower inputs from the old Salinas river channel). Or the alternatives could affect sediment deposition rates, which could affect marsh accretion and sustainability in response to sea level rise. But again, changes to sediment deposition rates have not been modeled and are uncertain (e.g., they might increase under Alternative 2 due to lower velocities, or might decrease due to lower sediment inputs from the old Salinas river channel or due to less suspension of sediments scoured from channels and creeks). Due to the lack of clarity about differences between alternatives due to such factors, no range of predictions that accounts for them has been made. All the predictions have high uncertainty associated with them due to such factors, but that uncertainty is similar for all alternatives. Similarly, rate of global sea level change is uncertain and may well differ from the 30 cm after 50 years modeled here, but this uncertainty affects all alternatives equally. Deep subsidence rates due to groundwater overdraft or tectonic events may also change marsh acreage from what is predicted above, but again, should not affect one alternative more than others.

Targeted restoration actions for pickleweed at Elkhorn Slough

Targeted restoration actions could be undertaken to enhance pickleweed in Elkhorn Slough. In particular, formerly diked areas that have subsided substantially could be brought to elevations that would sustain pickleweed through sediment addition. Extensive resources are available to inform salt marsh restoration in this region (e.g., Williams and Faber 2004) and this topic is outside the scope of the current review. In order to increase sustainability of salt marshes in the face of sea level rise, increase in sediment supply from riverine sources (Pajaro, Salinas) could also be explored. Strategies for facilitating salt marsh migration in the face of sea level rise could also be considered.

Importance of Elkhorn Slough salt marshes

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 thus are important also from the perspective of historical integrity. Salt marshes elsewhere have been shown to improve estuarine water quality, increase nutrient cycling, provide fish habitat, and support estuarine food webs and productivity. Such roles have not been demonstrated for pickleweed on the Pacific coast, but may play an important part in ecosystem health at Elkhorn Slough.

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Figure 1. Pickleweed at Elkhorn Slough. Photographs by K. Griffith.

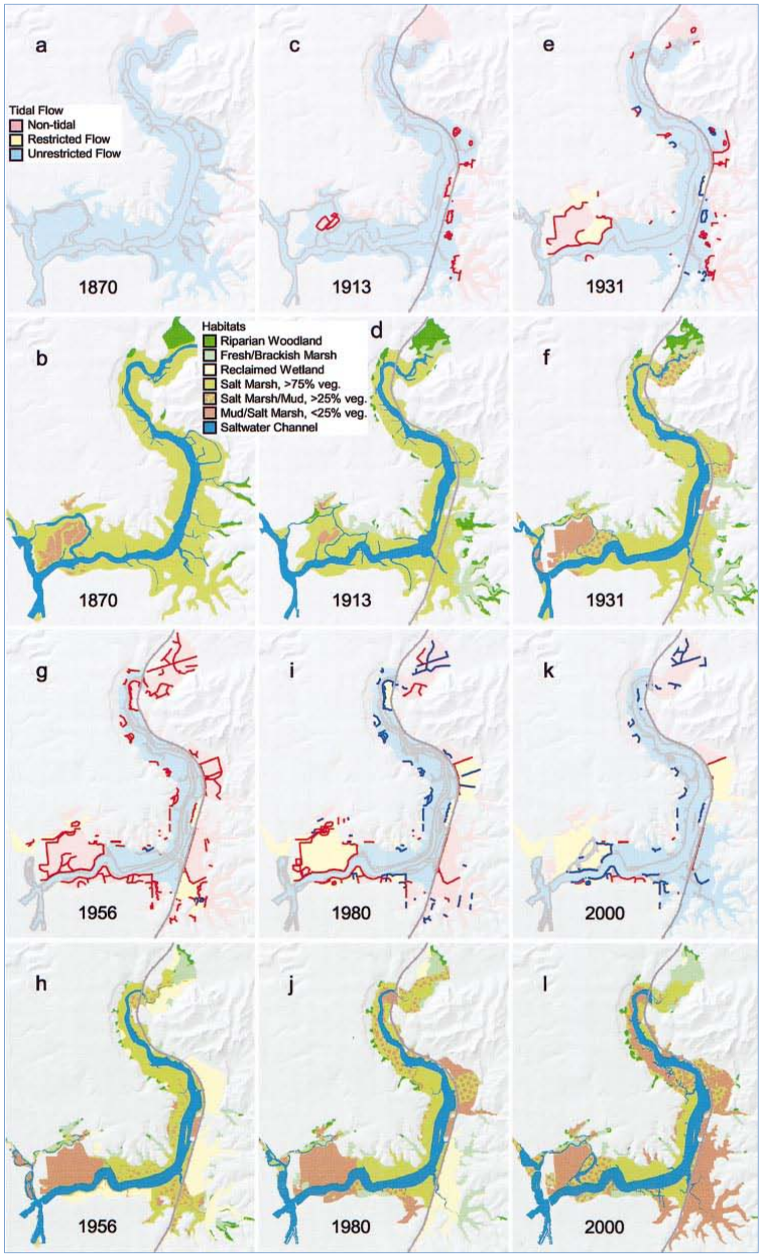

Figure 2. Map of habitat distribution at Elkhorn Slough over that past 150 years. Note dramatic decrease in salt marsh (olive green), which primarily represents pickleweed in this system. Red lines represent intact levees, blue lines represent breached levees. Adapted from Van Dyke and Wasson 2005.