Title

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Use of historical remote sensing to link watershed land use change and wetland vegetation response in a California estuary

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Abstract

While Elkhorn Slough wetlands are protected by a State ecological reserve and NOAA research reserve, intensified farming in the watershed has led to high soil erosion rates and sedimentation into the slough, where several sediment fans have formed at the base of slopes. The goal of this study was to determine how watershed land use change (i.e., increasing agriculture) and associated sedimentation over 30 years influenced changes in salt marsh soil physical properties, and in turn, plant composition through the use of remote sensing, GIS, and field methods. Objectives were to use current and historic aerial photographs to map historic wetland plant communities and quantify the extent and type of salt marsh vegetation change on sediment fans from 1971 to the present, and to explore the driving factors of this change through field sampling of marsh soil properties and topographic features. Analysis of historic aerial photos demonstrated that the formation of sediment fans in pickleweed salt marsh led to the expansion of arroyo willow into the marsh plain. A cattail and bulrush plant community also formed on the sediment fans, forming a band between the willow and pickleweed. This vegetation change occurred as sedimentation led to lower salinity levels, lower soil moisture, higher bulk density, higher elevation, and an increase in soil sand content. Resource managers are actively working with farmers to reduce soil erosion and off-farm sediment. Evidence of habitat change from sedimentation documented in this study supports the need for these continued erosion control efforts. As these efforts continue to reduce sedimentation into the slough, it would be valuable to continue to monitor the sediment fans to determine if any recovery in salt marsh vegetation occurs.

Introduction

Pacific Coast salt marshes are small, fragmented, yet important ecosystems in California that have experienced significant loss or degradation over the past century. They are highly productive, provide habitat for several endangered species, and support important commercial fisheries (Zedler 1993, Semlitsch and Bodie 1998, Mitch and Gosselink 2000, Talley 2000). These functions have been lost or compromised as salt marshes have been diked, drained or developed (Simenstad and Thom 1996, Zedler 1996). The patterns and processes of these wetland losses can be identified using remotely sensed data. Aerial photography, which began early in the 20th century, is an especially important tool for monitoring long-term ecological changes. Not only can aerial photographs be used to quantify ecosystem changes, but they can help explore explicit linkages between ecosystem change and human resource uses that drive those changes. A record of these historical processes has recently become of greater use to managers as they seek to prevent wetland loss and restore wetlands to past conditions.

In this study we developed an approach for discerning decadal scale changes to salt marshes in Elkhorn Slough, California. We used multiple sources of historic aerial photographs from the archive of the NOAA Elkhorn Slough National Estuarine Research Reserve (ESNERR), and automated and manual image processing techniques such as classification and change detection to establish patterns of wetland vegetation change caused by major disturbance processes occurring in the watershed. Following, we used field sampling methods to determine how disturbance altered edaphic properties in the salt marsh and facilitated vegetation change.

Study Area

The Elkhorn Slough watershed is situated on the coast of Monterey Bay in Monterey and San Benito Counties, and supports one of the largest coastal marshes in California.

While Elkhorn Slough contains a State ecological reserve and a NOAA research reserve, agriculture, specifically strawberry farming, in the watershed has increased dramatically since 1970 on steep slopes adjacent to pickleweed (*Salicornia virginica*) dominated salt marshes. Intensified farming has produced high soil erosion rates in the watershed. Average erosion rates on strawberry farms here have been calculated at 33 tons per acre per year (USDA-SCS 1994).

Soil eroding from farms moves downslope, and leads to sedimentation along the margin of the slough, where several sediment fans have formed at the base of slopes that have filled marshes, mudflats, and channels, and altered the wetland plant community. Between 1931 and 1980 there was a 5-fold increase in the number, and a doubling in the acreage of sediment fans in the pickleweed marsh. By 1980, at least 30 sediment fans had formed in salt marsh, ponds, and freshwater marsh of Elkhorn Slough (Dickert and Tuttle 1980).

The watershed is small (182 km^2), and the slough extends 11.4 km from Moss Landing on Monterey Bay to the furthest reach inland. Elkhorn Slough is a seasonal estuary surrounded by more than 1,420 ha of tidal marsh and flats (Caffrey et al. 2002). Steep hills rise 30 to 100 m from the marsh; while many hills are cultivated, the uplands are also characterized by oak woodland, grassland and maritime chaparral communities.

The Elkhorn Slough region has a Mediterranean climate, with a monthly mean temperature range of 11.1° to 15.4°C and an average annual rainfall of 55.3 cm that occurs generally between October and May (Caffrey et al. 2002). A majority of the soils in the watershed uplands are derived from the Aromas sands formation, an aeolian sandy parent material, producing soils with high sand content that are highly erodible when disturbed. The major soil series present in the hills adjacent to the slough are Arnold loamy sand, Santa Ynez sandy loam, and Elkhorn sandy loam. The marsh soil type is Alviso sandy clay loam (USDA-NRCS 2004a).

Farming in the vicinity of Elkhorn Slough began in the late 1880s (ABA Consultants 1989). But according to earlier interpretations of aerial photographs, the rate of land use change in most subwatersheds within Elkhorn Slough accelerated more between 1971 and 1980 than between 1931 and 1980, indicating that increased farming intensity began in the 1970s (Dickert and Tuttle 1980). Between 1981 and 1993, crop acreage in the watershed increased 29%, with strawberry acreage increasing 53% (USDA-SCS 1994). Currently, 24% of the Elkhorn Slough watershed is intensively farmed (Caffrey et al. 2002).

Objectives

The major goal of this study was to determine how watershed land use change (i.e., increasing agriculture) over 30 years influenced changes in salt marsh soil physical properties, and in turn, plant composition through the use of remote sensing, geographic information systems (GIS) and field methods. The research was organized into two objectives: The first objective was to use current and historic aerial photographs to map historic wetland plant communities and quantify the extent and type of salt marsh vegetation change on sediment fans from 1971 to the present, using imagery from 1931 as a base. The second objective was to explore the driving factors of this change through field sampling of marsh soil properties and topographic features. The objectives were driven by the following questions: 1) Since 1970, how did salt marsh vegetation change in areas impacted by upland sand and sediment deposition? 2) How do properties of soil and elevation differ in sediment fans compared to adjacent areas of undisturbed salt marsh, and which variables are driving the shift in wetland plant composition on the fans?

Methods

Part 1: Historic Vegetation Change

To quantify vegetation change on sediment fans in Elkhorn Slough, imagery from four decades, starting in 1971, were classified and used in a post-classification change detection analysis. Aerial photographs from 1931 provided reference conditions for the Elkhorn Slough watershed. This frequency of change detection was chosen based on the availability of imagery and its suitability for capturing significant vegetation changes occurring as a result of disturbance from sedimentation.

Study Sites: We chose 15 sediment fans present in salt marsh, both diked and undiked, as study areas (Figure 1). All existing fans were identified and included in the study after an older map of sediment fans from the late 1970s (Dickert and Tuttle 1980) was consulted, local experts were interviewed, and the perimeter of the slough was surveyed by foot in the summer of 2002. Cross-sections of the 15 targeted alluvial fans ranged in size from approximately 30 to 200 m across. Combined, all 15 study sites covered 37 hectares.

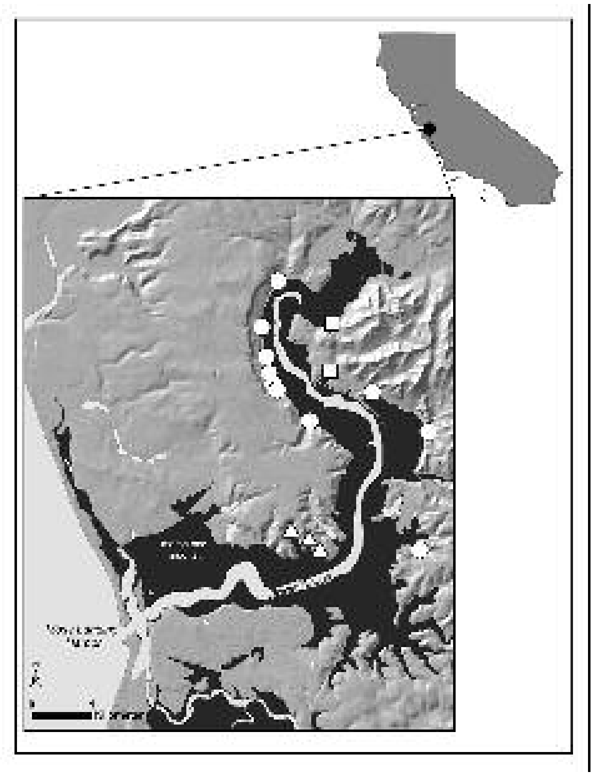


Figure 1. The Elkhorn Slough study area and study sites. There were 15 sediment fans studied in this project. Circles represent fans below active farming, squares represent fans below catchments with land taken out of cultivation and restored in the mid 1990s, and triangles represent fans below grazed areas.

Ten sites were located in sub-catchments with active agriculture, three were located downhill of a cattle ranch, and two sites were located in sub-catchments where land was taken out of cultivation and restored in the mid 1990s. Four sites on the east side of the slough have severely restricted or no tidal action, while other sites were at least partially connected to tidal flow.

Aerial Photographs: Aerial photographs from May 1971, April 1980, May 1992, and May and June 2001 (see index for references) were chosen to produce a time series of vegetation change on a decadal scale. May 1931 aerial photographs were also analyzed for reference conditions. The 1980 and 1992 photographs were color infrared (CIR) at a scale of 1:12,000. The 1971 and 1931 photographs were black and white, with scales of 1:20,000 and 1:19,000 respectively. The May 2001 image was a CIR digital orthoquad (DOQ) with a resolution of 0.6 meter per pixel. A June 2001 true color aerial photo with a scale of 1:12,000 was used for coverage of the far eastern extent of the slough not covered in the DOQ. All photos were scanned to generate digital images with a resolution of approximately 0.6 meter per pixel.

Image Processing and Analysis: All photos were georeferenced to the 2001 DOQ (and also to a 1999 DOQ when rectifying eastern areas not covered by the 2001 DOQ) using Erdas Imagine 8.7 (Leica Geosystems GIS & Mapping 1991-2003). Root mean square error for all georeferenced images was less than 0.5 pixel. The flat topography of the marsh made orthorectification unnecessary.

The CIR images were classified based on a scheme derived from *A Manual of California Vegetation* (Sawyer and Keeler-Wolf 1995), and classes included bare soil (including mudflat), pickleweed (*Salicornia virginica*), saltgrass/jaumea (*Distichlis spicata/Jaumea carnosa*), bulrush/cattail (*Scirpus* spp./*Typha* spp.), arroyo willow/coast live oak (*Salix lasiolepis/Quercus agrifolia*), coyote brush scrubland (*Baccharis pilularis*), and California annual grassland. In the black and white images, only pickleweed and mudflat areas were classified.

Arroyo willow and coast live oak were combined into one class because their similar spectral properties made separation of these species unsuccessful. From an ecological standpoint, combining these two species into one class was reasonable, as our objective was to focus on changes to salt marsh vegetation, and coast live oak was highly unlikely to establish in a salt marsh. Field surveys verified that only willows had encroached into the salt marsh. Visual interpretation of the aerial photographs provided evidence that change in this forest class was predominantly due to changes in willow cover.

The 1980, 1992, and 2001 images were classified using an automated supervised classification algorithm. In the 1971 and 1931 images, the mudflat/pickleweed boundary was manually digitized, and the mudflat and pickleweed areas were classified using an automated unsupervised classification algorithm. An accuracy assessment was conducted for each classified image using reference data obtained by ground-truthing, photointerpretation, and other published data sources. We computed a standard error matrix and kappa coefficient for each dataset.

Part 2: Changes in Marsh Physical and Chemical Properties

As in many coastal salt marshes, the vegetation in the study sites exist in distinct, almost monotypic zones. On the sediment fans, dominant plant communities present along a wetland – upland gradient are pickleweed, cattail and bulrush, and arroyo willow, and there are discrete breaks between each community. The cattail and bulrush community is dominated by *Typha latifolia*, *T. angustifolia*, their hybrid *T. x glauca* and *Scirpus californicus*. To determine the effects of sedimentation on marsh physical and chemical properties, we studied five sediment fans (out of the 15 present in the slough) that were down-slope of active agriculture. The cross-section of each sediment fan was approximately 200 meters. We also chose three reference sites adjacent to the fans that were characterized as relatively undisturbed pickleweed salt marsh.

Permanent transects running from upland to wetland were established at each site to sample vegetation and soil conditions. On the sediment fans, transects were systematically placed 50 meters apart, with the first transect location chosen randomly. The number of transects per site ranged from four to five, depending on the size of the fan. Sample points were placed in the center and edge of each plant zone to capture the entire range of environmental conditions in which each plant community was found, and to discriminate differences at the ecotone between plant communities. There were three transects in the reference sites running 25 meters from upland to wetland. Four sample points were established systematically along each transect. Overall, 170 sampling points were established among the eight sites.

The following variables were sampled over a two-year period beginning in August 2002: soil texture, soil salinity (electrical conductivity), soil moisture, elevation, soil nitrate (NO_3-N), and soil ammonium (NH_4-N). Nitrogen mineralization and nitrification rates were calculated from soil incubations. Elevation surveys were conducted using a level and stadia rod, and were referenced to benchmark readings in NAVD 88. A sub-set of soil samples was also analyzed for bulk density. Soil was sampled to a depth of 30 centimeters to capture the bulk of the root zone for all dominant species. Sampling occurred in August 2002, April and August 2003, and April 2004. These dates were chosen to account for the difference in some variables between spring – the end of the rainy season when freshwater flows and agricultural runoff is higher, and late summer – the height of the dry season when biomass is at its peak and salinity especially is at its highest point. Elevation surveys occurred in November 2003 when plants had senesced. Soil texture, elevation, and bulk density were sampled once. Soils were tested for salinity on all four dates, and soil moisture and soil nitrogen were sampled in April and August 2003 and April 2004.

Statistical Analysis: Data were analyzed using Classification Trees in the software package R 1.9.1. Classification trees are a useful non-parametric alternative to linear discriminant analysis and have several advantages. The results are invariant to transformations such as log transforms and they can use any combination of categorical and continuous predictor variables. They can handle missing data and they have the ability to capture hierarchical and nonlinear relationships and expose interactions among predictor variables (Feldesman, 2002). Rpart (in R 1.9.1) uses BFOS (binary recursive partitioning algorithm), and splits the response variable into increasingly homogeneous binary subsets based on critical thresholds in predictor variables. The split chosen is the one that most reduces the average impurity in the resulting bins. Cross validation is used to determine length of tree, which is a balance between misclassification error and tree size (smaller trees are preferred to prevent overfitting). Not all predictor variables may determine splits in the tree – those not influencing classification of response variables will not appear on the tree. Further analyses were conducted using multiple analysis of variance and one-way ANOVAs.

Results

Part 1. Historic Vegetation Change

Sediment fans are not a new phenomenon in Elkhorn Slough, but analysis of historic aerial photographs indicated that their acreage and number have increased greatly since the early 1900s. In 1931, within the study areas, only 2 fans out of 15 were present. One was dominated by willows while the other was unvegetated. Both were smaller than their 2001 size. The size of fans was estimated visually based on the presence of bare sediment or willows. In the 1971 image, fans were present in 8 out of the 15 sites. The 1971 fan areas were smaller, and they could be characterized by the presence of bare, unvegetated sand. Three of the 8 fans were partially vegetated by willows along the upper margin and partially covered in bare sand.

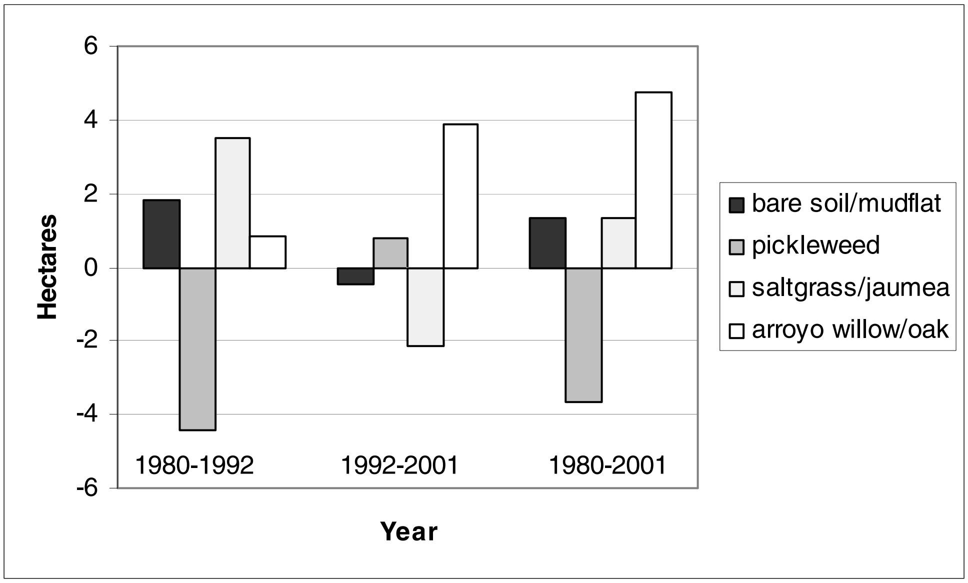
The overall classification accuracy and overall Kappa statistic for the five classified images were: 2001: 81.42% and 77.38%; 1992: 86.51% and 83.72%; 1980: 85.89% and 82.82%; 1971: 89.44% and 78.87%; and 1931: 89.76% and 72.00%. Bare soil/mudflat was most successfully classified in the CIR images, with accuracy levels higher than 92%. Other vegetation types that were successfully classified were arroyo willow/coast live oak and pickleweed. The saltgrass/jaumea class had relatively high accuracy for the 2001 and 1992 images, but was less accurate in the 1980 image. Classification of the bulrush/cattail vegetation type was less successful, probably since this class was not dominant in the study area, and the photo dates did not coincide with the period of maximum biomass for cattails, which is in late summer (Jensen 2000). California annual grassland and coyote brush scrubland were often confused with each other.

Changes in the area of each class from one decade to the next present some dominant trends within the study sites. Bare soil/mudflat increased continually from 1931 to 2001. Pickleweed showed a general decline from 1931 to 2001, with some recovery in 1980. Saltgrass/jaumea increased greatly from 1980 to 1992, then decreased in area. Arroyo willow/coast live oak coverage increased greatly from 1980 to 2001. Annual grasses decreased from 1980 to 2001 while coyote brush scrubland increased. These changes reflect patterns within the study sites only and do not necessarily extend to patterns across the entire Elkhorn Slough watershed.

As the objective of this project was to assess vegetation change in wetlands disturbed by sedimentation, further discussion of the results will center more on classes present in wetlands that were relatively well classified. These classes are: bare soil/mudflat, arroyo willow/coast live oak, pickleweed, and saltgrass/jaumea.

Bare soil/mudflat increased by 23% (1.33 ha), with the greatest increase between 1980 and 1992 at 32% (with loss occurring between 1992 and 2001). Pickleweed cover was reduced by 32% (3.64 ha) between 1980 and 2001 on sediment fans, with the greatest reduction (38%) between 1980 and 1992 (there was some recovery between 1992 and 2001) (Figure 2). Together these classes, which as a complex characterized a unit of pre-sedimentation salt marsh, lost 14% of their area between 1980 and 2001 (2.34 ha). Saltgrass/jaumea increased dramatically, from 0.63 ha in 1980 to 4.13 ha in 1992, then decreased by more than 50% in 2001. The area of arroyo willow/coast live oak increased from 6.75 ha to 11.5 ha (70%) between 1980 and 2001, with the greatest increase (51%) between 1992 and 2001. This increase was primarily due to willow expansion. Overall, between 1980 and 2001, pickleweed decreased in area, saltgrass/jaumea increased (predominately between 1980 and 1992), and arroyo willow/coast live oak also increased, mostly between 1992 and 2001.

Figure 2. Decadal change in the coverage of major classes (in hectares)



A time series image of a study site from 1980 to 2001 illustrates the relative change in area among pickleweed, bare soil, saltgrass/jaumea, and willows (Figure 3). The time series image demonstrates a process of succession that was typical on five sediment fans, all located on the western side of the slough where tidal action was still present. Between 1980 and 1992, as sedimentation occurred, pickleweed and mudflat were replaced by saltgrass and jaumea, in a fan-like area below upland drainages. Between 1992 and 2001, sedimentation likely continued, especially during the strong El Niño winter of 1997-98, and arroyo willow took the place of saltgrass and jaumea, and continued to extend into the marshplain. On the eastern side of the slough, the pattern of successional change lacked

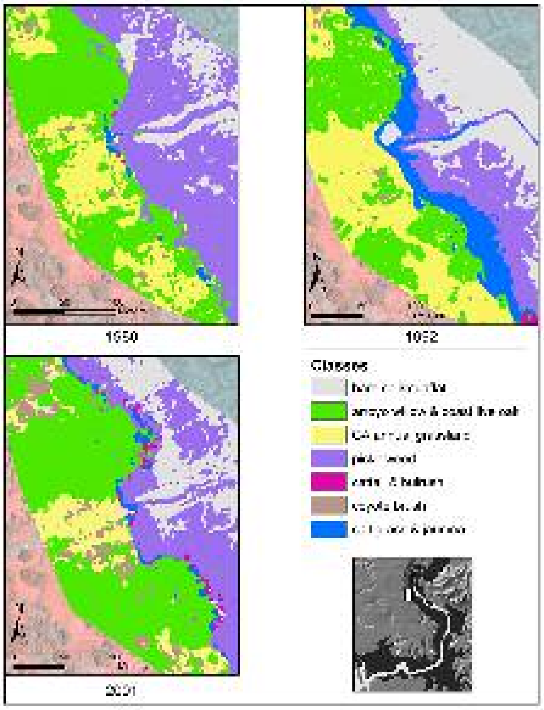


Figure 3. Time series depicting vegetation change from 1980 through 2001 on a selected region of Elkhorn Slough. Study area shown is 6.73 hectares. Highlighted areas of change are superimposed on the original 2001 color IR DOQ.

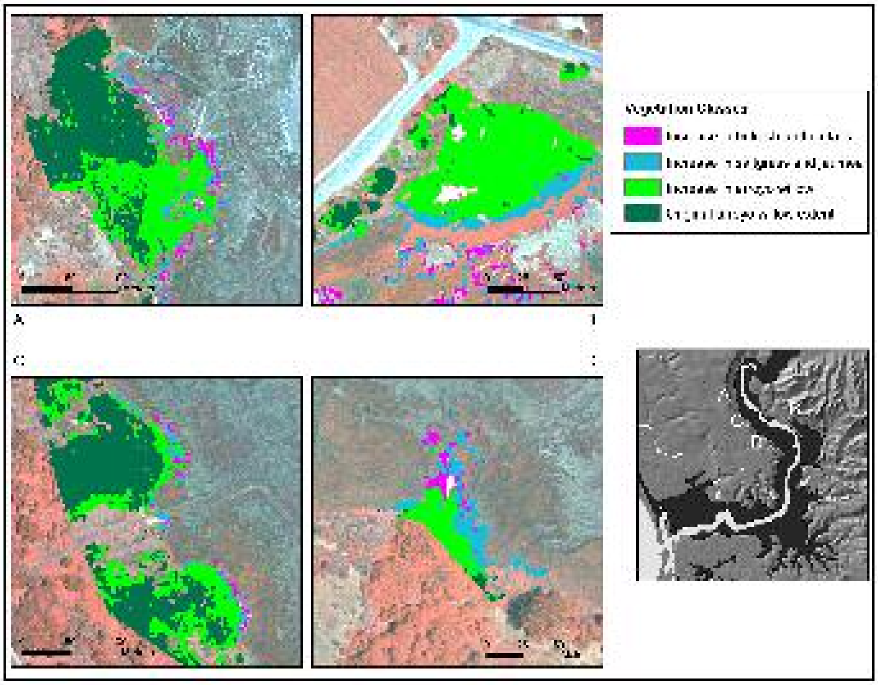


Figure 4. Arroyo willow expansion throughout Elkhorn Slough on sediment fans. Highlighted areas of change are superimposed on the original 2001 color IR DOQ.

the intermediate stage of saltgrass and jaumea, but the final outcome was still an expansion of willow cover, and movement of willows into the salt marsh.

Overall, the predominant effect of sedimentation was the expansion of willow into the marsh plain that occurred throughout the watershed. This pattern is illustrated in Figure 4. Willow expansion occurred on 11 of the 15 sediment fan study areas. Of the remaining four, three were small fans downhill of pasture land which were bare in 1980 but experienced pickleweed recovery by 1992. The fourth had minimal vegetation change.

Comparison with 1971 and 1931 images: Between 1931 and 2001, bare soil (mudflat) increased dramatically, from 0.44 ha to 7.01 ha. Other research has documented a dramatic increase in mud flats probably due to tidal erosion that began with the opening of Moss Landing Harbor in 1947 (Van Dyke and Wasson 2004). Pickleweed area decreased 47% from 14.68 ha to 7.84 ha. By 2001, the salt marsh present in 1931 had been replaced by 3.85 ha of other vegetation, of which 2.01 ha consisted of willows.

There was a slight overall decrease in pickleweed between 1971 and 2001, from 8.12 ha to 7.84 ha. Mudflat increased greatly, from 3.01 ha to 7.01 ha. Within the salt marsh area mapped in the 1971 image, by 2001, 1.61 ha of other vegetation, including willows, saltgrass and jaumea, and cattails, had invaded. Of this, willow cover consisted of 0.75 ha.

Part 2. Changes in Marsh Physical and Chemical Properties

Multiple analyses of variance (MANOVA) were conducted for all combined April data and for all combined August data to test for differences in mean vectors among four groups, which included reference sites, pickleweed (located on the sediment fans), cattail and bulrush (cattail), and arroyo willow. For both the April and August datasets, the MANOVA Wilks' Lamda test approximated an F statistic with P values less than 0.0001. (April: F Value 17.33, DF 202; August: F value 30.52, DF 187). Following, each variable was tested for significant differences among groups using one-way ANOVAs (Table 1). Bulk density increased along the wetland-upland gradient, and was significantly higher in willow and cattail communities (1.26 and 1.14 g/cc) than in pickleweed (0.93 g/cc) and reference sites (0.48 g/cc). In comparision, percent sand was similar in the reference and pickleweed groups with averages of 39.37% and 35.55% respectively. Percent sand increased significantly from pickleweed to cattail (59.79%) to willow (81.26%). Elevation was not significantly different between the reference, pickleweed, and cattail groups, but increased gradually from 1.34 m to 1.45 m on average. But there was a significant jump in elevation within the willows to an average height of 1.92 m.

In the spring, significant group differences in electrical conductivity were found among the reference sites, pickleweed, and cattail, as salinity decreased greatly along the wetland-upland gradient. However, the average electrical conductivity between cattails (6.64 dS/m) was not significantly greater than that for willows (0.99 dS/m) likely as a result of high variance in the cattail salinity data. April gravimetric soil moisture exhibited similar group differences to electrical conductivity: soil moisture decreased with increasing proximity to the upland, with significant differences among the reference (142%), pickleweed (66%), and cattail groups (37%), and similarities among the cattails and willows (17%). April soil nitrate-nitrogen was significantly higher in the reference sites than in all other areas on the sediment fans. April soil ammonium-nitrogen decreased from pickleweed to cattail to willow, with significant differences between pickleweed and cattail. Reference site soil ammonium-nitrogen was greater than in all other groups. There was no difference in nitrogen mineralization and nitrification in April among all groups. However, mineralization rates were slightly negative in the reference and pickleweed sites, compared to a slightly positive rate in the cattail and willow sites, indicating nitrogen immobilization taking place.

In August, the salinity gradient along the sediment fan became greater than in April. The reference sites still were significantly higher in salinity than all other groups. In contrast to the spring, a significant drop in salinity developed between the cattails (31.22 dS/m) and

Table 1. One-Way Anovas of all variables. Means and standard deviations provided. Means sharing a superscript letter are not significantly different.

	F value	**Prob > F**	**Reference**	**Pickleweed**	**Cattail**	**Willow**
Bulk density (g/cc)	88.78	<.0001	0.48^{A} ±0.18	0.93^{B} ±0.26	1.14^{C} ±0.21	1.26^{C} ±0.13
Elevation (m)	11.42	<.0001	1.34^{A} ±0.43	1.34^{A} ±0.40	1.45^{A} ±0.37	1.92^{B} ±0.51
Percent sand	25.87	<.0001	39.37^{A} ±21.70	35.55^{A} ±22.58	59.79^{B} ±27.24	81.26^{C} ±20.08
April						
Electrical conductivity (dS/m)	113.16	<.0001	86.62^{A} ±50.13	38.19^{B} ±35.15	6.64^{C} ±10.04	0.99^{C} ±0.77
Gravimetric soil moisture	73.21	<.0001	141.92^{A} ±87.03	66.26^{B} ±41.43	36.74^{C} ±12.29	16.70^{C} ±9.23
NO3-N (µg/g soil)	20.63	<.0001	3.23^{A} ±1.64	1.85^{B} ±0.77	1.87^{B} ±0.82	1.88^{B} ±1.39
NH4-N (µg/g soil)	25.27	<.0001	13.46^{A} ±13.95	7.51^{B} ±7.71	3.23^{C} ±3.06	1.29^{C} ±1.09
N mineralization (µg/g/day)	1.09	0.35	-0.16 ±1.12	-0.38 ±1.51	0.10 ±2.47	0.02 ±0.16
Nitrification (µg/g/day)	0.74	0.53	0.06 ±0.28	0.06 ±0.13	0.18 ±1.03	0.07 ±0.17
August						
Electrical conductivity (dS/m)	120.44	<.0001	146.38^{A} ±59.19	74.13^{B} ±37.43	31.22^{C} ±26.81	5.52^{D} ±9.20
Gravimetric soil moisture	29.09	<.0001	117.42^{A} ±79.18	65.69^{B} ±62.66	31.39^{C} ±21.14	8.33^{C} ±9.66
NO3-N (µg/g soil)	1.31	0.27	1.70 ±0.92	1.34 ±0.64	1.94 ±2.53	1.35 ±0.83
NH4-N (µg/g soil)	10.81	<.0001	6.38^{A} ±4.36	8.83^{A} ±11.05	2.71^{B} ±3.21	1.25^{B} ±0.75
N mineralization (µg/g/day)	8.17	<.0001	-0.02^{A} ±0.64	-0.95^{B} ±1.69	-0.10^{A} ±0.59	0.01^{A} ±0.12
Nitrification (µg/g/day)	0.86	0.47	0.04 ±0.14	-0.01 ±0.08	0.03 ±0.22	0.05 ±0.12

willows (5.52 dS/m), as the cattails became more saline while in the willows, conditions remained somewhat fresh to brackish. There was little change in soil moisture from April to August, though soil dried out in the willows to an average of 8.33%. Again, soil ammonium-nitrogen dropped along the wetland-upland gradient in August. The pickleweed sites had slightly higher levels than the reference sites. Together, pickleweed and reference sites had significantly higher ammonium levels the cattail and willow sites. Soil nitrate-nitrogen and nitrification rates did not differ among groups. Nitrogen mineralization rates were significantly lower in the pickleweed (-0.95 µg/g/day) than in all other groups again indicating nitrogen immobilization.

Classification Trees

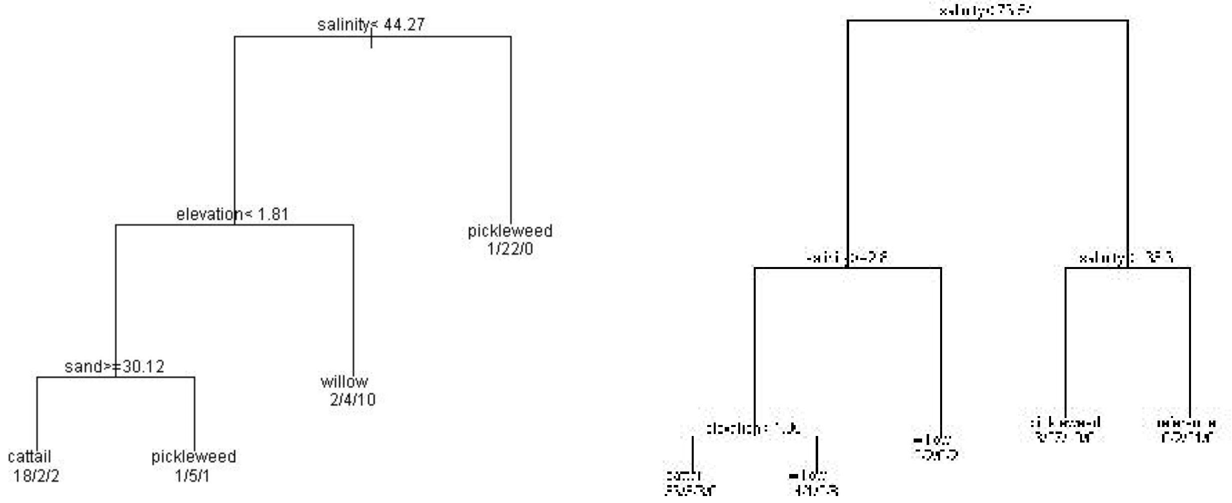
For all four sampling dates, salinity, or electrical conductivity, was the variable that produced the first bivariate split in each classification tree (Figure 5). The threshold level in electrical conductivity for these splits was different for all dates, with salinity levels being higher in August than in April. In August, when the sediment fans become more dry and hypersaline conditions appear in the marsh, salinity becomes a much greater factor in controlling the distribution of species. After salinity, elevation drove the split between willows and other groups with a threshold level of about 1.8 m, while percent sand produced a split between cattails and pickleweed in August 2002. August 2002 resubstitution accuracy was 80.9% and cross-validation accuracy was 66.2%. August 2003 resubstitution accuracy was 77.9% and cross-validation accuracy was 68.3% (Table 2).

The April 2003 data produced the most complex tree. Based on bivariate splits, pickleweed and reference sites can be described as areas with high salinity and low percent sand. Levels of ammonium-nitrogen divided these two groups. In contrast, willow sites were characterized as areas with soil moisture lower than 20.33%, or areas with elevation greater than 1.85 m. Cattails were found in areas with elevation less than 1.08 m, or if greater, than with soil moisture less than 45.81%. The repeated appearance of soil moisture and elevation along this branch of the tree suggests an interaction between the two variables. In contrast, the April 2004 data classification was much more driven by a salinity gradient, with pickleweed and reference sites divided from cattail and willow sites by a threshold level in electrical conductivity of 11.54 dS/m. Salinity threshold level of 1.18 dS/m further splits cattails from willows. April 2003 resubstitution accuracy was 77.2% and cross-validation accuracy was 55.0%. April 2004 resubstitution accuracy was 74.7% and cross-validation accuracy was 63.4%.

In August datasets, willow data points were classified most successfully, even holding up under cross-validation testing. Reference sites were poorly classified, and most often confused as pickleweed present on sediment fan, which is reasonable given that the reference sites were dominated by pickleweed. Pickleweed resubstitution classification levels were 82% and 77%, with misclassified points being confused with all other classes more or less equally. Cattail was also classified well (82% and 80%). Again, willows were classified well in April datasets (94% and 74%) and maintained relatively high classification levels in the cross-validation test. Reference sites were classified better (78% and 94%) but were again mostly confused for pickleweed. Pickleweed was classified less well (62.2% and 52.6%) and was confused for reference sites and cattail. Cattails in the April datasets were also classified less successfully than in August (77% and 78%) and were equally confused for pickleweed and willow.

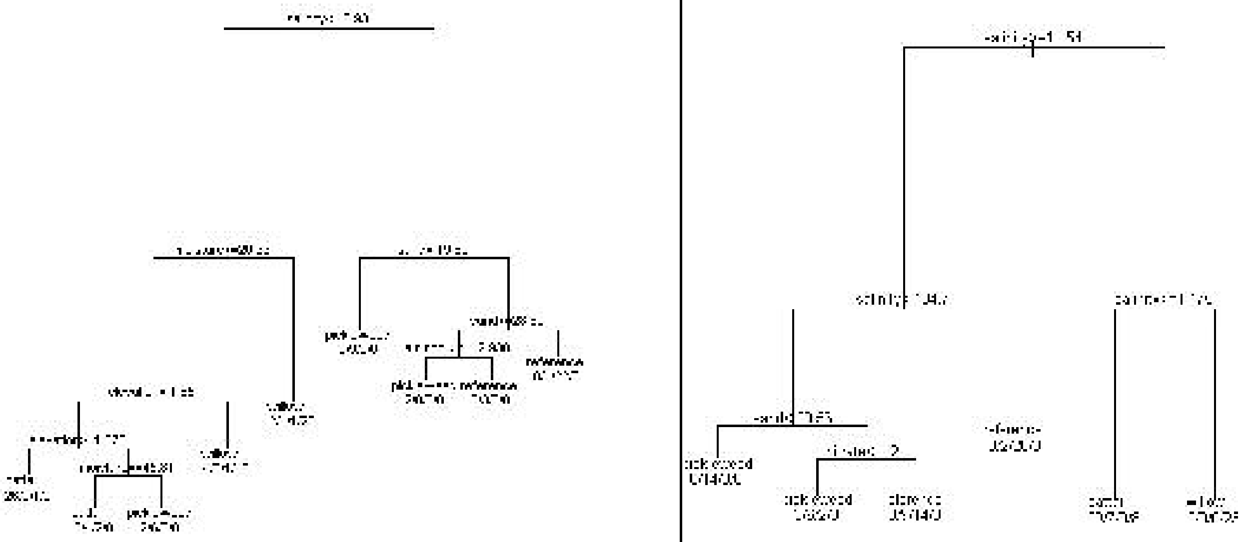
The August 2002 model was used to predict data from August 2003 (Table 3). Overall prediction accuracy was 64%. This low value was mostly due to the cattail class, which was only predicted with 33% accuracy, similar to that of chance alone. In contrast, pickleweed data was predicted with 94% accuracy and willows with 76% accuracy. Prediction of April 2004 data, using the April 2003 data was somewhat more accurate (73%). Reference sites were classified most successfully (80%), followed by willow (77%) and pickleweed (76%). Again, prediction of cattails was the lowest at 60%.

Figure 5. Classification Trees for August 2002, 2003, and April 2003, 2004. Labels of nodes represent data types assigned to that node, in order: cattail/pickleweed/reference/willow



August 2002

August 2003



April 2003

April 2004

Table 2. Classification Tree Resubstitution and Cross Validation Accuracy Matrices for August 2002, August 2003, April 2003, and April 2004

August 2002

Resubstitution Matrix
Accuracy: 80.9%

Class Actual	P	Ca	W	Class Accuracy
pickleweed	27	2	4	81.8%
cattail	2	18	2	81.8%
willow	1	2	10	76.9%

Cross-Validation Matrix
Accuracy: 66.2%

Class Actual	P	Ca	W	Class Accuracy
pickleweed	23	6	4	69.7%
cattail	8	12	2	54.5%
willow	1	2	10	76.9%

August 2003

Resubstitution Matrix
Accuracy: 77.9%

Class Actual	R	P	Ca	W	Class Accuracy
reference	21	10	3	2	58.3%
pickleweed	2	27	3	3	77.1%
cattail	0	3	36	6	80.0%
willow	0	0	0	29	100.0%

Cross Validation Matrix
Accuracy: 68.3%

Class Actual	R	P	Ca	W	Class Accuracy
reference	21	10	3	2	58.3%
pickleweed	6	21	5	3	60.0%
cattail	1	5	33	6	73.3%
willow	0	0	5	24	82.8%

April 2003

Resubstitution Matrix
Accuracy: 77.2%

Class Actual	R	P	Ca	W	Class Accuracy
reference	28	3	3	2	77.8%
pickleweed	4	23	6	4	62.2%
cattail	0	4	34	6	77.3%
willow	0	0	2	30	93.8%

Cross Validation Matrix
Accuracy: 55.0%

Class Actual	R	P	Ca	W	Class Accuracy
reference	21	11	2	2	58.3%
pickleweed	12	11	10	4	29.7%
cattail	1	8	25	10	56.8%
willow	0	2	5	25	78.1%

April 2004

Resubstitution Matrix
Accuracy: 74.7%

Class Actual	R	P	Ca	W	Class Accuracy
reference	34	2	0	0	94.4%
pickleweed	11	20	7	0	52.6%
cattail	3	3	29	2	78.4%
willow	0	0	8	23	74.2%

Cross Validation Matrix
Accuracy: 63.4%

Class Actual	R	P	Ca	W	Class Accuracy
reference	25	9	2	0	69.4%
pickleweed	12	19	6	1	50.0%
cattail	3	3	24	7	64.9%
willow	0	0	9	22	71.0%

Table 3. Classification predictions of August 2003 and April 2004 data based on previous years' data. *August 2003 reference sites were not predicted because there were no reference sites in the August 2002 model.

<table>
<tr><th colspan="6">August 2003 Predictions*</th></tr>
<tr><td colspan="6">Accuracy: 64.2%</td></tr>
<tr><td>Class
Actual</td><td>P</td><td>Ca</td><td colspan="2">W</td><td>Class Accuracy</td></tr>
<tr><td>pickleweed</td><td>33</td><td>2</td><td colspan="2">0</td><td>94.3%</td></tr>
<tr><td>cattail</td><td>25</td><td>15</td><td colspan="2">5</td><td>33.3%</td></tr>
<tr><td>willow</td><td>1</td><td>6</td><td colspan="2">22</td><td>75.9%</td></tr>
<tr><th colspan="6">April 2004 Predictions</th></tr>
<tr><td colspan="6">Accuracy: 73.2%</td></tr>
<tr><td>Class
Actual</td><td>R</td><td>P</td><td>Ca</td><td>W</td><td>Class Accuracy</td></tr>
<tr><td>reference</td><td>29</td><td>6</td><td>0</td><td>1</td><td>80.1%</td></tr>
<tr><td>pickleweed</td><td>6</td><td>29</td><td>2</td><td>1</td><td>76.3%</td></tr>
<tr><td>cattail</td><td>2</td><td>6</td><td>22</td><td>7</td><td>59.5%</td></tr>
<tr><td>willow</td><td>0</td><td>1</td><td>6</td><td>24</td><td>77.4%</td></tr>
</table>

Conclusions

Use of aerial photographs in an historic change detection within a coastal salt marsh revealed patterns of vegetation change associated with sedimentation caused by land use between 1971 and 2001. Through analysis of imagery, the encroachment of arroyo willow into pickleweed-dominated salt marsh was documented and quantified. A rich archive of photographs dating back to 1931 provided the historical context in which to interpret these changes.

While cattail and bulrush were not as easily classified on the aerial photos as other plant communities, it should be noted that field surveys verify the presence of a band of cattails and bulrush between the willows and pickleweed on several sites. In the field, the width of this band varied, depending on the site, from a few meters to 25 meters and served as a transition area between arroyo willow and pickleweed salt marsh.

Change detection of color infrared photographs revealed the stages in which pickleweed marsh is converted to an arroyo willow thicket. On five sediment fans on the west side of the slough, where tidal action is still present, successional transition from pickleweed to saltgrass and jaumea to arroyo willow occurred between 1980 and 2001. Because a series of historic aerial photographs existed for Elkhorn Slough, we were able to quantify patterns of change, but more importantly, we could produce a time series that exposed an ecological process of succession from one decade to the next.

Results from field sampling indicate that sedimentation into Elkhorn Slough salt marshes led to higher bulk density, higher soil sand content, higher elevation, lower salinity, and lower soil moisture. Arroyo willow preferred environments with low year-round salinity, high sand content, reduced soil moisture, and elevation greater than 1.8 meters. Cattails and bulrush were present in a transitional zone between willow and cattail, and could tolerate large seasonal fluctuations in salinity and lower elevations. Results from the classification trees suggest that willows exist in a well-defined habitat, restricted by thresholds in elevation, salinity, and soil moisture. Cattails and bulrush, on the other hand, may exist over a wider range of environmental conditions.

It is unknown whether one plant community facilitated the establishment of another. But probably as sedimentation occurred over the years, elevation rose until conditions were suitable for arroyo willow. Arroyo willow has no salt tolerance and is adapted to coarse textured soils as is found on the sediment fans (USDA-NRCS 2004b). The elevation on the fans may have increased until they were beyond the range of tidal influence and low salinity conditions could persist.

Conservationists in the Elkhorn Slough watershed debate the habitat value created from the spread of arroyo willow groves, as they do provide habitat for songbirds and wildlife. But the process of sedimentation by which willow expanded continues to be detrimental farmers who lose productivity and acreage from soil erosion, as well as to the salt marsh ecosystem, which is buried and lost as sediment builds. Results from this study may have applications for predicting potential effects of proposed land conversions on wetland habitat. Also, resource managers at the Elkhorn Slough Foundation, Natural Resources Conservation Service, and the Monterey County Resource Conservation District are actively working with farmers to reduce soil erosion and off-farm sediment. Evidence of habitat change from sedimentation documented in this study supports the need for these continued erosion control efforts. These efforts have already reduced sedimentation into the slough, and improvements are likely to continue in the future. As sediment loads into the slough are further reduced, it would be valuable to continue to monitor the sediment fans to determine if any recovery in salt marsh vegetation occurs.

Participants

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Papers

Kristin B. Byrd, N. Maggi Kelly, and Eric Van Dyke. Decadal changes in a Pacific estuary: a multi-source remote sensing approach for historical ecology. Accepted to GIScience and Remote Sensing, November 23, 2004.

Kristin B. Byrd and N. Maggi Kelly. Salt marsh vegetation response to edaphic and topographical changes from upland sedimentation in a Pacific estuary. In Progress.

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