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Temporal and Spatial Relationships Between Watershed Land Use and Salt Marsh Disturbance in a Pacific Estuary

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Abstract Historical and recent remote sensing data can be used to address temporal and spatial relationships between upland land cover and downstream vegetation response at the watershed scale. This is demonstrated for sub-watersheds draining into Elkhorn Slough, California, where salt marsh habitat has diminished because of the formation of sediment fans that support woody riparian vegetation. Multiple regression models were used to examine which land cover variables and physical properties of the watershed most influenced sediment fan size within 23 sub-watersheds (1.4 ha to 200 ha). Model explanatory power increased (adjusted $R^2 = 0.94$ vs. 0.75) among large sub-watersheds (>10 ha) and historical watershed variables, such as average farmland slope, flowpath slope, and flowpath distance between farmland and marsh, were significant. It was also possible to explain the increase in riparian vegetation by historical watershed variables for the larger sub-watersheds. Sub-watershed area is the overriding physical characteristic influencing the extent of sedimentation in a salt marsh, while percent cover of agricultural land use is the most influential land cover variable. The results also reveal that salt marsh recovery depends on relative cover of different land use classes in the watershed, with greater chances of recovery associated with less intensive agriculture. This research reveals a potential delay between watershed impacts and wetland response that can be best revealed when conducting multi-temporal analyses on larger watersheds.

Keywords Sedimentation · Salt marsh · Land use · Remote sensing · Multi-temporal analysis

Introduction

Wetlands are functionally interdependent with other parts of their landscape setting, generally defined by a cluster of watersheds with similar geomorphology and patterns of change or disturbance (Forman and Godron 1986; Bedford and Preston 1988). For example, properties of a wetland's landscape setting, such as slope and topography, percent area in wetlands, and spatial configuration of different land-use types, can influence inputs to wetlands (Bedford 1999). Accordingly, the structure and processes of a wetland are related to land use activities in its watershed (Brinson 1993), and the cumulative alteration of land cover surrounding a wetland is one of the greatest constraints to wetland restoration success (Bedford 1999). As a result, scientists have focused on processes operating at a watershed or ecoregion scale when considering wetland management strategies (Kentula and Magee 1999).

Historical features of land use within a watershed such as past arrangement of land use types may also influence the extent of wetland disturbance. The study of historical environmental conditions can reveal the presence of land use legacies, which relates to the concept that site history is embedded in today's ecosystems (Foster et al. 2003). Much work on land

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use legacies has focused on temporal changes occurring within a single ecosystem (Aber et al. 1997; Foster and Motzkin 2003), and some address connections between past upland land use and current downstream condition (Harding et al. 1998; Bennett et al. 1999; Bennett et al. 2001).

Remote sensing and GIS analyses of historical imagery can be powerful tools to address land use legacies in part because these tools allow us to conduct landscape level analyses as opposed to studying only site scale phenomena. Remote sensing applications in this field were discussed during a symposium at the 89th Annual Meeting of the Ecological Society of America and reviewed topics such as how historical land use drives current species composition in forests, shrubland, and arid landscapes (Elmore et al. 2004; Hamburg et al. 2004; Kouchoukos 2004; Turner 2004).

Numerous studies in aquatic ecology have applied statistical methods including multiple regression, correlations, and ordination to model relationships between upland land use change and instream conditions. Typically, the objectives of the studies were to quantify the effects of land use activities such as timber harvest, agriculture, and grazing on water quality and habitat for salmonids and macroinvertebrates (Meehan 1991; Lenat and Crawford 1994; Allan et al. 1997; Strayer et al. 2003; Pan et al. 2004; Potter et al. 2004; Townsend et al. 2004). These studies found that nutrient levels, features of stream channel morphology, benthic macroinvertebrate diversity, and lotic diatom assemblages were correlated with the spatial extent of land use at the watershed scale and/or the riparian zone scale.

Efforts to quantify the impacts of upland land use on downstream ecosystems are challenging because of natural variation within and between watersheds. First, the contribution of anthropogenic attributes, such as land use change, must be separated from the effects of natural geologic attributes, such as slope, soil type, and rainfall patterns of a watershed (Richards et al. 1996). Second, the scale at which upland changes are studied can influence the results; local versus watershed conditions can have differing effects on stream quality, and effects can differ from region to region. For example, land use within 100 meters of a stream was found to be significantly related to biotic integrity, defined by biotic indices that comprise multiple metrics of fish and macroinvertebrate communities (Lammert and Allan 1999). The scale of watersheds may also influence the explanatory power of land use variables on downstream impacts (Strayer et al. 2003).

Despite a large body of research in this area, few researchers have used these statistical methods to explain watershed impacts to wetlands and estuaries. Those that have, have focused on inputs of non-point source pollution to wetlands (Howarth et al. 1991; Hopkinson and Vallino 1995; Poiani et al. 1996; Schwarz et al. 1996; Basnyat et al. 1999; Houlahan and Findlay 2004), but not on changes to ecological structure and diversity, though there are exceptions (Owen 1999; Greer and Stow 2003; Hall et al. 2004).

The main objective of this study is to establish relationships between current and former watershed-scale land cover and physical properties and the extent of disturbance in a salt marsh ecosystem. Additionally, we explore whether the potential for marsh recovery may be tied to past land cover. We conducted our study in the Elkhorn Slough watershed, a coastal watershed in Monterey County, California, where off-farm sediment has led to the formation of numerous sediment fans that have buried salt marsh and mudflats. We refer to land cover as the type of feature on an area of the earth's surface, such as farmland or forest (Lillesand and Kiefer 2000). Our analysis was conducted at the scale of sub-watersheds within the Elkhorn Slough watershed.

These relationships between land cover and salt marsh conditions are expected because inputs to wetlands, such as freshwater flow and type and quantity of sediment and nutrients, are greatly controlled by the surrounding landscape, or its hydrogeologic setting, defined by a set of climate and physiographic characteristics (Winter 1988; 1992; Bedford 1999). Disturbance to the hydrogeologic setting, such as land cover change, may alter upland inputs to wetlands, leading to wetland degradation or loss.

Our research specifically addresses: how do past and present land cover attributes and physical properties of the watershed explain the extent to which sediment fans have impacted coastal salt marsh? Is riparian woody vegetation establishment on sediment fans also related to past and present physical watershed and land cover attributes? Does the size of sub-watersheds influence the ability to identify these relationships? Also, is it possible for salt marsh to recover from disturbance and if so under what conditions?

Other studies have shown that upland land use explains downstream condition better in large watersheds (Strayer et al. 2003; Opperman et al. 2005). In both these studies and in Elkhorn Slough, there is a wide distribution (about a 100-fold range) in watershed size. Therefore, we hypothesize that the same relationship between large sub-watersheds and wetland conditions may be true for areas draining into Elkhorn Slough. We also expect sediment fan size to be related to past land use; there is likely a time lag between

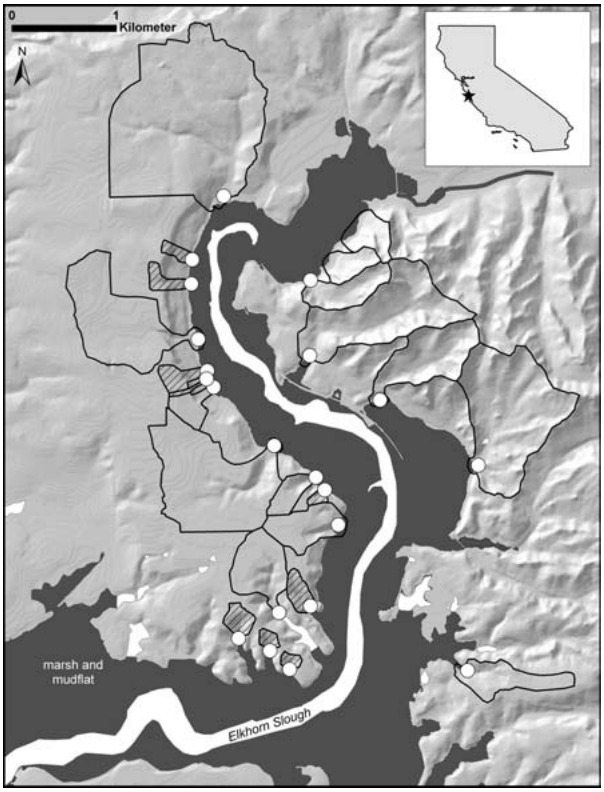

Fig. 1 Elkhorn Slough watershed and 23 study sub-watersheds. Sub-watersheds with cross-hatches were not included in the large sub-watershed (> 10 ha) data subset. Circles represent sediment fans

watershed land conversion and sedimentation in the marsh since sedimentation events are generally stochastically driven by intense storm events following land conversion (Benda and Dunne 1997). We also expect that improvements in upland land use practices that reduce erosion and sediment transport to Elkhorn Slough will help recover salt marsh habitat.

The Study Area

This study took place in the Elkhorn Slough watershed, located on the coast of Monterey Bay, California (Figure 1). 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 hectares of tidal marsh and flats (Caffrey et al. 2002), making it one of the largest salt marsh systems in California (Dickert and Tuttle 1985). 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 watershed is drained by many small seasonal streams and one main channel, Carneros Creek.

The Elkhorn Slough region has a Mediterranean climate, with a monthly mean temperature range of 11.1° to 15.4°C. Rainfall occurs almost entirely between October and May averaging 55.3 cm with a range of 27.1 and 122.8 cm between 1948 and 2004 (Caffrey et al. 2002). Most 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. When eroded, these soils produce sediment fans with a high sand content, which is observed throughout the watershed. In contrast, the marsh soil type is Alviso sandy clay loam (USDA-NRCS 2004).

While Elkhorn Slough contains a National Estuarine Research Reserve, designated in 1979, and other protected lands, intensified farming has produced high soil erosion rates in the watershed (Dickert and Tuttle 1980; USDA-SCS 1984). Farming and dairy operations have been present in the Elkhorn Slough watershed since the late 1880s. However, agriculture expanded resulting in significant land use change in the region between 1971 and 1980 (Dickert and Tuttle 1980). In the early 1980s, three-fourths of the soil erosion in the Elkhorn Slough watershed was attributed to human activity. Three-fourths of this erosion occurred on strawberry farms, many of which were found on slopes as steep as 15 to 30% (USDA-SCS 1984). Average erosion rates on strawberry farms here have been calculated at 74 metric tons per hectare per year (USDA-SCS 1994). Most soil erosion on strawberry farms occurs as large volumes of water erode vegetated slopes located below fields, forming large gullies that continue to erode (USDA-SCS 1984).

During the rainy season, water carries sediment down steep drainages located between farms and the marsh. Sediment transport in these drainages normally occurs during episodic, extreme winter storm events, with little transport during intervening periods. As sediment deposits, alluvial or sediment fans form on the margin between marshes and the base of these steep hillslopes, filling marshes, mudflats, and channels.

As erosion rates increased between 1931 and 1980 there was a five-fold increase in the number and a doubling in the acreage of sediment fans in the pickleweed (*Salicornia virginica* L.) marsh (Dickert and Tuttle 1980). By 1980, at least 30 sediment fans had formed in the Elkhorn Slough watershed, and more formed during the 1990s. Analysis of historical aerial

Table 1 Summary statistics per sub-watershed (n = 23) for land cover and watershed variables

Variable	Code	Mean	Std. Dev.	Min	Max
Sub-watershed area (ha)	catarea	33.7	47.2	1.4	199.8
Sediment fan area (ha)	fanarea	0.5	0.5	0.0	1.8
2001 %agriculture	2001 %ag	31.8	28.2	0.0	90.6
1980 %agriculture	1980 %ag	38.0	28.8	0.0	90.9
%change in agriculture	agdiffpc	–24.9	36.0	–100	23.2
1980 %grazing (ha)	1980 %graze	29.0	40.4	0.0	96.1
2001 %riparian tree cover	2001 %riparian	14.1	10.3	1.9	43.0
1980 %riparian tree cover	1980 %riparian	11.2	11.4	0.3	48.1
%change in riparian tree cover	treediffpc	92.6	140.6	–10.5	621.7
2001 average %slope of farmland	2001 agslp	7.9	6.2	0.6	17.8
1980 average %slope of farmland	1980 agslp	6.6	6.3	0.0	18.8
Average %slope of 2001 riparian flowpath	2001 Rpathslp	13.8	5.3	4.8	22.6
Average %slope of 1980 riparian flowpath	1980 Rpathslp	14.3	4.8	4.9	22.6
Average %slope of longest sub-watershed flowpath	pathslp	11.5	4.7	4.4	22.6
2001 riparian flowpath length (m)	2001 Rpathl	407.7	264.5	108.8	1085.4
1980 riparian flowpath length (m)	1980 Rpathl	337.7	169.3	108.9	749.5
Length of longest sub-watershed flowpath (m)	pathl	801.3	565.3	184.5	1907.5

Codes are provided for variables used in multiple regression analyses

photos revealed that where sediment fans formed, arroyo willow (*Salix lasiolepis* Benth.) and several brackish and freshwater species, including cattail (*Typha* spp.) and bulrush (*Scirpus* spp.), replaced salt marsh vegetation present in the 1970s and 1980s (Byrd et al. 2004).

Since 1994, several government agencies and non-profit organizations have made substantial efforts to reduce soil erosion and restore farmland to native vegetation. Practices to reduce erosion and prevent sedimentation into the marsh have included furrow alignment, native vegetation planting, water diversions, construction of water and sediment control basins, and stream channel stabilization. As a result, significant improvements have been made in reducing soil erosion throughout the watershed (USDA-NRCS 2002).

Methods

In this study, regression analysis was used to explore the relationships between present-day sediment fan size with current (2001) and past (1980) land cover and watershed variables derived from remote sensing. Watershed variables were those that represented physical properties of the watershed, such as slope or area. We also analyzed relationships between 2001 riparian forest cover and present and past land cover and watershed variables since riparian forest, mostly arroyo willow, expanded due to increased upland sand deposition (Byrd et al. 2004). In addition, the probability of salt marsh recovery was examined in relation to land cover variables. Dependent variables included present-day sediment fan area, percent riparian forest cover in 2001, and presence or absence of salt marsh recovery on a fan. Independent variables for each sub-watershed were as follows: sub-watershed area, percent agriculture in 1980 and 2001, percent change in agriculture from 1980 to 2001, percent grazing in 1980, percent riparian forest cover in 1980 and 2001, percent change in riparian forest cover from 1980 to 2001, average percent slope of farmland in 1980 and 2001, average percent slope of the riparian flowpath in 1980 and 2001, riparian flowpath length in 1980 and 2001, average percent slope of longest flowpath, and length of longest flowpath (Table 1).

Study Sites

Twenty-three sub-watersheds that drain into Elkhorn Slough were included in this study (Figure 1). All sub-watersheds with sediment fans, a total of 21, were selected plus two additional sub-watersheds that served as references where there was no farming over the 20-year study period (though there was grazing) and sediment fans had never formed. Some of the fans were present in the 1980 image but had experienced salt marsh recovery by 2001, while others were only present in the 2001 image. Of the 21 sediment fans, 20 had formed in salt marsh and one had formed in a freshwater pond.

GIS and Remote Sensing Analysis

The Elkhorn Slough National Estuarine Research Reserve (ESNERR) maintains a large archive of historical aerial photographs of the Elkhorn Slough watershed that proved to be very useful for this research. We relied primarily on April 1980 color infrared (CIR) aerial photos (California Coastal Commission 1980) and a June 2001 color infrared digital orthoquad (DOQ) (Monterey County Information Technology 2001). The 2001 DOQ had a resolution of 0.6 meter per pixel and was projected in UTM Zone 10 WGS 1984. Because the 2001 DOQ coverage did not extend to the far eastern edge of the watershed, a 1999 DOQ with the same resolution was used for this area (Monterey County Information Technology 1999). A visual comparison of forest and agricultural land cover between the 1999 DOQ and a non-georeferenced June 2001 true color photo (California Department of Water Resources 2001) indicated that essentially no change had occurred in these classes within the eastern portion of the watershed.

The 1:12,000 scale 1980 aerial photos were scanned and digitized at 600 dpi to produce a matching resolution of 0.6 meter per pixel. The 1980 images were orthorectified to the 2001 DOQ (and also to the 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 images was approximately 2.5 meters, based on validation by check (test) points.

Sub-watershed delineation

Sub-watersheds were first automatically delineated in ArcView GIS 3.3 (Environmental Systems Research Institute 1992–2002) using the Hydrologic Modeling and Spatial Analyst extensions. We field-verified and manually corrected the sub-watershed boundaries because activities that modified natural water flow patterns, including construction of roads, installation of culverts, and redirection of water on agricultural fields, created boundary changes not evident using a DEM alone. Conversations with local resource managers and farmers helped to verify and revise boundaries, which were recorded using a Trimble© GeoXT global positioning system (GPS) post-processed to produce sub-meter accuracy.

Sediment fan delineation

Delineation of present-day sediment fans required two steps: the first to determine the upland edge of the fan and the second to delineate the furthest extent of the fan into the wetland. The upland extent of the fan was generated by on-screen digitizing the upland/wetland transition zone delineated by interpretation of the 1980 images. The second step was conducted in the field by visually inspecting the texture of 15-centimeter-deep soil pits along upland-wetland transects extending from the fans. Because the fans were composed primarily of sand in contrast to the silty-clay of natural salt marsh soils, the presence of a layer of sand in the sample indicated upland deposition. Along the transect, the soil sample furthest from the upland with a sand layer present was recorded with the sub-meter accuracy GPS. Four to five regularly spaced transects were tested for each fan, and from the recorded endpoints, the wetland extent of the sediment fan boundary was on-screen digitized in ArcGIS 9.0 (Environmental Systems Research Institute 1999–2004).

Salt marsh recovery on fans (presence or absence)

Between 1980 and 2001, other vegetation such as arroyo willow had established on sediment fans where salt marsh plants previously dominated. In some cases, salt marsh vegetation including pickleweed, salt grass (*Distichlis spicata* L.), and jaumea [*Jaumea carnosa* (Less.) A. Gray] had completely recolonized a sediment fan. Fans where complete salt marsh recovery occurred and other species did not colonize were coded "1" for recovery. Other fans were coded "0."

Hydrologically important forest cover

We were interested in creating a layer of riparian forest cover within the drainages coming off farmland and running into the sediment fans. A watershed-scale forest coverage was determined by hierarchical supervised classification of the 1980 and 2001 images and then field data were collected with a sub-meter accuracy GPS to train data classifiers (algorithms) to ground-truth the resulting map (Byrd et al. 2004). Two classes were generated: forest and non-forest.

It was not possible to distinguish riparian forest cover from other types of forest cover; therefore, we developed a method using topographic data to model the likely distribution of riparian forest. This was accomplished with the program FLOW 95 (Schäuble 1999), which predicts areas of high sediment accumulation. FLOW 95 uses a multiple flow algorithm to calculate cumulative flow accumulation in watersheds from a DEM, and is based on the logic of Desmet and Govers's algorithm (Desmet and Govers 1996), which calculates overland flow. In contrast to the usual flow accumulation model, which is useful for delineating linear flow paths and stream channels, this model estimates flow accumulation over an areal extent, which is more suitable for estimating sediment flow and deposition. The FLOW 95 algorithm produced a flow accumulation grid with higher cell values corresponding to higher levels of sediment accumulation. Overlying the forest cover map with the flow accumulation grid, forest cover meeting a flow accumulation value of 65 or higher was selected and labeled as riparian forest in ERDAS IMAGINE 8.7 Spatial Modeler. This value was chosen based on experimentation to find the intersection between flow accumulation values and the presence of riparian forest cover (mostly arroyo willow), which were identified through photointerpretation and ground-truthing.

For both the 1980 and 2001 forest classifications, we generated at least 150 stratified random reference data points for use in an accuracy assessment in ERDAS 8.7 (approximately 50 points per class: upland forest, riparian forest, and non-forest). For the 1980 image, overall classification accuracy was 88% and the overall Kappa statistic was 0.81 (Lillesand and Kiefer 2000). The 1980 riparian forest class Producer's Accuracy (probability that a reference area on the ground is classified accurately on map) was 95% and the User's Accuracy (probability that classification of a pixel on map accurately represents that category on the ground) was 87%. For the 2001 image, overall classification accuracy was 90% and the overall Kappa statistic was 0.84. Producer's Accuracy of the riparian forest class was 98% and User's Accuracy was 82%.

Agricultural land

Agricultural land in the 1980 and 2001 images was mapped through on-screen digitizing guided by a Soil-Adjusted Vegetation Index (SAVI) layer classified into bare ground and vegetation. Classification accuracy of the 1980 farmland was 96% and accuracy of the 2001 farmland was 98%.

Grazing

Grazing was common in 1980 but had mostly diminished by 2001. By then, only moderate grazing was present in one reference sub-watershed within which sediment fans did not form. As a result, a map of grazing areas was only produced for 1980. Grazing areas in 1980 were determined by interviewing land owners and resources managers, researching historical records, and interpreting aerial photos. Grazing land was digitized on-screen. Classification accuracy was 98%.

Flowpath

A flowpath is the drainage course by which water flows through a watershed, and is represented on a map as a linear feature. The longest flowpath for each sub-watershed was calculated from a 10-meter DEM and a flow direction grid, which defines the direction of water flow from one grid cell to the next, using Arc Hydro Tools 1.1 Beta 8 (Maidment 2002) in ArcGIS 9.0. The riparian flowpaths for 1980 and 2001 were calculated by selecting the flowpath segment in each sub-watershed that extended from below farmland to the upland boundary of the sediment fan. As agricultural coverage changed over 20 years, the riparian flowpath changed accordingly.

Slope

Slope was generated in the Spatial Analyst extension using the 10-meter DEM. The average percent slope of agricultural land per sub-watershed was calculated using the 1980 and 2001 agriculture land coverage with the zonal statistics feature in Spatial Analyst. The average slope of each sub-watershed's longest flowpath and riparian flowpath was similarly calculated using the 1980 and 2001 data.

Statistical Analysis

Data were analyzed using Pearson correlation coefficients, multiple linear regression models, and logistic regression in Intercooled Stata 8.2 (StatacorpLP 1985–2004) and SAS 9.0 (SAS Institute 2002). Multiple linear regression models were chosen through R^2 selection in SAS, which finds a specified number of models with the highest R^2 in a range of model sizes. This method is an alternative to step-wise regression. Variables with significance levels less than 0.05 were retained in the model. Partial correlations were also calculated for each significant variable. Logistic model accuracy was assessed by assigning presence cases to fitted probabilities of 0.6 or greater. Dependent variables were present-day sediment fan size, 2001 percent riparian forest cover, and presence or absence of fans where salt marsh recovery occurred. We ran diagnostic checks of model residuals to test for multiple regression assumptions of normality and constant variance. Residuals were checked for normality with the Shapiro-Wilk test and for variance heterogeneity by examining plots of residuals vs. fitted values. The dependent variables, sediment fan size and 2001 percent riparian forest cover, were square-root transformed in order to generate a normal distribution of residuals and meet the assumptions of multiple regression.

Several pairs of variables exhibited high collinearity (tolerance value less than 0.10) and were not included together in models (Quinn and Keough 2002). These variables included: 1980 and 2001 percent agriculture,

Table 2 Correlation coefficients for dependent variables sediment fan area and 2001 %riparian forest

Variable	fanarea (all)	fanarea (>10ha)	2001%riparian (all)	2001%riparian (>10ha)
Sub-watershed area (ha)	**0.64**	**0.51**	–0.30	–0.45
2001 %ag	**0.50**	**0.57**	0.16	–0.18
1980 %ag	**0.54**	**0.59**	0.20	–0.056
agdiffpc	0.18	0.08	0.11	–0.13
1980 %grazing	***–0.37***	–0.40	**–0.46**	0.16
1980 %riparian	–0.31	**–0.58**	**0.96**	**0.90**
2001 %riparian	–0.25	–0.43	1	1
treediffpc	–0.15	0.32	**–0.46**	–0.23
2001 agslp	–0.22	–0.14	–0.25	***–0.48***
1980 agslp	0.058	–0.11	–0.05	***–0.48***
2001 Rpathslp	**–0.52**	**–0.55**	0.27	0.0072
1980 Rpathslp	**–0.43**	***–0.47***	0.33	0.24
Pathslp	**–0.64**	**–0.67**	0.077	–0.043
2001 Rpathl	0.28	0.068	–0.25	–0.23
1980 Rpathl	0.14	–0.073	–0.24	–0.15
pathl	**0.68**	***0.52***	***–0.35***	**–0.67**

Correlations were calculated for all sub-watersheds ($n = 23$) and for sub-watersheds > 10 ha ($n = 14$). Variable codes are provided in Table 1. Bold = $p < 0.05$, Bold italics = $p < 0.10$

1980 and 2001 percent riparian forest, 1980 and 2001 percent farmland slope, and 1980 and 2001 percent riparian flowpath slope. In order to assess the effect of each of these variables, several regression models were generated that included all possible combinations of collinear variables. Final models were then compared to find the one with the greatest explanatory power. Percent grazing in 1980 was also removed from the multiple regression analysis since it was considered the inverse of 1980 percent agriculture.

Two datasets were analyzed: one containing all 23 sub-watersheds and another containing sub-watersheds greater than 10 hectares ($n = 14$). This size threshold was chosen because of a natural break in the data observed in a histogram of sub-watershed sizes.

Results

In Elkhorn Slough, our study sub-watersheds ranged in area from 1.4 ha to 200 ha, with an average of 33.7 ha. Sediment fans ranged from 0.01 ha to 1.8 ha, with an average of 0.5 ha (Table 1). The area of sediment fans had a strong positive correlation with sub-watershed area, flowpath length, and percent agriculture in 1980 and 2001 in pairwise comparisons made with the entire dataset (Table 2). Fan area was negatively correlated with percent grazing in 1980, flowpath slope, and 1980 and 2001 riparian flowpath slopes, which extended from below farmland to the fan. In correlations of sub-watersheds greater than 10 hectares, sediment fan area was again positively related to sub-watershed area, flowpath length, and percent agriculture in 1980 and 2001. Correlations were greater for percent agriculture and were smaller for sub-watershed area and flowpath length. Fans in large sub-watersheds were negatively correlated with 1980 and 2001 riparian flowpath slope and sub-watershed flowpath slope. Fan size was also negatively correlated with percent riparian forest in 1980.

Percent cover of riparian forest in 2001 was not correlated with as many variables. Forest cover in 2001, using all data, was negatively correlated with percent change in forest cover, 1980 percent grazing and flowpath length. Among sub-watersheds greater than 10 hectares, forest cover was negatively correlated with 1980 and 2001 average farmland slope and flowpath length. In pairwise correlations of independent variables, sub-watershed area and flowpath length were found to be significantly correlated with the most variables (Table 3).

After examining data from all 23 sub-watersheds through several permutations of regression models that accounted for all combinations of collinear variables, a final model was produced that best explained sediment fan size. The final model included both past and present land cover and watershed variables. Regression results indicated that sediment fan size increases with greater percent agriculture in 2001, longer flowpath length, less steep riparian flowpath slopes in 2001, and shorter riparian flowpath lengths in 1980 (adjusted $R^2 = 0.75$). The 2001 riparian flowpath slope was most strongly associated with fan size, based on partial correlations ($r = -0.64$) (Table 4) (Figure 2).

Historical variables became more important in the final regression equation of large sub-watersheds. In this case, sediment fan size increased with less riparian forest in 1980, less steep agricultural slopes in 1980, less steep sub-watershed flowpath slopes, and shorter riparian flowpath lengths in 1980. The explanatory power of this model greatly increased, with adjusted R^2 = 0.94. Partial correlations between independent variables and fan size also increased; variables most correlated with fan size were 1980 %riparian forest cover (r = –0.94) and longest flowpath slope (r = –0.94) (Table 4) (Figure 2).

The explanatory power of regression models that explained percent riparian forest cover in 2001 also increased when analyzing data from just large sub-watersheds (from adjusted R^2 = 0.24 to R^2 = 0.74). Historical variables were again significant explanatory variables and partial correlations increased. Riparian forest cover increased with less steep riparian flowpath slopes in 1980, less steep agricultural slopes in 1980, and shorter flowpath lengths (Table 5) (Figure 3).

Four land cover variables, 1980 percent grazing, 1980 percent agriculture, 2001 percent agriculture, and sediment fan size were all related to salt marsh recovery after disturbance from sedimentation. Based on simple logistic regression model results and fitted probabilities, the smaller the fan size, the greater the chance of recovery (Table 6, Figure 4a,b). As percent agriculture in the watershed increases, the probability that salt marsh vegetation will recolonize on a sediment fan decreases. In contrast, as percent grazing increases, the probability that salt marsh vegetation will come back on a fan increases. Figure 4a illustrates differences in disturbance intensities associated with grazing as compared to more intensive row-crop farming. Sediment fan area most accurately predicted recovery (75%) while the other land cover variables had identical prediction rates (62.5%)

Table 3 Correlation coefficients for independent variables for all sub-watersheds (n = 23)

Variable	Catarea	2001 %ag	1980 %ag	agdiff pc	2001 %riparian	1980 %riparian	tree diffpc	1980 %graze	2001 agslp	1980 agslp	2001 Rpathslp	1980 Rpathslp	pathslp	2001 Rpathl	1980 Rpathl
2001 %ag	0.30	1.00													
1980 %ag	0.33	**0.93**	1.00												
agdiffpc	0.17	**0.69**	**0.46**	1.00											
2001 % riparian	–0.30	0.16	0.20	–0.11	1.00										
1980 %riparian	–0.30	0.09	0.11	–0.18	**0.96**	1.00									
treediffpc	–0.04	–0.33	**–0.37**	–0.36	**–0.46**	**–0.49**	1.00								
1980 %graze	–0.32	**–0.69**	**–0.78**	–0.24	**–0.46**	***–0.37***	**0.39**	1.00							
2001 agslp	0.18	0.16	0.14	0.32	–0.13	–0.23	0.08	***–0.38***	1.00						
1980 agslp	0.18	0.13	0.14	0.19	–0.05	–0.15	0.06	**–0.45**	**0.98**	1.00					
2001 Rpathslp	**–0.59**	0.04	–0.06	0.11	0.27	0.34	–0.27	0.10	0.07	0.05	1.00				
1980 Rpathslp	**–0.66**	0.01	–0.02	0.00	0.33	***0.35***	–0.25	0.12	–0.07	–0.08	**0.94**	1.00			
pathslp	**–0.48**	**–0.56**	**–0.59**	–0.28	0.08	0.11	0.06	***0.40***	0.25	0.26	**0.64**	**0.58**	1.00		
2001 Rpathl	**0.65**	–0.07	0.10	–0.22	–0.25	–0.20	–0.21	–0.02	–0.04	–0.04	***–0.35***	–0.34	–0.18	1.00	
1980 Rpathl	**0.60**	0.03	0.02	0.09	–0.24	–0.16	–0.16	0.16	–0.15	–0.21	–0.19	–0.24	–0.09	**0.73**	1.00
pathl	**0.86**	**0.44**	**0.47**	0.27	***–0.35***	–0.34	–0.12	**–0.44**	0.31	0.31	**–0.45**	**–0.55**	**–0.50**	**0.58**	**0.53**

Variable codes are provided in Table 1. Bold = $p < 0.05$, Bold italics = $p < 0.10$

Discussion

This study identified connections between watershed land cover, wetland disturbance, and vegetation response that spanned over a 20-year time period. Relationships between past and present watershed characteristics and the extent of wetland disturbance were found through the use of historical and modern remote sensing data combined with GIS and statistical analyses.

Regression results indicated that the size of sediment fans in salt marsh could be explained by a combination of land cover and watershed variables. With analysis of just large sub-watersheds within the Elkhorn Slough watershed, explanatory power of the models increased and historical variables, such as 1980 riparian forest cover, average farmland slope, and

Table 4 R^2 of final multiple regression analysis of sediment fan area including coefficients and partial correlations for each variable

fanarea√	R^2	Adjusted R^2	Intercept	2001 %ag	2001 Rpathslp	pathl	1980 Rpathl
All sub-watersheds (*n* = 23)	0.80	0.75	0.81	0.0049	–0.033	0.00035	0.00065
Partial correlation				0.54	–0.64	0.58	–0.45

fanarea√	R^2	Adjusted R^2	Intercept	1980 %riparian	1980 agslp	pathslp	1980 Rpathl
Sub-watersheds > 10 ha (*n* = 14)	0.96	0.94	2.07	–0.055	–0.021	–0.050	–0.00047
Partial correlation				–0.94	–0.73	0.94	0.68

Sediment fan area was square root transformed. Regressions were performed on the entire dataset and on a subset of sub-watersheds with area greater than 10 hectares using 1980 and 2001 watershed and land cover variables. All variables have a *p* value < 0.05. Variable codefinitions are provided in Table 1

Table 5 R^2 of final multiple regression models of 2001 %riparian forest cover including coefficients and partial correlations for each variable

2001 %riparian	R^2	Adjusted R^2	Intercept	1980 %ag	Rpathl
All sub-watersheds (*n* = 23)	0.31	0.24	3.58	0.26	–0.0013
Partial correlation				0.50	–0.50

2001 %riparian	R^2	Adjusted R^2	Intercept	1980 Rpathl	1980 agslp	pathl
Sub-watersheds > 10 ha (*n* = 14)	0.80	0.74	7.29	–0.11	–0.067	–0.0018
Partial correlation				–0.71	–0.72	–0.86

2001 %riparian forest cover was square root transformed. Regressions were performed on the entire dataset and on a subset of sub-watersheds with area greater than 10 hectares using 1980 and 2001 watershed and land cover variables. All variables have a *p* value < 0.05. Variable code definitions are provided in Table 1

Table 6 Logistic regression results estimating likelihood of salt marsh recovery on sediment fans

Variable	Coefficient (*p* value)	Chi-Square (*p* value)	Prediction accuracy
fanarea	–6.80 (0.042)	10.98 (0.0009)	75%
1980 %ag	–0.082 (0.016)	11.85 (0.0006)	62.5%
2001 %ag	–0.10 (0.016)	13.24 (0.0003)	62.5%
1980 %graze	0.055 (0.04)	10.3 (0.0013)	62.5%

Probability values of coefficients are provided in parentheses. Variable code definitions are provided in Table 1. *n* = 21. Reference sub-watersheds without fans were not included in the analysis

riparian flowpath length, became more significant estimators of sediment fan size. The extent of percent riparian forest cover in 2001 could also be explained in part by historical watershed variables including 1980 riparian flowpath slope and average farmland slope.

Strong relationships between wetland conditions and watershed land cover may exist in large watersheds, while in smaller watersheds, the spatial arrangement of landscape patches or land use management may be more critical than the dominant land cover in explaining downstream impacts (Strayer et al. 2003). This pattern was also observed in a study that investigated the influence of watershed land use on embeddedness, the burial of stream gravel with fine sediment, in salmonid spawning streams in the Russian River basin in California (Opperman et al. 2005). Their study considered that sediment flux may be highly variable in smaller watersheds, but less variable in large watersheds because they integrate random pulses of sediment occurring over their smaller sub-catchments (Benda and Dunne 1997). Because of this integration, in large watersheds the overall effect of land use on embeddedness would be stronger, as soil erosion rates would vary according to land cover (Opperman et al. 2005).

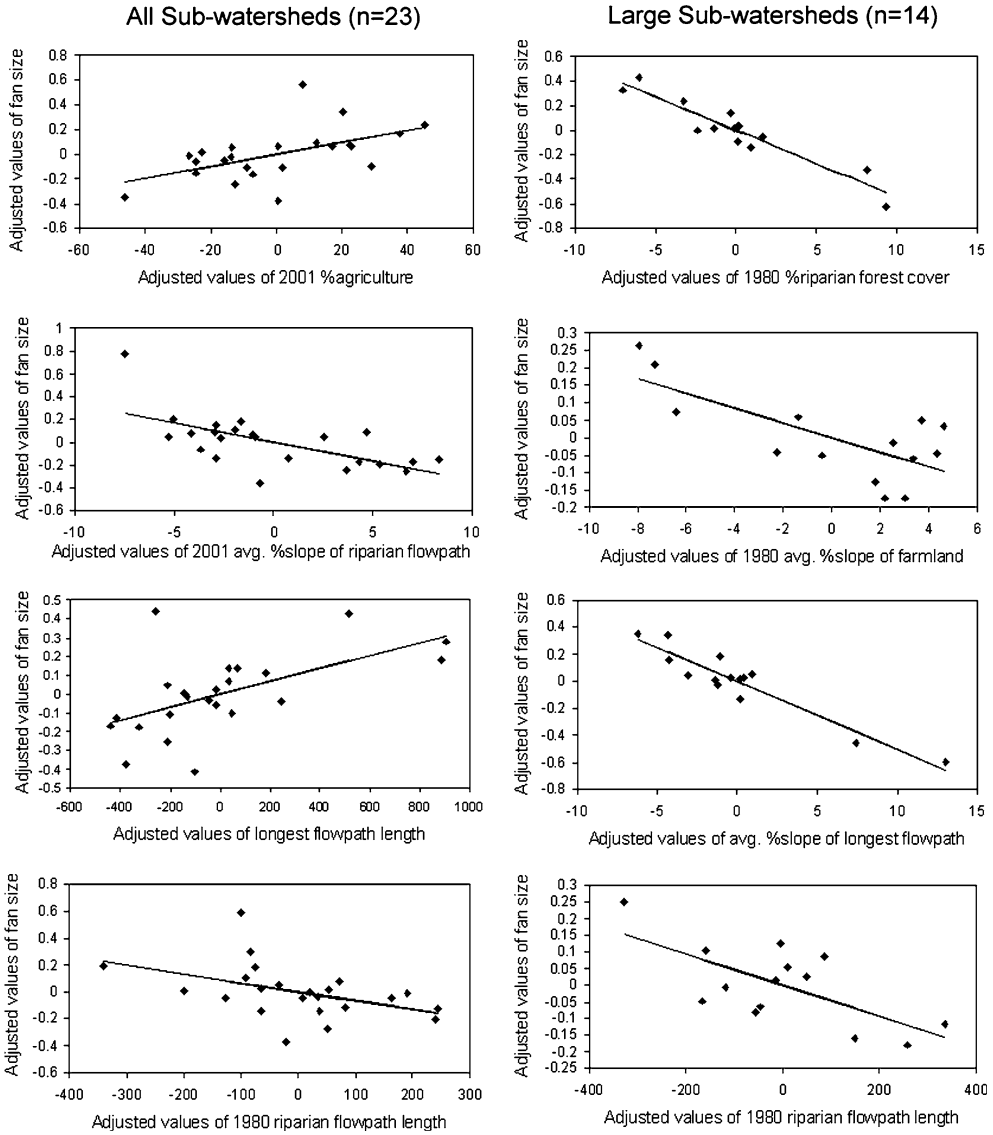

Fig. 2 Partial regression plots of significant independent variables against sediment fan size (square root transformed). Residual values are represented by diamonds and fitted values are represented by lines

Explanation of Sediment Fan Size

Historical watershed variables help explain present-day sediment fan size in the Elkhorn Slough salt marsh. In Elkhorn Slough, farmland practices, especially those common in the 1980s, and crop choice, usually strawberries, produced high soil erosion rates (USDA-SCS 1984). Along with these land use practices were weather conditions that increased the probability of erosion and sedimentation during this time period. Between 1980 and 2001, there were two major El Niño events that produced large winter storms (1982/83 and 1997/98). Transport of soil into the marsh is driven by the timing of these storms (Benda and Dunne 1997). For example, one of the largest fans present in the slough formed during the single El Niño winter of 1997/98 though farming had been occurring up slope for decades. These stochastic, intense disturbance events lead to a time lag between land cover change and impacts to wetlands.

In the analysis of large sub-watersheds, 1980 percent riparian forest cover became the most significant land cover variable with larger fans found in sub-watersheds with less historical riparian forest cover. Riparian vegetation buffers have been found to greatly reduce sediment into waterways and the desired width of the buffer remains a critical issue for land management and policies (Lee et al. 2003; McKergow et al. 2003; Broadmeadow and Nisbet 2004). Therefore, this result suggests that riparian vegetation located below farmland may have reduced sediment loading into the marsh, resulting in smaller fans. However, the riparian vegetation was dominated by arroyo willows, which are widely spaced with little understory present between

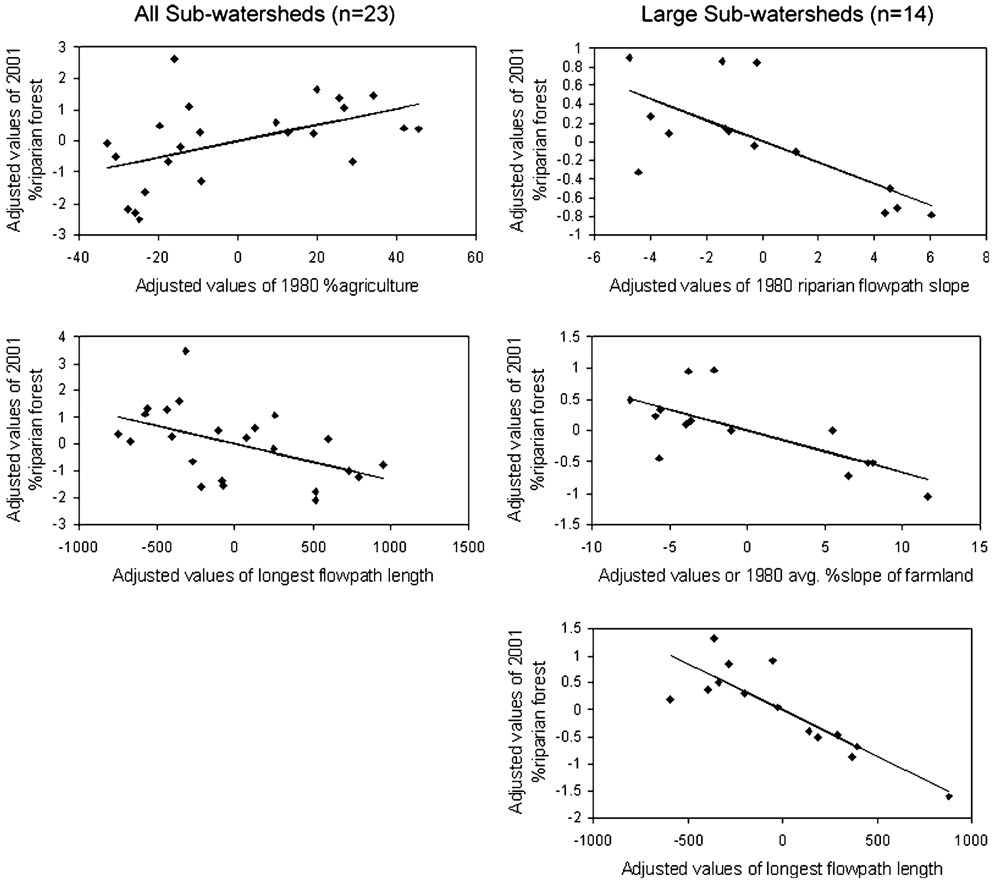

Fig. 3 Partial regression plots of significant independent variables against 2001 %riparian forest cover (square root transformed). Residual values are represented by diamonds and fitted values are represented by lines

trees. The streams that carry sediment to the slough are typically very narrow, about 1 to 3 meters wide, and spaces between mature willow are approximately 2 to 3 meters wide and would have little effect on flow and consequently little sediment trapping capability (Largay 2005).

More likely, the negative relationship between past levels of riparian forest cover and present day fan size is because sub-watersheds with sparse riparian cover in 1980 experienced a disproportionate increase in fan size over the past 20 years. This relationship reflects the contrasting conditions found in the watershed versus the marsh over time. In 1980, riparian forest cover was sparse on watershed hillsides but over 20 years the larger a fan became the more its size contrasted with pre-existing riparian vegetation.

Subsequently, once sediment is deposited, several years pass as vegetation succession progresses and arroyo willow dominates the sediment fans. Between 1980 and 2001 in Elkhorn Slough, riparian forest, mainly arroyo willow, increased dramatically on sediment fans and within the drainages carrying sediment from farmland, replacing grassland and salt marsh plant communities. While many sediment fans formed during the 1980s, arroyo willow expansion on fans occurred most during the 1990s (Byrd et al. 2004). As a result, a time-delay developed between marsh disturbance (sedimentation) and ecological response (willow expansion).

Sediment fan size was also greatly influenced by physical features that were reflective of the erosion and sediment transport potential of each sub-watershed. Drainage networks in larger sub-watersheds have existed for thousands of years (Schwartz et al. 1986), and through erosive processes they have formed valleys with lower flowpath slopes (Bloom 1998). As a result, there is a significant negative relationship between sub-watershed area and flowpath slope (Table 3). When the uplands were converted to intensive agriculture, the amount and velocity of stream flow increased due to increased surface runoff, destabilizing the natural drainage. As large drainages began downcutting, they had the erosive power to generate much larger sediment yields than smaller drainages because of high runoff volume. In contrast, the steepest flowpaths receive less stormwater because stormwater is diverted through culverts under roads (Largay 2005). In summary, we suspect that the identified relationship between lower slopes and fan size is related to sub-

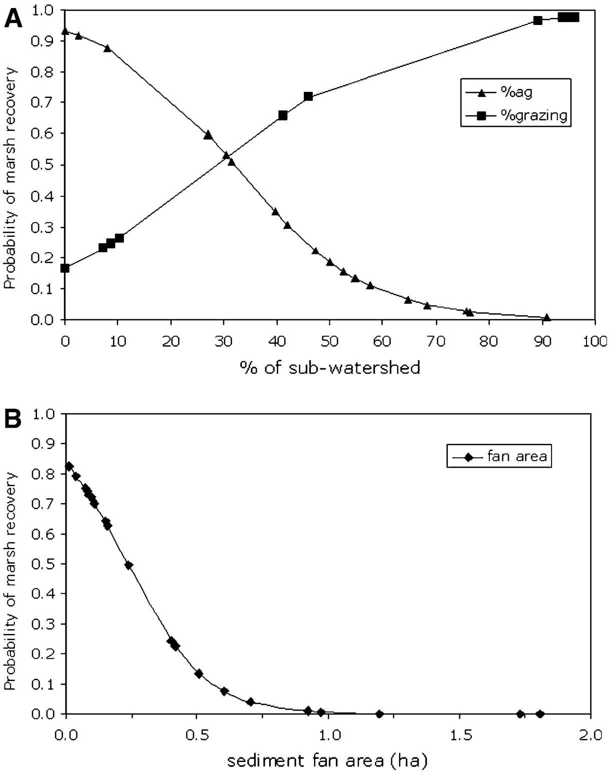

Fig. 4 Probability of salt marsh recovery from sedimentation according to 1980 land use and sediment fan size, based on fitted logistic regression models. **a:** Probability of salt marsh recovery increases with greater percent grazing and less percent agriculture (row crops) in a sub-watershed; **b:** Probability of salt marsh recovery decreases as sediment fan size increases

watershed area and characteristics of the drainage network that influence sediment transport.

Another important point is that the steeper the flowpath slope, the less farmland in the sub-watershed (Table 3). In fact, the two reference areas with no sediment fans had the steepest slopes (21% and 23%) but were never farmed. Steep hill slope could have impeded extensive agricultural development, a major contributing factor to erosion. This negative relationship between slope and downstream impacts was also observed in North Carolina, where better water quality was correlated with greater topographic complexity and a slope/relief ratio (elevation change/flowpath length) (Potter et al. 2004). Here it was determined that watersheds with flatter terrain may have been more disturbed by human activities including hydrologic modifications associated with farming, leading to degraded downstream water quality.

Historical riparian flowpath was also related to sediment fan size, with short flowpaths leading to larger fans as we would expect. Some flowpaths in the Elkhorn Slough watershed have increased over the past 20 years as land was removed from cultivation. Over all, study sub-watersheds agricultural land was reduced by 60 hectares (15%) between 1980 and 2001. At the same time, riparian flowpath length increased 70 meters on average from 1980 to 2001, generally from the mid 1990s onward when most restoration activities began. We would expect that if riparian flowpaths continue to lengthen then the amount of sediment transported to the marsh will be reduced.

Sub-watershed area had a strong positive correlation with sediment fan size (Table 2) but was not included in the regression analysis because of collinearity with other variables. Flowpath length and slope are related to sub-watershed area (Table 3) and were significant variables in our estimates of fan size. Overall, the relationships between other watershed variables and areas indicate that sub-watershed area is an overriding feature influencing the extent of sedimentation in a salt marsh. Our results also reveal that agricultural land use is the most influential land cover variable across the Elkhorn Slough watershed.

Explanation of Present-Day Riparian Forest Cover

Intensive farming can lead to high sedimentation rates and over time riparian vegetation (arroyo willow) becomes established in areas with high sediment accumulation. In fact the timing of most willow expansion coincided with major restoration and erosion control efforts that began in the mid 1990s (USDA-NRCS 2002; Byrd et al. 2004). In contrast, there was less of a relationship between 1980 riparian forest and 1980 percent agriculture and flowpath length ($R^2 = 0.20$, $p = 0.10$), further illustrating a time lag between watershed land use change and ecosystem response.

Low gradient slopes can also provide more suitable conditions for willow colonization as they provide a greater area that is within rooting depth of a shallow water table. The colonization of a wide extent of woody riparian vegetation around a gravel pit on the Russian River in Northern California was attributed to gently sloping bank topography as water table elevation was found to control vegetation establishment (Kondolf et al. 1997).

Recovery of Salt Marsh Vegetation

Salt marsh recovery was explained in part by percent agricultural and grazing land and fan area. Considerable management efforts have been made to reduce soil erosion in the Elkhorn Slough watershed since 1980. The Elkhorn Slough Foundation, a non-profit land trust founded in 1982, owns or manages 3600 acres in the watershed where they have implemented several erosion control practices, including construction of sediment basins, native grass, and willow plantings, soil stabilization, and reduction of annual crops (www.elkhornslough.org). The Natural Resources Conservation Service and the Resource Conservation District of Monterey County, through the Elkhorn Slough Watershed Project, have worked with farmers to implement conservation practices on 3260 acres and prevent approximately 79,463 tons of soil loss between 1994 and 2001 (USDA-NRCS 2002).

These improvements in upland land management should have a beneficial effect on the Elkhorn Slough marshes. Salt marshes are able to recover if disturbance from sediment occurs on a smaller scale, which has been demonstrated in other California salt marshes as well (Allison 1995). The intensity of disturbance and the probability of recovery depend partly on the type of land use in the watershed, since different land uses produce varying levels of erosion. Agriculture has a higher impact on salt marsh, given poor rates of recovery below farmland (Figure 4a). Livestock grazing can lead to soil erosion and sedimentation in the marsh, but its impact on the marsh is less compared to intensive agriculture, as fans formed below grazed areas have shown a greater chance of recovery.

In general, knowledge of the relationships between watershed land use, wetland disturbance, and vegetation response in the Elkhorn Slough watershed will help managers consider cumulative effects of watershed inputs when developing wetland management and restoration strategies. With the marsh receiving less inputs from upland sources through restoration and conservation efforts, there should be continued monitoring of sediment fans to determine if fan formation slows and natural recovery continues to occur even during large storm events.

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