Physical and Functional Responses to Experimental Marsh Surface Elevation Manipulation in Coos Bay's South Slough

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Abstract

Dike material was used as fill to construct high, mid, and low intertidal elevations in a subsided marsh located in the South Slough National Estuarine Research Reserve, Oregon. Marsh surface elevation change (including fill consolidation and compression of the original marsh soils), vertical accretion, tidal channel development, emergent vegetation colonization, and fish use were monitored over 3 years. Significant marsh surface elevation loss was detected at all elevations, with fill consolidation accounting for 70% of the loss at the highest elevation. Vertical accretion averaged 0.19 cm/yr in the sparsely vegetated Kunz Marsh compared with 0.70 cm/yr at the densely vegetated reference sites. Tidal channel development was influenced as much by marsh surface gradient as by marsh surface elevation. Vegetation colonization was directly correlated with elevation, whereas density and species richness of fish was inversely correlated with elevation. Manipulating the marsh surface to mid-marsh elevations favors rapid vegetation colonization and facilitates vertical accretion-dominated tidal channel development. Low marsh elevations result in initially slower developing vegetation colonization and channel development but are more beneficial to fish during the early stages of marsh recovery. High marsh elevations appear to sacrifice tidal channel development and associated fish access for rapid vegetation colonization.

Key words: coastal wetland restoration, diked wetlands, marsh elevation, marsh vegetation, subsidence, tidal channels.

Introduction

Accelerating the recovery of habitat diversity and complexity associated with mature estuarine wetlands has taken on a new urgency in the Pacific Northwest, driven in part by an expanded understanding of estuarine habitats and their critical role in the life histories of *Oncorhynchus* spp. (pacific salmon) (Healey 1982; Myers & Horton 1982; B. Miller & S. Sadro 1999, unpublished report). Typically, relatively passive means have been used to restore diked and drained estuarine wetlands. Dikes and/or tide gates have been removed to reintroduce tidal flooding to the formerly tidal wetlands, initiating recovery processes toward mature marsh function. However, marsh surfaces can subside over time, due to oxidation and consolidation of soil peats, physical compaction, and absence of tide-borne sediment deposition (Roman et al. 1984; Frenkel & Morlan 1991; Portnoy & Giblin 1997; Anisfeld et al. 1999; Reed et al. 1999). For elevation-sensitive wetland attributes such as emergent salt marsh vegetation (Earle & Kershaw 1989; Scholten & Rozema 1990; Zedler et al. 1999), restoring subsided wetlands using conventional methods may prolong recovery of marsh function.

Active restoration approaches, such as manipulation of marsh surface elevation using dredge or dike fill material, may speed recovery of estuarine wetland structure and function. Valuable insights into active manipulation of marsh surface elevation using dredge material have been provided by projects in San Francisco Bay implemented over the past 25 years (Williams & Florsheim 1994; Coats 1995; Williams & Faber 2001; Williams & Orr 2002, this issue). But uncertainty remains about potential trade-offs when using active restoration methods. For example, one elevation-driven estuarine wetland attribute may develop at the expense of another (i.e., emergent vegetation in place of tidal channels). There is also uncertainty about the long-term stability of dike or dredge material used as fill.

Here we provide initial results from an experimental restoration project at the South Slough National Estuarine Research Reserve, Oregon, where the marsh surface of a diked and subsided estuarine wetland was manipulated to examine the structural and functional recovery of a marsh at three constructed intertidal elevations. The following hypotheses were tested: (1) Constructed marsh surface elevation change over time will be directly related to depth of fill material placed on the marsh sur-

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face; (2) vertical accretion (buildup of organic and inorganic material on the marsh surface) will be inversely related to constructed marsh surface elevation; (3) size of tidal channels will be inversely related to constructed marsh surface elevation; (4) relative abundance and species richness of emergent vegetation will be directly related to constructed marsh surface elevation; and (5) density and species richness of fish using the marsh will be inversely related to constructed marsh elevation.

Materials and Methods

Project Site Description

Estuarine wetland restoration efforts at South Slough National Estuarine Research Reserve have been focused on the 20-ha Winchester Tidelands Restoration Project area (43°17′N, 124°19′W). The 5-ha Kunz Marsh restoration project (Fig. 1), located in the northernmost portion of the Winchester Tidelands Restoration Project area (Fig. 1), is the focus of this study. Originally a mature high marsh, Kunz Marsh was diked and drained in the early 1900s for agricultural uses. The site's original tidal channels were filled and replaced with a series of simplified linear ditches designed to improve site drainage efficiency. Due to the long-term effects of diking and draining, the surface of Kunz Marsh subsided up to 80 cm relative to the adjacent relatively undisturbed Danger Point Marsh, a mature high marsh (Fig. 2). Salinity in Kunz Marsh ranges from near 0 ppt during winter flood events to 32 ppt during low summer flows.

Kunz Marsh Restoration

Kunz Marsh was divided into four separate cells and dike material used as fill to establish three different intertidal elevations among the four cells. The cells, referenced according to their constructed elevation as Kunz high, Kunz mid, Kunz low 1, and Kunz low 2, were constructed in August 1996 and have an average area of

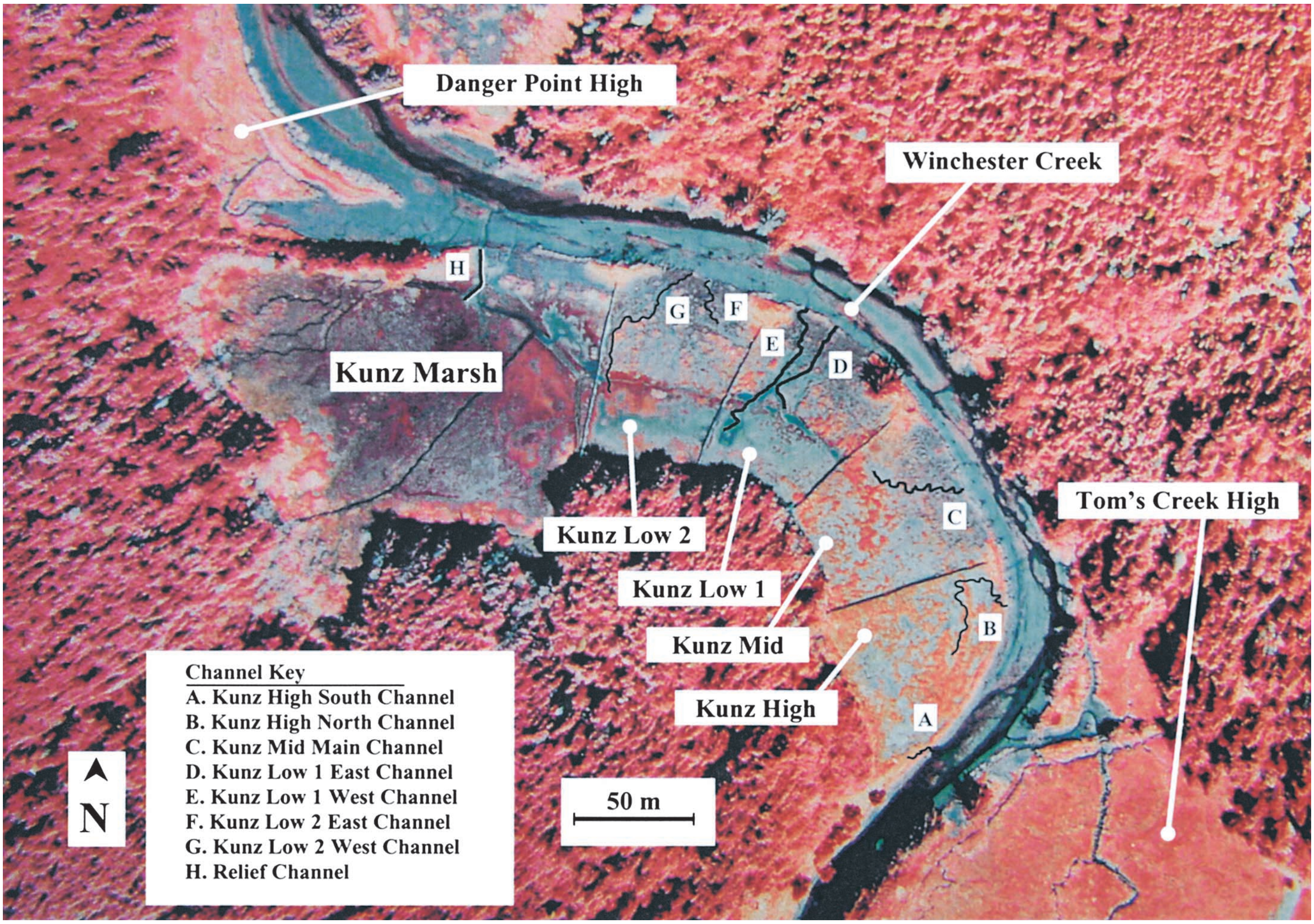

Figure 1. Locations of incipient tidal channels in Kunz Marsh (1999 aerial photo). Marsh cells are separated by geotextile fences keyed into small dike islands.

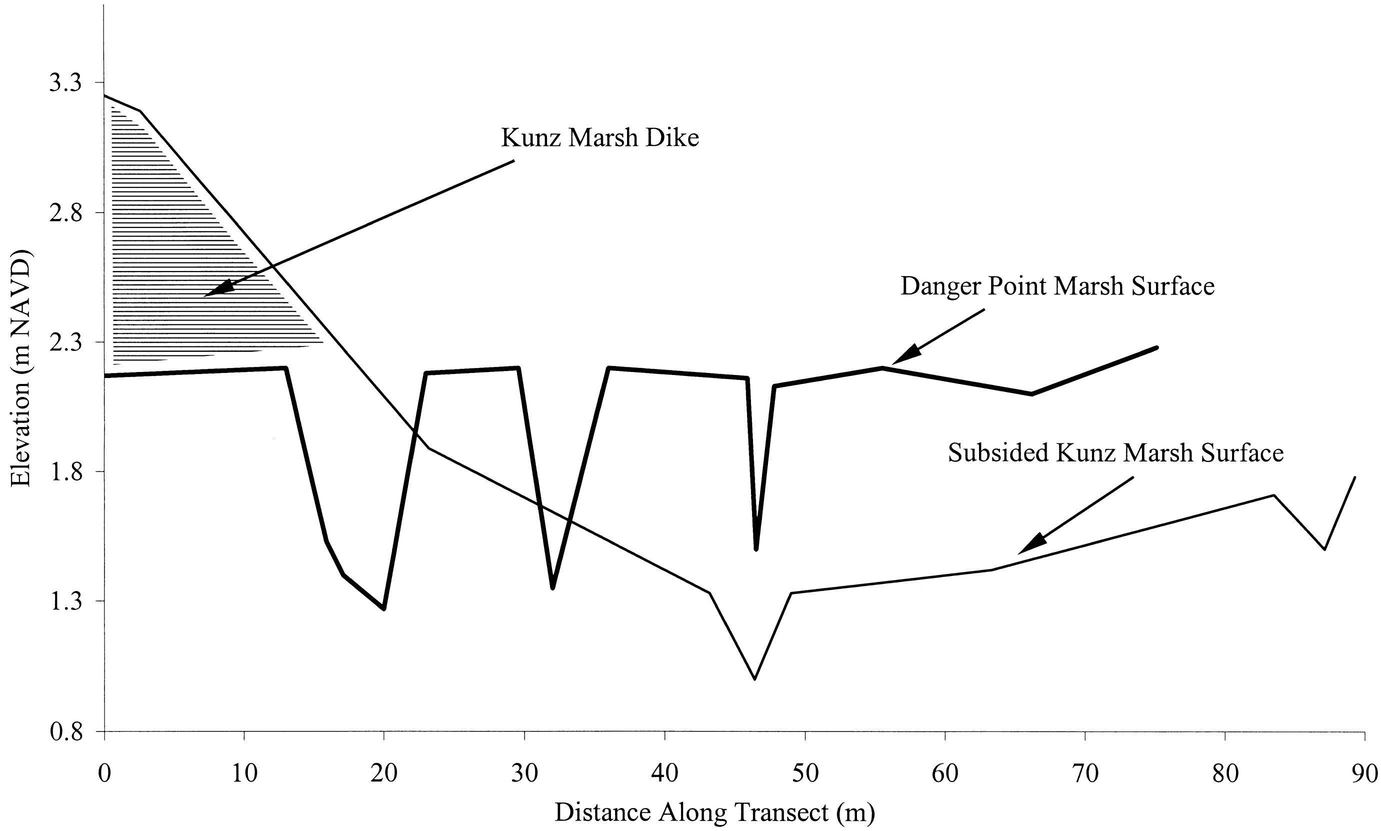

Figure 2. Kunz and Danger Point Marsh topographic profiles before restoration construction.

0.56 ha (Fig. 1, Table 1). Each cell was separated from its neighboring cell by a 1.8-m tall geotextile fence designed to encourage independent hydrological development. Cell elevations were established to represent the local intertidal elevation range supporting emergent marsh vegetation. Kunz high represents a mature marsh elevation roughly equal to the elevation of mean higher high water (MHHW). Kunz low 1 and low 2 represent elevations at the lower limit of emergent marsh vegetation colonization. Kunz mid represents the intertidal midpoint between the two extremes. Based on results from soil compression tests on the prefill Kunz Marsh soils (referred to as subsoil here), we anticipated fill material consolidation and subsoil compaction under the weight of fill material. We compensated for the expected marsh surface elevation loss by grading Kunz high and mid cells 0.15 m higher than their design elevations (Table 1). No elevation compensation was necessary for the low cells. Saturated soils prevented us from adding fill to the rear portions of Kunz low 1 and low 2 (farthest from Winchester Creek). The gradient of Kunz high, mid, and low 1 was constructed at an approximately 200:1 slope (Table 1), the average slope of local reference sites. Kunz low 2 was not graded to any particular slope. Kunz low

Table 1. Summarized statistics for the Kunz Marsh cells.

						Tidal Inundation Period	
Cell	*Area (ha)*	*Design Elevation*[a]	*1996 Constructed Elevation*	*Design Gradient*	*1999 Marsh Surface Gradient*	*Maximum*[b] *(ave. hr/day)*	*Minimum*[c] *(ave. hr/day)*
Kunz high	0.53	2.20 (2.38)	2.35 (2.53)	200:1	322:1	0.84	0.18
Kunz mid	0.56	1.80 (1.98)	1.95 (2.13)	200:1	163:1	3.61	2.25
Kunz low 1	0.54	1.50 (1.68)	1.50 (1.68)[d]	200:1[d]	217:1[d]	7.12	5.91
Kunz low 2	0.59	1.50 (1.68)	1.50 (1.68)[d]	[e]	−526:1[d]	6.23	5.00

[a] Elevations in meters referenced to North American Vertical Datum 1988 (elevations referenced to mean lower low water).
[b] Calculated for January 1999.
[c] Calculated for August 1999.
[d] Front half of cell only.
[e] Cell not graded.

2 was originally intended to be a control site altered only as necessary to fill the ditch running through the middle of the cell. However, the action of filling the ditch (it was necessary to temporarily place fill on the front portion of the cell to provide equipment access to the ditch) sufficiently altered the cell to more closely resemble that of an ungraded replicate of Kunz low 1.

To facilitate emergent macrophyte community development, approximately 15 to 30 cm of topsoil and associated vegetation was removed from the original marsh surface and redistributed in clumps over each cell after grading. The remaining dike was then removed during a single low tide cycle, restoring full tidal circulation to the site. Four small dike islands, each approximately 185 m^2 in area, were left in place as anchoring points for the geotextile fences.

Reference Sites

Two relatively undisturbed high elevation marshes adjacent to Kunz Marsh were used as reference sites (Fig. 1). Danger Point high (0.4 ha) was never diked and was most likely part of the original Kunz fringing marsh. Tom's Creek high (5 ha) had historically been diked but was never fully converted to agricultural use and has been open to tidal circulation for at least 25 years.

Marsh Surface Elevation Change

Marsh surface elevation change in Kunz Marsh is influenced by three soil processes: (1) vertical accretion, defined by Cahoon et al. (1995) as the buildup of organic and inorganic material on the marsh surface; (2) subsoil compression; and (3) fill material consolidation.

Marsh surface elevation change (± 0.001 m) was measured two to four times per year using a sedimentation-erosion table (SET; Haupt Machine and Manufacturing Corp., Baton Rouge, LA, U.S.A.) as described by Boumans and Day (1993) (Fig. 3). A SET station was established at each reference site in 1994 and in each Kunz Marsh cell in 1996. Because SET station pipes were driven 4.5 m into marsh soils without reaching bedrock, SET station pipe elevations were surveyed when first established and again in May 2000 to detect possible elevation change. In 2000 the elevation of the SET station pipes in all Kunz Marsh cells were found to have subsided between 0.2 and 2.4 cm, and SET data were adjusted accordingly. Reference site SET station pipe elevations remained unchanged.

Marsh surface topography and slope were measured yearly along one permanent transect in each Kunz Marsh cell (averaging 84 m in length) using an autolevel (Topcon AT-G3, Tokyo, Japan) and a stadia rod (Crain Enterprises, Mound City, IL, U.S.A.). An average of 140 elevation data points per transect were recorded. All topographic data were referenced to North American Vertical Datum 1988; temporary benchmarks and topographic data points were established with less than 0.005 m error. Tidal inundation periods were calculated for the spring and neap high tides in August and January 1999 using site elevation data, local NOAA tide gauge data, and the Tide Miner program (from http://www.numberstoknowledge.com).

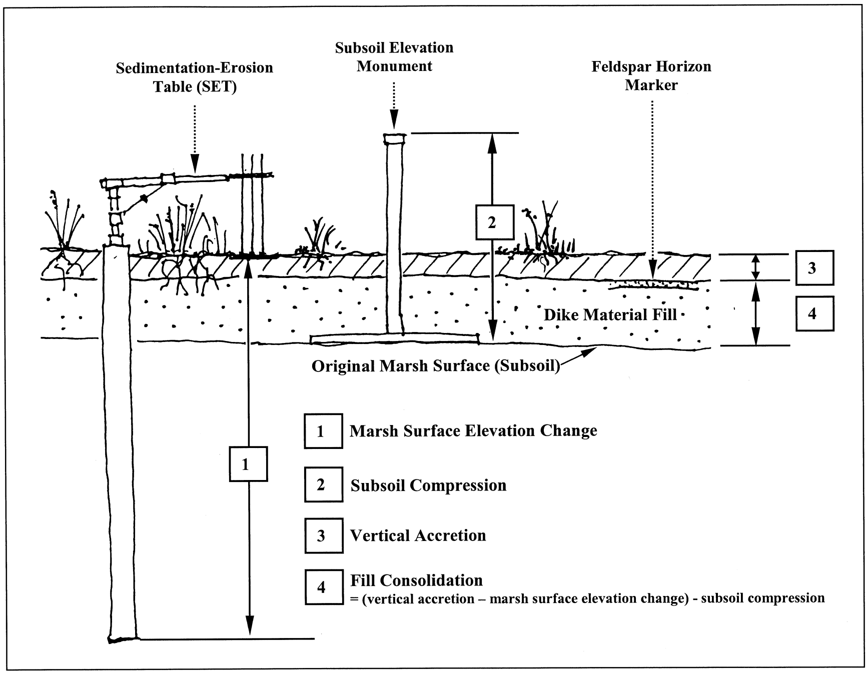

Figure 3. Conceptual diagram (not to scale) showing those portions of the Kunz Marsh post-construction soil profile measured by the sedimentation-erosion table, feldspar horizon markers, and subsoil elevation change monuments. (After Cahoon et al. 1995.)

Vertical Accretion

Vertical accretion was measured using feldspar horizon markers as described by Cahoon and Turner (1989) (Fig. 3). In 1994 six 0.25-m^2 feldspar marker sites were established in Danger Point high and 12 in Tom's Creek high. In 1996 three 1-m^2 feldspar marker sites were established in each Kunz Marsh cell. Vertical accretion was measured one to three times per year until 2000. Compaction was minimized by cutting feldspar cores in half longitudinally and taking replicated measurements from inside the core. Vertical accretion measurements could not be made at two sites where sediments were too unconsolidated for cores to be taken and at one site where the feldspar marker was unrecoverable. No distinction was made between organic and inorganic components of vertical accretion.

Subsoil Compression

Subsoil compression was measured in Kunz high and mid cells using replicate (three times) galvanized steel subsoil elevation monuments placed on the existing marsh soil during construction. Monuments consisted of a 1.2 × 1.2 m base with a 1.8-m steel post welded to the center (Fig. 3) and were covered with fill material during construction, leaving only the top 1 to 1.2 m of the post visible. The post tops were surveyed before dike removal in 1996 and again in 1999.

Fill Consolidation

Fill consolidation was calculated by the following formula: Fill consolidation = (vertical accretion − marsh surface elevation change) − subsoil compression (Fig. 3). The component (vertical accretion − marsh surface elevation change) is described by Cahoon et al. (1995) as shallow subsidence (Table 2). Shallow subsidence is only calculated when vertical accretion and marsh surface elevation change are significantly different.

Tidal Channel Morphology

Measurements of incipient tidal channels greater than 10 cm deep at channel mouth and greater than 15-m long were made in each Kunz Marsh cell in May 2000 (Fig. 1). Four channel attributes were measured: length, width and depth at mouth and at approximate midsection (used to calculate cross-sectional area), sinuosity ratio (length divided by linear distance between end points), and number of associated tributaries. These attributes were also measured in the main tidal channel associated with Danger Point high.

Emergent Marsh Vegetation

Emergent macrophyte presence/absence data were collected from Kunz Marsh cells annually during late summer (July to September) from 1997 through 1999. Three permanent transects in each cell were sampled from an average of 23, 1-m^2 randomly positioned plots (Smith et al. 1986, 1987; Frenkel & Morlan 1990; Simenstad et al. 1991). Three transects in Danger Point high in July 1999 and two in Tom's Creek high in 1997 and 1999 were sampled using the same methods. Total vegetation percent cover (inclusive of nonvascular plants) within each cell was measured from digitized color infrared aerial photos (1″ = 600′) acquired in 1999.

Vegetation was divided into categories described by Frenkel and Morlan (1990), Bertness et al. (1992), and Bertness and Pennings (2000): competitively dominant species (including permanent colonizers) and competitively subordinate species (including residual freshwater species and fugitive species, colonizers of ephemeral habitats resulting from disturbance events). Vegetation

Table 2. Marsh surface elevation change, vertical accretion, shallow subsidence, subsoil compression, and fill consolidation in the Kunz Marsh cells and reference sites after 3.1–3.6 years (Kunz) and 5.6 years (reference).

Site	*Marsh Surface Elevation Change (cm)*[a]	*Vertical Accretion (cm)*[a]	*Shallow Subsidence (cm)*[b]	*Subsoil Compression (cm)*[a]	*Fill Consolidation (cm)*[c]
Kunz high	−4.50 ± 0.13[d]	0.79 ± 0.24	5.29	1.57 ± 0.13[e]	3.72
Kunz mid	−3.96 ± 0.10[d]	0.44 ± 0.23	4.40	2.40 ± 0.55	
Kunz low 1	−1.57 ± 0.62[d]	0.77 ± 0.27	2.34		
Kunz low 2	−1.38 ± 0.26[d]	0.00 ± 0.00	1.38		
Danger Point high	3.88 ± 1.45	3.77 ± 0.18			
Tom's Creek high	6.47 ± 1.27	3.98 ± 0.23			

[a] Data are means ± SE.
[b] Shallow subsidence = vertical accretion − marsh surface elevation change.
[c] Fill consolidation = shallow subsidence − subsoil compression.
[d] Indicates that vertical accretion and marsh surface elevation change means are significantly different ($p < 0.001$).
[e] Indicates that vertical accretion and marsh surface elevation change means are significantly different from subsoil compression means ($p < 0.001$).

data were used to determine (1) percent frequency of species occurrence along each transect (as a measure of relative abundance), (2) Shannon-Wiener diversity index, (3) species richness (the sum of all species detected), and (4) species evenness (Moore 1978; Vandermeer 1981). Diversity, evenness, and species richness were calculated both for all species and for competitively dominant species only.

Fish

Each Kunz Marsh cell was sampled once monthly from November 1998 to March 1999, during the spring tide series. Species composition and density were assessed for each cell by placing a 50 × 1.8-m (5-mm mesh) modified nylon fyke (Cain & Dean 1976) across the cell opening at high slack tide. A 4.5 × 1.8-m (tapering) bag was positioned at the lowest point along each cell opening and the cod end staked out in Winchester Creek channel. Fish were collected from the fyke wings and bag after the tide had ebbed sufficiently. In cases where ponding occurred in front of the bag, a small hand seine was used to collect stranded fish.

Results

Marsh Surface Elevation Change

There was a decrease in marsh surface elevation in all Kunz Marsh cells (Table 2). Rate of elevation change ranged from −0.42 cm/yr in Kunz low 2 to −1.25 cm/yr in Kunz high. As of 1999, neither Kunz high nor mid had yet subsided to their design elevation. Marsh surface elevation increased in both reference sites at a rate of 0.69 and 1.16 cm/yr for Danger Point high and Tom's Creek high, respectively.

Tidal inundation period estimates indicated that Kunz low cells were submerged 7.9 times longer than Kunz high during the winter spring tide series and 30.3 times longer during the summer neap tide series (Table 1). Kunz mid was inundated 4.3 times longer than Kunz high during the winter spring tide series and 12.5 times longer during the summer neap tide series.

Vertical Accretion

Vertical accretion rates averaged 0.19 cm/yr for all cells except Kunz low 2, where no vertical accretion was detected (Table 2). Vertical accretion rates in the reference sites averaged 0.70 cm/yr. Elevation change and vertical accretion means were significantly different for all Kunz Marsh cells, enabling a calculation of shallow subsidence. Elevation change and vertical accretion means were not significantly different at either reference site (Table 2). Rates of shallow subsidence ranged from 0.42 to 1.48 cm/yr between Kunz low 2 and Kunz high (Table 2). Shallow subsidence was not calculated for reference sites because vertical accretion and marsh surface elevation change data were not significantly different.

Subsoil Compression and Fill Consolidation

Subsoil compression was 0.50 cm/yr in Kunz high and 0.76 cm/yr in Kunz mid (Table 2). Subsoil compression in Kunz high was significantly different from both vertical accretion and elevation change, allowing calculation of fill consolidation of 1.04 cm/yr. They were not significantly different in Kunz mid.

Tidal Channel Morphology

Nascent tidal channels developed in all cells but varied in character (Fig. 1, Table 3). Channels were the widest, deepest, and least sinuous in Kunz low 1. The development of both measured channels in Kunz low 1 was influenced by scouring action from a small freshwater stream that, contrary to project design, flowed through the cell for 11 months before a relief channel was dug in another part of the marsh (Fig. 1). The channels in Kunz high and Kunz low 2 were similar in sinuosity, depth, and width (Table 3). Kunz mid developed one main

Table 3. Tidal channel attributes in Kunz Marsh cells and Danger Point Marsh reference site.

	Kunz High			*Kunz Low 1*		*Kunz Low 2*		*Danger Point High*
	North	*South*	*Kunz Mid*	*West*	*East*	*West*	*East*	
Channel length (m)	65	15	50	75	30	88	28	91
Width/depth at mouth (cm)	[a]	[a]	80/25	210/95	290/85	95/21	90/10	300/65
Cross-sectional area at mouth (m^2)	[a]	[a]	0.13	1.60	1.24	0.13	0.09	1.77
Typical width/depth (cm)	30/5	30/2	25/10	80/75	80/20	35/4	15/3	70/30
Sinuosity ratio (SR)[b]	2.27	1.43	1.37	1.17	1.03	1.29	1.33	1.16
Tributaries	2	0	2	0	1	12	3	10

Cells with more than one channel are referenced by cardinal direction.
[a] No defined channel mouth.
[b] Straight (SR = 1); sinuous (SR = 1–1.5); meandering (SR > 1.5)

Table 4. Percent frequency values for emergent marsh vegetation species in the Kunz Marsh cells and reference sites.

Spp. Code	*Kunz High*			*Kunz Mid*			*Kunz Low 1*			*Kunz Low 2*			*Danger Point*	*Tom's Creek*
	1997	*1998*	*1999*	*1997*	*1998*	*1999*	*1997*	*1998*	*1999*	*1997*	*1998*	*1999*	*1999*	*1999*
Competitively Dominant Permanent Colonizers														
AGAL	26.3 ± 37.3	79.2	92.4 ± 7.5	31.0 ± 2.4	52.2	31.1 ± 6.0	2.2 ± 3.8	5.0	4.1 ± 4.0	5.1 ± 5.0		1.2 ± 2.1	72.2 ± 24.1	100.0 ± 0.0
CALY	7.5 ± 6.6	37.5	41.2 ± 11.0	13.6 ± 13.8	47.8	66.5 ± 11.6	17.2 ± 16.0	30.0	32.9 ± 18.8	15.3 ± 0.5	17.0	41.0 ± 18.1	100.0 ± 0.0	96.7 ± 4.7
GRIN		8.3	38.5 ± 20.0		4.3	1.2 ± 2.1							28.0 ± 41.0	
POPA	31.7 ± 11.7	33.3	20.8 ± 13.5	4.3 ± 4.8	13.0	6.9 ± 3.4					3.0		2.8 ± 4.8	7.8 ± 3.1
DECA	18.6 ± 7.7	16.7	13.2 ± 7.4	14.3 ± 6.7	21.7	57.8 ± 14.1	9.2 ± 10.8	10.0	12.2 ± 8.2	10.1 ± 4.9	7.0	6.6 ± 6.3	83.3 ± 28.9	42.5 ± 1.2
TRMA			10.0 ± 4.2	2.3 ± 4.0	52.2	52.8 ± 23.3	10.0 ± 8.5	25.0	28.7 ± 15.4	10.1 ± 4.9	31.0	35.7 ± 21.6	88.9 ± 4.8	83.3 ± 23.6
SAVI			3.8 ± 3.8	2.3 ± 2.0	4.3	24.3 ± 14.0			4.1 ± 4.0			6.8 ± 8.8	44.4 ± 45.9	8.3 ± 11.8
SCMA			2.6 ± 4.4	1.6 ± 2.7					2.7 ± 4.6		3.0			
DISP	4.0 ± 4.0	3.6	1.3 ± 2.2				7.0 ± 12.2	5.0	9.9 ± 11.0	3.5 ± 6.1		8.0 ± 4.4	66.7 ± 57.7	50.0 ± 0.0
HOBR	2.0 ± 4.0												19.4 ± 33.7	
GLMA													36.1 ± 55.5	4.4 ± 1.6
JACA													33.3 ± 50.7	30.6 ± 3.9
JUBA													30.6 ± 52.9	
Total	90	179	224	69	196	240	46	75	95	44	61	99	606	424
Fugitive Species*														
COCO	70.6 ± 9.2	75.0	14.1 ± 12.4	82.8 ± 2.9	100.0	62.0 ± 4.2	62.5 ± 18.9	60.0	47.4 ± 15.5	47.4 ± 4.6	48.0	48.3 ± 6.9		
ATPA	31.6 ± 26.2	70.8	50.8 ± 17.3	15.6 ± 5.7	56.5	9.2 ± 5.5			1.3 ± 2.3				36.1 ± 41.1	4.4 ± 1.6
ELPR				8.0 ± 11.1	52.2	66.5 ± 16.4	16.5 ± 13.3	25.0	46.9 ± 30.0	11.9 ± 6.0	34.0	67.9 ± 10.2		
SCCE				4.8 ± 8.2	21.7	30.0 ± 9.3			1.4 ± 2.5					
SPMA			7.2 ± 3.1		13.0	86.2 ± 3.6			57.7 ± 8.4		10.0	53.2 ± 7.3		
TRCO					8.7	8.0 ± 1.7						1.4 ± 2.4		
RUMA									3.7 ± 6.4			5.2 ± 4.6		
Total	102	146	72	111	252	262	79	85	159	59	92	176	36	4
Residual Freshwater Species*														
JUBU	76.9 ± 6.0	42.0		1.6 ± 2.7						2.0 ± 2.9				
HOLA	73.7 ± 13.1	16.7	2.6 ± 4.4	5.6 ± 5.1										
LOCO	18.5 ± 16.4	16.7	9.0 ± 8.0											
ELPL	5.3 ± 6.5	4.2	6.4 ± 11.1											
SCMI		8.3	9.0 ± 8.0	1.6 ± 2.7						1.7 ± 2.9				
ALAE				6.3 ± 11.0			1.9 ± 3.2							
JUEF		16.7	13.2 ± 9.2	1.1 ± 2.0						2.0 ± 2.9				
JUTE														9.2 ± 1.2
PHAR			5.1 ± 8.9											
TYLA										3.3 ± 5.8				
Total	174	105	45	16			2			9				9
All Species Total % Freq.	367	429	341	197	448	502	126	160	253	112	153	275	642	437

Values are % frequencies ± SD. Standard deviation was not calculated for 1998 data since only a single transect in each cell was sampled that year. Species with % frequency values no greater than 2.0 were omitted from the table. AGAL, *Agrostis alba*; ALAE, *Alopecurus aequalis*; ATPA, *Atriplex patula*; CALY, *Carex Lyngbyei*; COCO, *Cotula coronopifolia*; DECA, *Deschampsia caespitosa*; DISP, *Distichlis spicata*; ELPL, *Eleocharispalustris*; ELPR, *Eleocharis parvula*; GLMA, *Glaux maritimus*; GRIN, *Grindellia integrifolia*; HOLA, *Holcus lanatus*; HOBR, *Hordeum brachyantherum*; HOLA, *Holcus lanatus*; JACA, *Jaumea carnosa*; JUBA, *Juncus balticus*; JUBU, *Juncus bufonius*; JUEF, *Juncus effusus*; JUTE, *Juncus tenuis*; LOCO, *Lotus corniculatus*; PHAR, *Phalaris arundinacea*; POPA, *Potentilla pacifica*; RUMA, *Ruppia maritima*; SAVI, *Salicornia virginica*; SCCE, *Scirpus cernuus*; SCMA, *Scirpus maritumus*; SCMI, *Scirpus microcarpus*; SPMA, *Spergularia marina*; TRCO, *Triglochin concimun*; TRMA, *Triglochin maritimum*; TRWO, *Trifolium wormskjoldii*; TYLA, *Typha latifolia*.
*Competitively subordinate species.

channel with two tributaries just below channel size requirements.

Emergent Marsh Vegetation

After project construction in 1996 there was no vegetation cover in any Kunz Marsh cells. By 1999 total percent cover averaged 53% for all cells, compared with 100% cover at the mature reference sites. Total relative abundance for all vegetation in Kunz Marsh cells was greatest in the high and mid cells and lower in the low cells during each of the 3 years sampled (Table 4). Total relative abundance increased each year for every cell except Kunz high, where there was a 21% decline between 1998 and 1999.

Species composition in Kunz high in 1997 consisted of 75% competitively subordinate species (47% residual freshwater species + 28% fugitive species; Table 4). By 1999 competitively subordinate species declined in abundance to 34% of the total (21% fugitive species + 13% residual freshwater species), whereas competitively dominant species increased in abundance.

Similarly, *Cotula coronopifolia* (brass buttons), a competitively subordinate fugitive species, dominated composition in the mid and low cells, averaging 45% in 1997 (Fig. 4, Table 4). The competitively dominant permanent colonizers did not become established as rapidly in these cells as they did in Kunz high (Fig. 4). By 1999 competitively subordinate species still dominated composition in the lower cells, averaging 59%. Residual freshwater

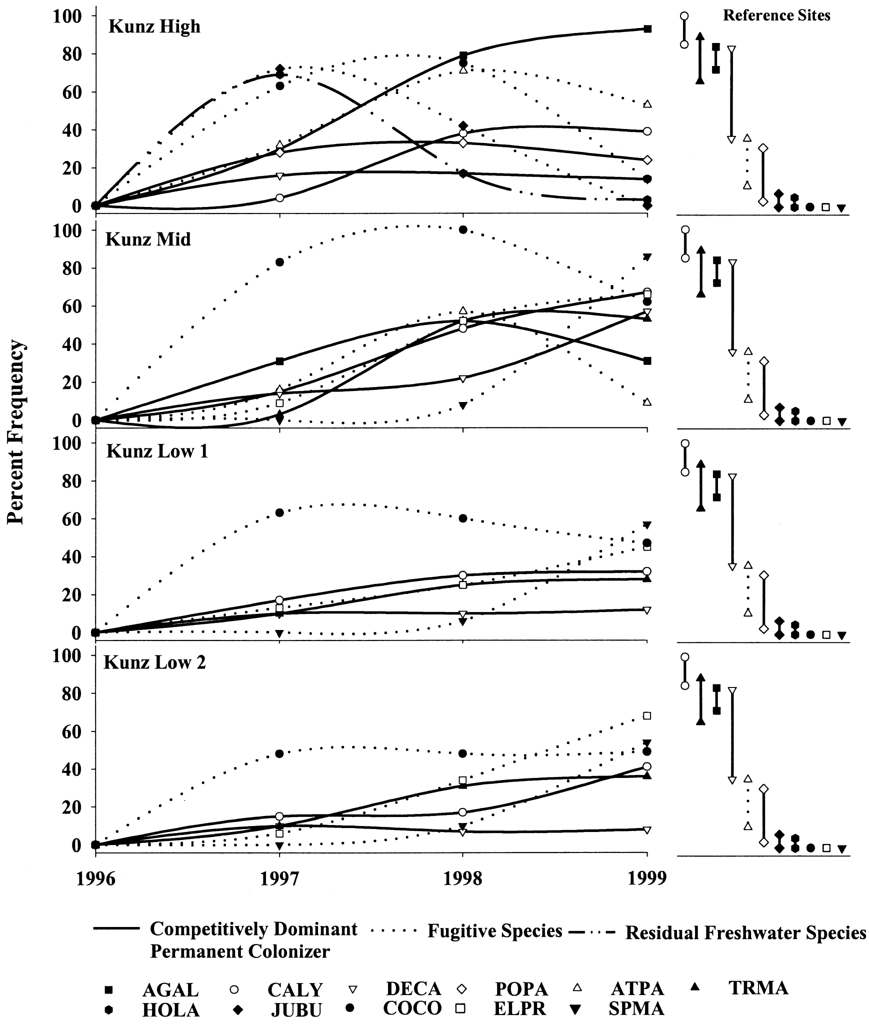

Figure 4. Percent frequency over time of the most abundant emergent marsh vegetation species for each Kunz Marsh cell. Percent frequency ranges for the same species in the reference sites appear to the right of each graph. See Table 4 for plant codes.

species were absent from all cells by 1999. *Spergularia marina* (salt marsh sandspurry), a competitively subordinate fugitive species, appeared in all cells after 1997. By 1999 salt marsh sandspurry was the most frequently encountered species in Kunz mid and low 1 and second in abundance in Kunz low 2 (Table 4, Fig. 4).

In 1999 competitively dominant species comprised 94% and 97% of Danger Point and Tom's Creek high, respectively (Table 4). Kunz high and mid developed relative abundances of individual competitively dominant species approaching, equaling, or exceeding those in the reference sites (Fig. 4). Relative abundance of competitively dominant species in Kunz low 1 and low 2 were well below those in the reference sites.

Shannon-Weiner diversity indices increased over time for all cells but Kunz high, which showed a decrease. There was a direct relationship between cell elevation and diversity in all years. By 1999 all cells had approached values of the reference sites (Table 5). Excluding competitively subordinate species the two low cells did not approach reference site diversity values. Species richness indices followed the same general pattern seen in diversity.

Evenness indices indicated a weak trend away from single or few species dominance in all cells but Kunz low 2 (Table 5). Excluding competitively subordinate species, both low cells tended toward single or few species dominance, whereas Kunz high and mid showed little change.

Fish

A total of 4,589 fish representing eight species were caught in Kunz Marsh cells; 3.4% were in Kunz high, 13.6% were in Kunz mid, and 28.2% and 54.8% were in Kunz low 1 and low 2, respectively. *Atherinops affinis* (topsmelt) and *Leptocottus armatus* (staghorn sculpin) comprised over 98.3% of total catch for all cells (Fig. 5). The composition of the high and mid cells was dominated by staghorn sculpin; they accounted for 98% and 79% of catch, respectively. The two low cells were dominated by top smelt, where they accounted for 64% to 67% of catch. The remaining six species caught were all

Table 5. Emergent marsh vegetation diversity, species richness, and evenness for all species and competitively dominant species only.

	Shannon-Weiner Diversity (± SD)			*Species Richness (± SD)*			*Evenness (± SD)*^{a}		
All Species	*1997*	*1998*^{b}	*1999*	*1997*	*1998*^{b}	*1999*	*1997*	*1998*^{b}	*1999*
Kunz High	2.64 ± 0.57	2.56	2.17 ± 0.29	27.0 ± 11.79	20.0	13.3 ± 4.04	0.81 ± 0.07	0.85	0.85 ± 0.01
Kunz Mid	1.94 ± 0.40	2.35	2.27 ± 0.04	10.0 ± 1.73	16.0	12.7 ± 0.58	0.84 ± 0.12	0.85	0.89 ± 0.01
Kunz Low 1	1.26 ± 0.47	1.65	1.91 ± 0.21	5.0 ± 1.73	7.0	9.3 ± 2.08	0.79 ± 0.12	0.85	0.86 ± 0.01
Kunz Low 2	1.67 ± 0.24	1.82	1.89 ± 0.13	7.3 ± 1.53	9.0	9.7 ± 0.58	0.84 ± 0.03	0.83	0.83 ± 0.04
Tom's Creek High	2.11 ± 0.43		2.27 ± 0.37	9.5 ± 0.70		11.0 ± 1.40	0.82 ± 0.01		0.83 ± 0.01
Danger Point High			2.10 ± 0.19			10.3 ± 2.08			0.91 ± 0.00
Competitively Dominant Species Only									
Kunz High	2.01 ± 0.23	1.86	2.06 ± 0.26	10.3 ± 3.06	9.00	11.7 ± 3.21	0.88 ± 0.07	0.85	0.85 ± 0.00
Kunz Mid	1.62 ± 0.23	1.95	1.82 ± 0.04	6.7 ± 1.53	10.00	8.7 ± 0.58	0.86 ± 0.02	0.85	0.84 ± 0.02
Kunz Low 1	0.88 ± 0.76	1.36	1.42 ± 0.39	2.7 ± 2.31	5.00	5.7 ± 2.52	0.97 ± 0.04	0.85	0.87 ± 0.04
Kunz Low 2	1.45 ± 0.12	1.41	1.24 ± 0.32	4.7 ± 0.58	6.00	5.0 ± 1.73	0.94 ± 0.02	0.79	0.80 ± 0.02
Tom's Creek High	2.11 ± 0.43		2.27 ± 0.37	9.5 ± 0.71		11.0 ± 1.41	0.82 ± 0.01		0.83 ± 0.01
Danger Point High			2.10 ± 0.19			10.3 ± 2.08			0.91 ± 0.00

Values are means ± SD.

[a] 1.0, evenness; 0.0, single species dominance.

[b] Standard deviation was not calculated for 1998 data because only a single transect in each cell was sampled that year.

found in the low cells, where they made up less than 2% of total catch.

Marsh elevation had a significant effect on both density (analysis of variance, $F_{3,16} = 3.73$, $p < 0.03$) and species richness (analysis of variance, $F_{3,16} = 5.04$, $p < 0.01$). Density and species richness were significantly lower in Kunz high than in Kunz low 2, but there was no significant difference between the high and mid cells, the mid and two low cells, or the two low cells (Bonferroni pairwise comparison on ranked data, $p < 0.05$; Fig. 6).

Discussion

Marsh Surface Elevation Change and Vertical Accretion

Elevation loss occurred in all Kunz Marsh cells and was directly correlated with the amount of fill material placed on the marsh surface. This result was anticipated for the two higher cells but not the low cells. Soils in the two higher cells have not yet subsided sufficiently to reach design elevations. If current elevation loss rates remain unchanged it will take 12 years for them to do so.

Despite some vertical accretion in three of the four cells, the marsh surface elevation of all cells fell as a result of shallow subsidence, a combination of fill material consolidation and subsoil compression. Fill material consolidation was only measurable in Kunz high and represented 70% of shallow subsidence in that cell. In the reference sites vertical accretion and elevation change were not significantly different and followed a positive trajectory attributed to sedimentation, buildup of organic matter and belowground biomass, and seasonal shrinking and swelling of marsh soils (Cahoon et al. 1995; Turner et al. 2000). Because vertical accretion

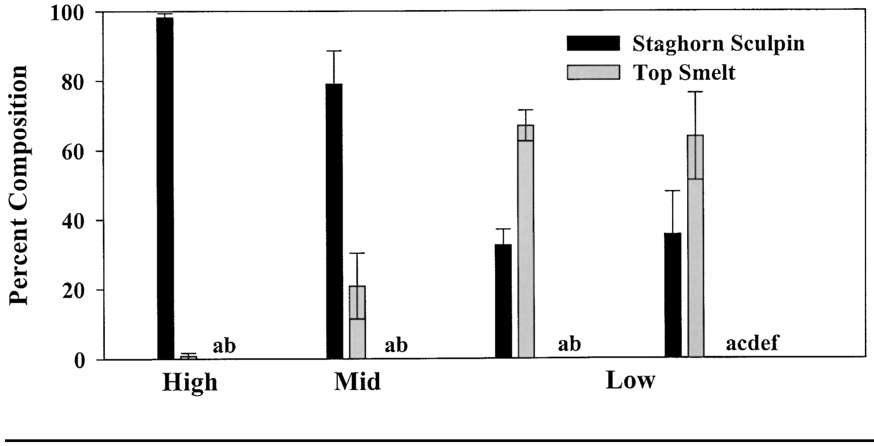

Figure 5. Mean fish species composition from November 1998 to March 1999 for Kunz Marsh. Error bars are standard error and represent monthly variation. Fish species accounting for less than 1% composition each included a, *Gasterosteus aculeatus* (threespine stickleback); b, *Cottus asper* (prickly sculpin); c, *Platichthys stellatus* (starry flounder); d, *Pleuronectes vetulus* (English sole); e, *Oncorhynchus kisutch* (coho salmon); and f, *Oncorhynchus clarki clarki* (cutthroat trout).

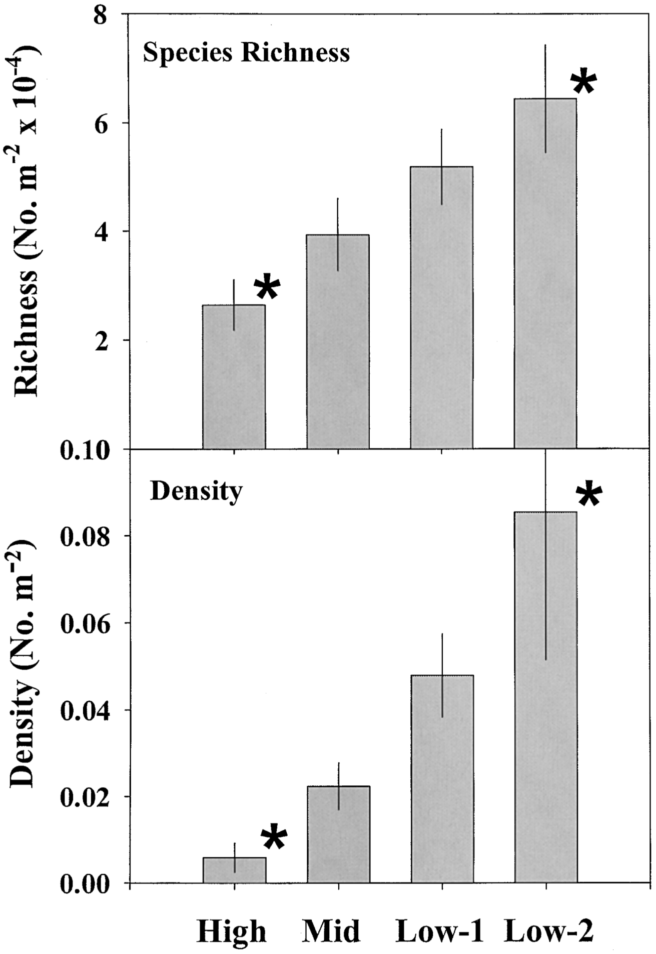

Figure 6. Mean total density and species richness (adjusted for area) of fish for Kunz Marsh between November 1998 and March 1999. Bars marked with an asterisk are significantly different from each other (Bonferroni pair-wise comparisons on ranked data, $p < 0.05$). Error bars are standard error and represent monthly variance.

measurements could not be made at all sites in Kunz low 1 and low 2, vertical accretion may have been underestimated.

Marsh elevation and associated tidal inundation period did not influence vertical accretion and exerted only minor compensatory affects on elevation loss. However, numerous studies indicate a positive relationship between accretion and tidal inundation period (Frenkel & Morlan 1990; Coats 1995; Cahoon & Reed 1995; Anisfeld et al. 1999; Reed et al. 1999). Had vertical accretion been the sole means by which marsh surface elevation change was measured at Kunz Marsh, elevation change would have been highly underestimated. Cahoon et al. (1995) similarly found vertical accretion alone to be under-representative of marsh surface elevation change.

We attribute discrepancies in vertical accretion rates between Kunz Marsh and reference sites to differences in vegetation cover and tidal channel development in the restoration site. Lower levels of vegetation cover can result in reduced sediment trapping (Boorman et al. 1998), sediment instability (Brown et al. 1998), and low abundance of organic material available to contribute to vertical accretion (Frenkel & Morlan 1990; Turner et al. 2000). In addition, relatively small tidal channels in Kunz Marsh may limit delivery of sediment from Winchester Creek. Sediments typically accumulate near the channels through which they are transported (Reed et al. 1999; Eertman et al. 2002, this issue), but we did not specifically attempt to measure sediment accumulation near channels. We expect vertical accretion and associated tidal channel formation in Kunz Marsh to increase with increasing vegetation cover.

A concern during project development was that newly deposited fill material on the marsh surface would become resuspended by tidal and wind-induced wave action and be redistributed off site. Although there was some unquantified amount of sediment observed moving off the marsh surface into the adjacent Winchester Creek during several large precipitation events, after 3 years fill material had largely remained on site (Table 2) and massive redistribution of material had not occurred. The relatively sheltered position of Kunz Marsh and the use of geotextile fences between cells to reduce fetch both contributed to minimal resuspension of sediment.

Tidal Channel Morphology

Naturally formed blind tidal channels evolve from meandering rivulets on low intertidal mudflats around which vegetated marshes develop by long-term processes dominated by vertical accretion; mature marsh surfaces eventually reaching an elevation approximately equal to MHHW (Pestrong 1965; Coats 1995). The elevation of subsided marshes can be adjusted using dike or dredge material as fill, but channel formation by vertical accretion may be inhibited in marshes constructed at elevations close to MHHW (Coats 1995). This was the case in San Francisco Bay, where tidal channels were found to be less likely to develop at sites constructed to match high marsh elevations (approximately equal to MHHW) and more likely to develop if marsh surface elevations were established below MHHW (Williams & Florsheim 1994; Coats 1995; Williams & Faber 2001; Williams & Orr 2002, this issue). In Kunz Marsh incipient tidal channels formed in all cells, but channel size was not strongly correlated to elevation. This was primarily due to differences in marsh surface gradient. Short tidal inundation period and associated lack of tidal energy did not prevent the formation of two highly sinuous blind tidal channels in Kunz high, but the channels were exceedingly narrow and shallow and had formed in accumulated sediments. Similarly, small and sinuous channels formed in Kunz low 2 despite the much longer tidal inundation period. The small channel size was likely influenced by the negative gradient in the front part of Kunz low 2 (Table 1). Assuming patterns of channel development continue as described by Coats (1995) there will be no further development of channels in Kunz high, but those in Kunz low 2, constructed approximately 0.70 m below MHHW, will continue to evolve through vertical accretion processes. Channel formation in Kunz mid and low 1 was likely facilitated by erosional processes. Because both cell elevations have between 0.4 and 0.7 m of vertical space below MHHW, channel development is expected to continue through erosional processes and long-term vertical accretion (Pestrong 1965; Coats 1995).

Emergent Marsh Vegetation

Although responses of emergent marsh vegetation were found to be positively correlated with constructed marsh elevation, the mechanisms driving such patterns remain untested. Vegetation is most likely responding to environmental stresses associated with tidal inundation period as suggested by Frenkel and Morlan (1990) and Thom et al. (2002, this issue). Marsh soils at lower intertidal elevations generally have higher soil salinities and lower redox potentials (Bertness & Ellison 1987) that inhibit vegetation growth (Howes et al. 1981; Mendelssohn et al. 1981; Linthurst & Seneca 1980). The patterns we observed in Kunz Marsh suggest a similar link between low elevation and conditions stressful for vegetation establishment.

Early colonizing fugitive plant species most likely facilitated the recruitment of competitively dominant species in Kunz Marsh. Salt-tolerant early colonizers have been shown to reduce soil salinities by shading hypersaline bare spaces, allowing less salt-tolerant competitively dominant species to successfully invade (Bertness 1991). However, the decline in species richness and abundance in Kunz high between 1998 and 1999 likely indicates the effects of interspecific competition. When stress levels are reduced over time, plant interactions can shift from facilitative to competitive (Bertness 1991; Bertness & Shumway 1993), which can result in a decline in species richness and abundance, as described by Brewer et al. (1997). In the mid and lower cells, facilitation likely continued as fugitive species, such as small spike rush and salt marsh sandspurry, increased in abundance.

In the sense that indicators of vegetation diversity can provide a basic indication of ecosystem function (Vitousek & Hooper 1993; Callaway et al. 2001), the vegetation functions of Kunz Marsh are already approaching or are equal to those in the reference sites. Diversity and richness data indicate competitively subordinate species may work to enhance marsh function while competitively dominant species become established, particularly in the low cells. Evenness data suggest a trend away from few or single species dominance, influenced principally by competitively subordinate species.

Fish Use

There was a significant inverse relationship between marsh elevation and distribution and abundance of most fish. Staghorn sculpin seemed to be ubiquitous in their distribution, making up a higher percentage of composition in Kunz high and mid due to low abundance of other fish. It remains unclear whether fish such as topsmelt, coho salmon, and cutthroat trout are selectively entering the low marsh cells or are passively flooded into those areas with a higher tidal volume. Although not significant, there were differences in mean density and species richness between the two low cells. The presence of more highly developed tidal channels in Kunz low 1 and the subsequent higher velocity of water draining from the marsh surface may have adversely effected catch efficiency, negatively skewing density and species richness results.

Many factors interact to influence the density and distribution of fish in a restored marsh. The shape of the creek bank adjacent to a marsh (McIvor & Odum 1988), complexity of constructed habitats (Havens et al. 1995), number and physical parameters of rivulets providing access to the marsh surface (Rozas et al.1988), and marsh elevation (this study) have all been shown to effect distribution of fish. This high variability in factors underscores the importance of accounting for the effects of individual habitat characteristics on fish use (Williams & Zedler 1999). Data from a reference site would have been helpful in providing a context for patterns of fish use observed in the Kunz restoration cells, but local reference sites did not offer comparable habitats.

Conclusion

The relative ease with which we were able to influence site hydrology by manipulating marsh surface elevation and the marsh's relatively rapid response are indicative of those aspects of tidal wetland restoration that offer significant hope for recovering lost wetland function in coastal areas. Our experience in Kunz Marsh indicates there may be further promise for accelerating the development of structure and function when actively restoring subsided estuarine wetlands.

Manipulating the marsh surface to mid-marsh elevations provided conditions favorable for relatively rapid emergent marsh vegetation colonization while providing the vertical space below MHHW for vertical accretion-dominated tidal channel development. A positive feedback loop is generated when vegetation colonization facilitates and contributes significantly to vertical accretion (Turner et al. 2000). This enhances long-term channel formation that in turn enhances vertical accretion and vegetation colonization (Bradley & Morris 1990; Coats 1995) by providing a conduit for sediment and nutrient delivery to the marsh surface (Reed et al. 1999). In addition, marsh surface gradient is at least as important as elevation in affecting the size and sinuosity of incipient channels incising into fill material.

Manipulating the marsh surface to low marsh elevations resulted in slower development of the vegetation-vertical accretion-tidal channel feedback loop but resulted in more immediate and prolonged benefits to fish in the early stages of marsh recovery. Fish access to the marsh surface may be limited in the future by differential rates of vegetation and tidal channel development. Establishing high marsh elevations eliminates the possibility of the vegetation-vertical accretion-tidal channel feedback loop from forming.

Constructed marsh surface elevations must eventually stabilize to allow the long-term persistence of desired habitat characteristics and processes. Shallow subsidence is a significant and potentially ongoing process. At Kunz Marsh we speculate that rates of vertical accretion will increase over time, which will ultimately offset the effects of shallow subsidence. Relative sea level change in Coos Bay, measured at -0.05 cm/yr due to tectonic uplift (Vincent 1989), will also contribute to this offset.

Early trends in the recovery of this manipulated marsh may not be fully indicative of ultimate marsh character. Long-term monitoring will more completely address the uncertainties associated with this active restoration method. We have refined key aspects of our monitoring protocols to address some of these uncertainties, and we encourage other interested investigators to help develop a detailed understanding of the recovery processes occurring in Kunz Marsh.

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