Sea level rise vulnerability assessment for State wildlife areas surrounding Humboldt Bay, northern California

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FULL RESEARCH ARTICLE

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Abstract

Humboldt Bay has the highest rate of sea level rise (SLR) in California (47.2 cm/century). Due to compaction and tectonic subsidence, former tidelands and pastures behind dikes surrounding Humboldt Bay are lower in elevation than bay waters at high tide. Adaptation to future climate change and SLR requires that resource managers understand vulnerability and risk to each wildlife area at a local level, because adaptation to SLR is a risk-based management strategy against an uncertain future requiring site-specific solutions. We conducted a vulnerability assessment of the shoreline of three State wildlife areas surrounding Humboldt Bay: Elk River (ERWA), Fay Slough (FSWA), and Mad River Slough (MRSWA). Breaching of shorelines that border each refuge has the potential to flood a diversity of wetland communities, wildlife habitats, and critical infrastructure within the historic tidal inundation footprint. The total length of diked 1-m shoreline segments potentially impacted by SLR was 6.2 km. The relationship between vulnerability and elevation of diked shoreline segments was significantly correlated for all wildlife areas. Vulnerability of diked shoreline was significantly affected by the type of surface covering. MRSWA had the highest percentage of shoreline fortified with concrete and rock (62.2% [2,876 m]), followed by ERWA (0.3% [2,815 m]). ERWA and FSWA had the greatest percentage of shoreline anchored by vegetation (99.3% [2,834 m] and 91.5% [3,385 m], respectively); FSWA had the highest percentage of unvegetated (i.e., exposed) shoreline (7.4% [252 m]); and ERWA had the highest percentage (86.6% [436 m]) of diked shoreline followed by FSWA (69.2% [633 m]) and MRSWA (33.0% [276 m]). The highest overall ratings of shoreline vulnerability were at ERWA (91.7%), followed by FSSWA (72,4%), and MRSWA (34.4%). Issues related to retention of unique characteristics of each wildlife area, natural resources and species at risk, and adaptive planning for future SLR are discussed.

Key words: coastal, diked shoreline, inundation, management, salt marsh, natural resources, wildlife

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Introduction

During this century, global sea levels will rise at an increasing rate. Conservative estimates are ~15.2 cm by 2030, ~30.5 cm by 2050, and ~91.4 cm by 2100 (Russell and Griggs 2012). Humboldt Bay in coastal northern California has the highest rate of sea level rise (SLR) in California (**Fig. 1**; ~47.2 cm/century; Montillet et al. 2018).

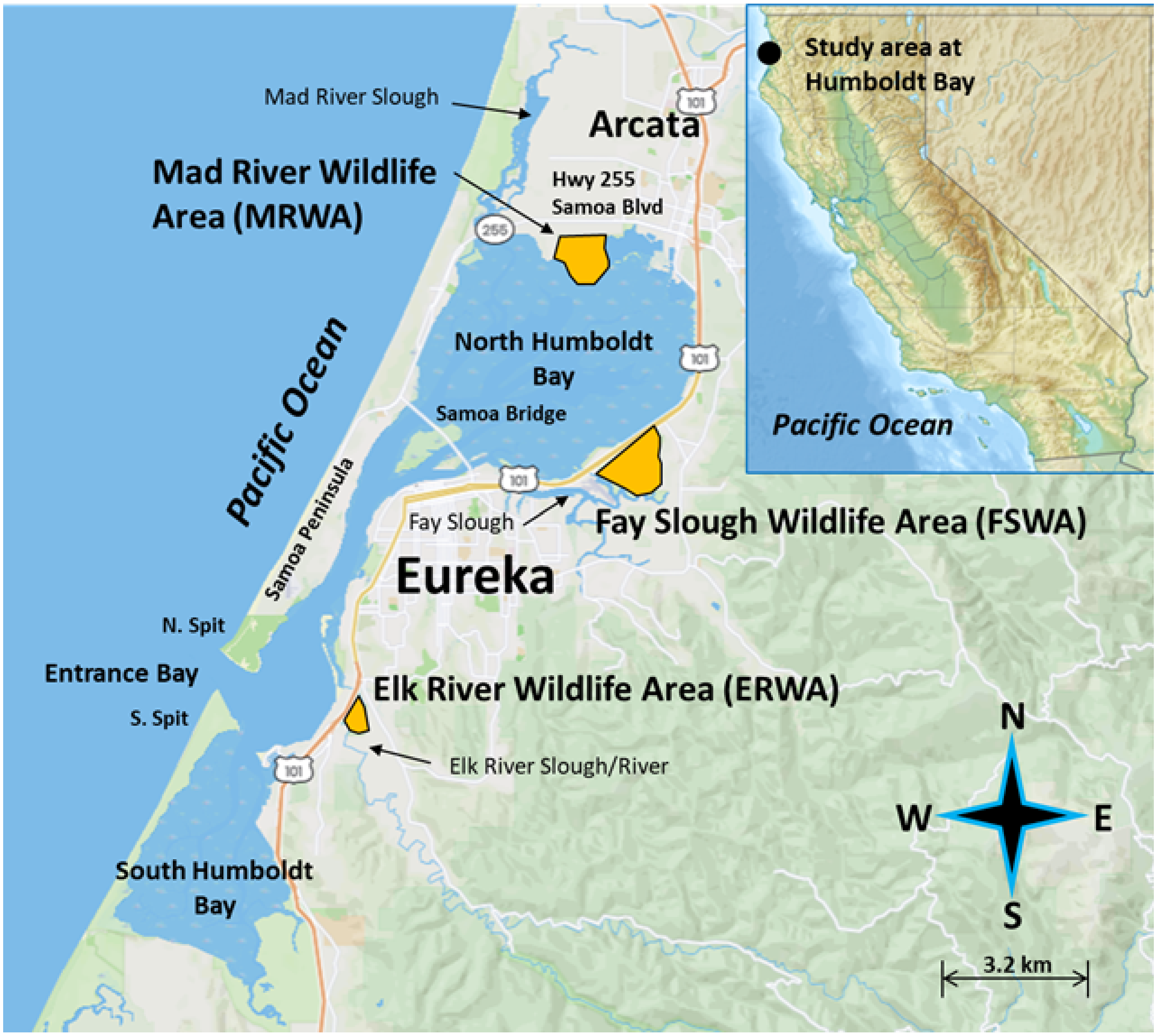

Figure 1. Map of the location of California Department of Fish and Wildlife (CDFW) wildlife areas surrounding the margin of Humboldt Bay.

Due to compaction and tectonic subsidence, former tidelands and pastures behind dikes surrounding Humboldt Bay are lower in elevation than bay waters at high tide (Clarke and Carver 1992; Valentine et al. 2012; CG 2013; Laird 2013, 2015). In the last decade, State declarations of emergency shoreline breaching, and overtopping have documented the vulnerability of existing shoreline structures that caused saltwater flooding of lands behind these diked structures (Laird 2013, 2015). In response to the 2008 California Executive Order S-13-08, which identified the need to plan for and adapt to SLR, the State Coastal Conservancy authorized funding for a multi-phase SLR adaptive planning effort for Humboldt Bay. This action resulted in the Humboldt Bay Inventory, Mapping, and Sea Level Rise Vulnerability Assessment (SLRVA; Laird 2013; Powell et al. 2013; Laird 2015). Products of this action included: 1) a GIS-based inventory, database, and mapping of the existing shoreline conditions surrounding Humboldt Bay; 2) an assessment of existing 1-m segments of shoreline vulnerability to breaching under current tidal conditions and SLR; and 3) identification of land uses and infrastructure potentially affected if the existing shoreline fails to retain rising tides. The SLRVA, however, did not specifically address potential threats to the diverse array of natural resources and wildlife habitat found on several State wildlife refuges located adjacent to Humboldt Bay.

Estuaries and tidal marshes perform valuable ecosystems functions within the natural environment (Mitsch and Gosselink 2000). SLR has the potential to affect water quality in estuarian ecosystems including suspended sediment, salinity, temperature, and nutrients, which are critical factors influencing plant and animal biological diversity in all bay environs. Wetland and marsh habitats within wildlife refuges surrounding Humboldt Bay help absorb nutrients, reduce loading to the coastal ocean, and protect local communities from flooding by storing floodwaters and damping the energy of wave height during storm surges. Herbaceous wetlands continually inundated with fresh, brackish, or saline water are found within estuarine embayment's of Humboldt Bay and adjacent wildlife areas. Modeled scenarios predict that changes in elevation may degrade the habitat quality of salt marsh ecosystems, a process predicted to dominate in the latter half of this century as the rate of SLR accelerates (Swanson et al. 2013). Increased rates of inundation may be particularly significant ecologically for obligate and endemic plant and wildlife marsh species (Takekawa et al. 2013; Roberts et al. 2019; Thorne et al. 2019).

Adding to concerns about SLR, elevated water temperature during El Niño events combined with heavy rain and high tides have acted simultaneously to increase sea level during winter by > 31 cm in Humboldt Bay (Laird 2013, 2015). During the El Niño events of 1983, the winter extreme high tide (EHT or "King Tide") was 2.9 m and in 1998 it was 2.8 m. Since 2000, King Tides during seven of the last twelve years have exceeded the average EHT of 2.7 m at the Humboldt Bay North Spit tidal station, with the highest tide reaching 2.9 m. Fortified shorelines surrounding the bay are considered the least vulnerable, vegetated shoreline intermediate in vulnerability, and unvegetated shoreline most vulnerable to erosion from extreme tides, storm surges, and future SLR. While it is true that fortified slopes of a dike would be less prone to erosion than non-fortified slopes, the interior slopes of dike structures are not usually fortified. Thus, during extreme water events that overtop dikes, even fortified dikes could become eroded on their back unfortified slopes. Breaching and overtopping of shorelines surrounding California Department of Fish and Wildlife (CDFW) lands along the Eureka, Mad River, Fay, and Elk River sloughs have the potential to flood these wildlife refuges, other land use infrastructure, utilities, and agricultural resources located within the historic tidal inundation footprint of 1870 (Laird 2007; **Fig. 2**).

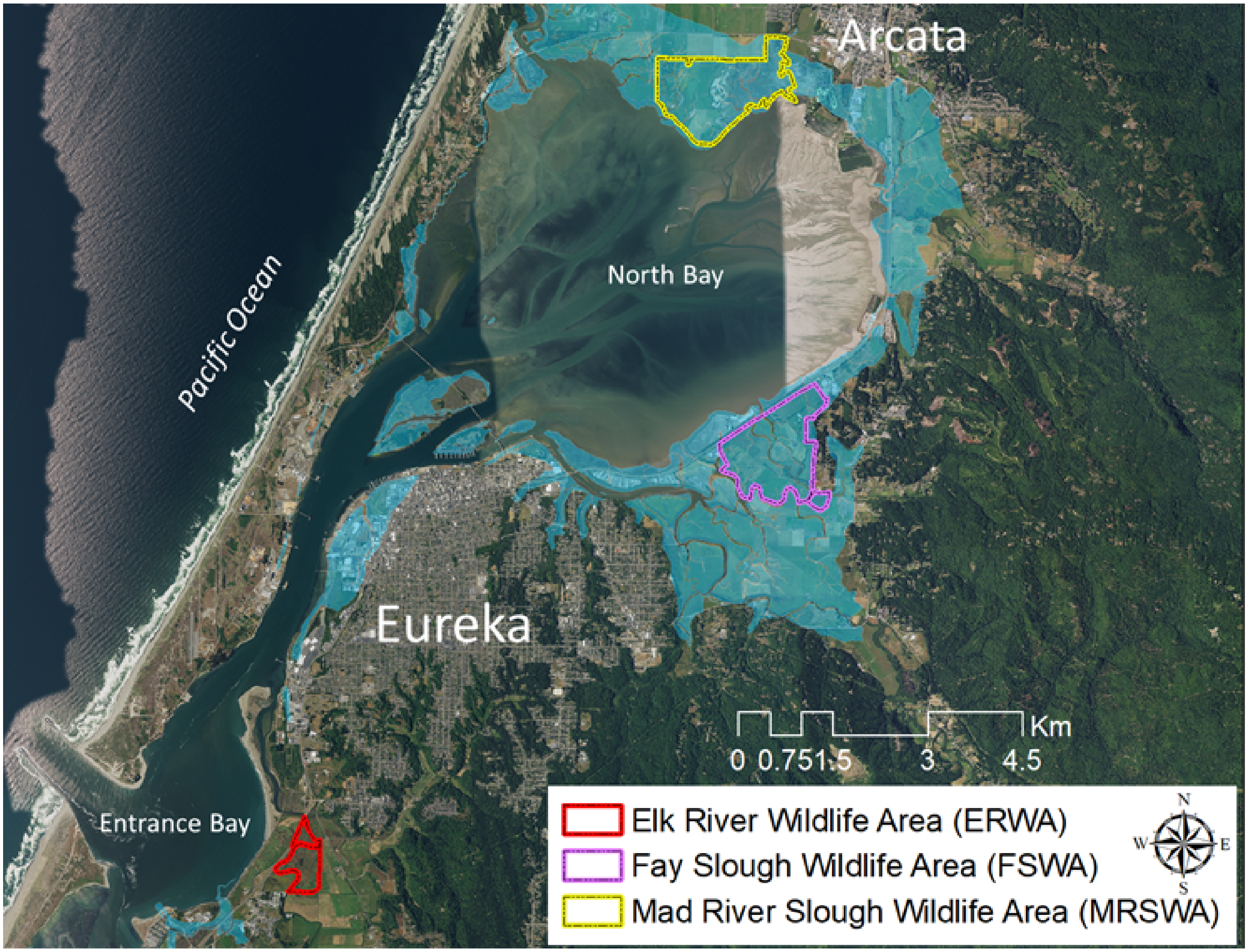

Figure 2. Map of the historic (1870) tidal inundation footprint (light blue shading) for Humboldt Bay showing the location of each wildlife area.

Adapting to future SLR requires that coastal wildlife and land managers understand the vulnerability and risk because adaptation to SLR is a risk-based management strategy against an uncertain future (Sullivan 2013). A risk-based vulnerability assessment is an evaluation of the likely sensitivity and response capacity of natural and anthropogenic systems to the effects of expected phenomena, which constitutes the majority effort in preparing for future SLR and derived coastal hazards (Lester 2006; Griggs et al. 2005; Russell and Griggs 2012). The SLRVA vulnerability assessment geo-spatial database provides an excellent opportunity to rate shoreline vulnerability on CDFW wildlife areas surrounding Humboldt Bay. Therefore, the primary purpose of our study was to identify specific locations along the property boundaries of each wildlife area that abut Humboldt Bay, which are vulnerable to flooding, elevated saltwater intrusion, and erosion from future rising sea levels, and impacts from linked wave and climate change. Using a subset of the information derived from the SLRVA geo-database, we produced a comprehensive metric-based GIS inventory of artificial shoreline elevation, structure, and cover, surrounding the Elk River (ERWA), Fay Slough (FSWA), and Mad River Slough (MRSWA) wildlife areas focused specifically on threats to property boundaries and associated natural resources.

Faced with the effects of SLR, the ability of coastal wildlife areas to protect the States’ natural resources, infrastructure, and provide ecosystem services is in jeopardy not only from climate change but from numerous other factors as well (i.e., land-use and availability, tectonic activity, groundwater overdraft, etc.). Rating shoreline vulnerability can assist in identifying assets at risk to flooding in the near-term from existing threats of shoreline erosion or overtopping. Quantitative assessment of future risk will assist CDFW land managers to: 1) identify areas along the boundary of regional wildlife areas that are potentially at risk from future shoreline breaching, erosion, and overtopping of water control structures; 2) identify specific natural resource, wildlife, and biological diversity issues potentially threatened by SLR; 3) prioritize, plan, and budget for future infrastructural needs and proactively identify solutions to issues in anticipation of potential effects from SLR in the short and long term; and 4) reassess the overall purpose and ability of each wildlife area to continue to support the existing priorities of their current land management plans. This information is timely, has not been initiated for any other coastal State wildlife refuge to our knowledge, and is provided at a scale necessary to help coastal resource managers plan for future SLR in combination with climate change.

Methods

Study Area

The study areas are located along the edge of Humboldt Bay, Humboldt County, northern California (**Fig. 1**). Humboldt Bay is 23 km long, 0.80 km wide at its narrowest point (entrance) and 6.9 km wide at its widest point (North Bay; Schlosser and Eicher 2012). The bay has three general regions: North Bay ("Arcata Bay" north of Samoa Bridge), Entrance Bay (Samoa Bridge to South Jetty), and South Bay (remainder of bay to the south). Surface area of Humboldt Bay is 65 km^2 of which 24 km^2 are intertidal mudflats (Schlosser and Eicher 2012). At high tide the surface area of the bay is 62 km^2, at low tide it is 28 km^2. Each tidal cycle replaces 41% of the water in the bay but in small channels and sloughs exchange can up to three weeks. The annual sediment budget from the few sources of fluvial suspended fine-sediment discharged into the bay is ~442 km^2. In contrast, the Eel River (15 km south of the entrance to the bay) discharges directly into the Pacific coastal margin and has a contributing area of ~9,415 km^2 (Barnhart et al. 1992). Although ~20 km^2 of bay habitat consists of eelgrass habitat that has remained comparatively constant since 1871, > 80% of the bay's coastal marsh habitats have been lost and fragmented by levee, railroad, and highway construction since that time (Laird 2013). Salt marsh habitat currently occupies ~10% of Humboldt Bay (Barnhart 1992; Pickart 2001); and ~70%, 25%, and 5% of the remaining salt marshes (< 3.6 km^2) are found in the North Bay, Entrance Bay, and South Bay, respectively (Schlosser and Eicher 2012).

Habitat interior to diked shorelines surrounding each wildlife area consists of varying extents of interconnecting roadways, pastureland, freshwater marsh, or mudflat, which supports grazing and numerous avian species, particularly waterfowl and shorebirds (Galbraith et al. 2002; Sullivan 2013, 2014a, 2014b, 2015; Colwell and Feucht 2018). ERWA is 43.1 ha in area. It is intertwined with the Elk River Slough, just south of the Elk River, 3.2 km south of Eureka on the east side of Highway 101 directly across from Entrance Bay. It consists of both coastal salt marsh and riparian wetlands. There is approximately 1.0 km of natural shoreline on the right bank of Elk River Slough in the southern segment of the ERWA. Tidal influence is evidenced by the occurrence of salt tolerant plants such as cordgrass (*Spartina* spp.) and pickleweed (*Salcornia virginica*) in low spots. Adjacent to the wildlife area the low-lying areas of Elk River at the bay interface constitute sinks for fine-sediment, which historically represented former tidelands that were subsequently diked, drained, and experienced local subsidence (Schlosser and Eicher 2012; Curtis et al. 2021). Overbank flooding in low-lying areas continues to occur during wet years and excessive floodplain sedimentation continues in the lower reaches of Elk River

(Lewis 2013). Elk River Spit protrudes out to the shipping channel and contains several unique shoreline environments (i.e., sandy beaches, salt-tolerant foredune plants, salt marsh, riparian-freshwater wetlands) that help protect the wildlife area, agricultural lands, and the neglected railroad grade.

FSWA adjacent to Fay Slough to the south is 195.9 ha in area located on the east side of North Humboldt Bay between Fay Slough to the south and Highway 101 to the west. This property consisted of previously grazed land, but it was restored to coastal and seasonal wetlands. Riparian woodlands occur along the eastern and southern edges of the property, which is dominated by red alder (*Alnus rubra*) and willows (*Salix* spp.; Sullivan 2014b). Many species of resident and migratory songbirds, waterfowl, egrets and herons, and numerous species of resident raptors use this area. Northern red-legged frog (*Rana aurora*), pacific chorus frog (*Pseudacris regilla*), northwest salamander (*Ambystoma gracile*), and newts also inhabit this site.

In 2010, the maximum high tide reached 2.7 m and a dike on Fay Slough, a tributary to Eureka Slough, was overtopped flooding 6.5 ha of the wildlife area (Laird 2013). The Fay Slough shoreline immediately adjacent to the wildlife area is covered in vegetation and is not grazed. Importantly, the diked shoreline of Fay Slough is protecting Highway 101 from tidal inundation (Laird 2015). A breach in that shoreline anywhere along its length could initiate tidal flooding of the highway-railway road prism, wildlife area, agricultural lands along Highway 101, commercial land at Indianola Cut-off, Murry Field Airport, and residential land south between Arcata and Eureka (Van Kirk 2007)

MRSWA east of Mad River Slough is 237.6 ha in area and consists of two units (McDaniel Slough and MRSWA proper). These units are located just west of the southern extent of the Arcata City limits along Samoa Boulevard. This wildlife area was formerly part of Arcata Bay’s extensive intertidal salt marsh and mudflats. Old tidal sloughs still meander through the property that periodically flood during heavy rain. Shoreline segments are predominant earthen dikes that protect agricultural uses on former tidelands. Additionally, numerous segments of unvegetated and concrete revetments and steel bulwarks exist on the Humboldt Bay side. This property is heavily used by resident and migrating waterfowl and a variety of egrets, herons, raptors, and shorebirds (Galbraith et al. 2002; Sullivan 2014b, 2015; Colwell and Feucht 2018). In 2003, a winter EHT combined with a storm surge of 2.9 m breached an un-fortified earthen dike 70 m in length on MRSWA, which flooded 243 ha of agricultural lands (Laird 2013).

Data Collection

Data and background information were obtained from: 1) the SLRVA project surrounding Humboldt Bay (Laird 2013); 2) Geographic Information System (GIS) geo-spatial shoreline vulnerability ratings (Powell et al. 2013); and 3) National Oceanic and Atmospheric Administration (NOAA) coastal LiDAR “hydro-flattened bare earth” digital elevation model (DEM; Anderson 2012, 2015). Inventory, field mapping, and LiDAR analyses of the entire Humboldt Bay shoreline and assignment of unique segment identifiers was based on a change in the attributes of four primary elements: elevation, structure, cover, and marsh types of adjacency onto 11×17 aerial photo base maps (scale of 1 = 200; Powell et al. 2013). Shoreline segments were digitized and attributed in GIS. Metadata provided with LiDAR DEM reported a vertical accuracy RMSE < 18 cm and a horizontal accuracy of < 50 cm RMSE. A subset of the LiDAR DEM was included in all portions of the Humboldt Bay shoreline. A contour layer was derived from the DEM that was color coded in 0.5-m elevation increments. Digitized artificial shoreline segments were realigned with the contours and the color-coded DEM to ensure that the segments were aligned with the structures that they represent.

A hydrology DEM was prepared of Humboldt Bay representing water surface elevations of the present day mean monthly maximum tidal water surface (MMMW; Anderson 2012). In this context, MMMW is used as a surrogate for spring tides. The MMMW surface was subtracted from the LiDAR DEM to produce a third DEM of “relative” elevations to the MMMW. Elevations were assigned to the shoreline segments at 1-m spacing (i.e., DEM = 1-m pixel resolution). One-meter spaced vertices of the shoreline segments were exported to a 3D point feature class. Shoreline segments were then broken at each vertex to produce 169,903 1-m shoreline segments, which contained the original unique segment identifier, shoreline attributes, and start and end elevation values in the attribute table. An average elevation was calculated for each 1-m shoreline segment and used as the basis for all follow-on analyses (Powell et al. 2013).

A GIS database containing spatial data for the three primary attributes was then used to quantify and support a vulnerability assessment of existing shoreline, tidal conditions, and various sea level scenarios. Dike types were extracted from the shoreline mapping dataset for input into the vulnerability analysis because they are the most prevalent and vulnerable structures to impacts from extreme tides, storm surges, and SLR (**Fig. 3**)

Figure 3. Photographs of diked shorelines illustrating examples and categories of degradation caused by heavy rain, extreme high tide events, and SLR used to categorize environmental parameters in our analyses: 1) Flooded levee on Mad River Slough (photo L. Miller), 2) highly eroded dike at the Humboldt Bay National Wildlife Refuge above lowland terrain, 3) and 4) vegetated shorelines along Fay Slough, 5)

typical functioning tide gate, 6) rock-concrete diked shoreline revetment, 7) rocked shoreline, 8) steel bulwark diked shoreline, 9) railroad segment on top of dike surround by salt grass and flooded bay water, 10) salt grass semi-natural herbaceous stand along McDaniel Slough (photo: A. Eicher), 11) flooded pasture caused by stormwater runoff and high tide inundation, and 12) characteristic freshwater marsh habitat for northern red-legged frog on Fay Slough Wildlife Area (photo: R. M. Sullivan). All other photos are by A. Laird (Laird 2013, 2015).

If these structures fail, thousands of ha of former tidelands would be exposed to potential flooding (Laird 2013, 2015). Dike and railroad shoreline segments were rated based on three cover-types: 1 = fortified, 2 = vegetated (both least vulnerable to erosion), and 3 = unvegetated (most vulnerable to erosion). Using measures of elevation each segment was ranked to produce a Vulnerability Index (VINDEX) value (Table 1).

Table 1. Combined shoreline vulnerability rating values (i.e., Fig. 5F and Fig. 6) create High (7–10; red color on maps and below), Moderate (5–6; blue color on maps and purple below), and Low (2–4; green color on maps and below) vulnerability ratings based on elevation to mean monthly maximum tidal water surface (MMMW) and cover-type. (CIV = cover index value; VRATE = overall combined vulnerability rating).

Elevation(m)	Vulnerability Index (VINDEX)	CIV Fortified	CIV Vegetated	CIV Unvegetated	VRATE
<1	7	1	2	3	8,9,10
1-2	6	1	2	3	7,8,9
2-3	5	1	2	3	6,7,8
3-4	4	1	2	3	5,6,7
4-5	3	1	2	3	4,5,6
5-6	2	1	2	3	3,4,5
>6	1	1	2	3	2,3,4

To model MMMW, 1-m segments of elevation and cover vulnerability were added together to assign a final Vulnerability Rating (VRATE) between 2 and 10 to each 1-m shoreline segment. The combined overall VRATE was designated by color: red = High, blue = Moderate, and green = Low (Table 1). Vulnerability ratings represent a quantitative metric that combines shoreline attributes in modeling MMMW to rate the vulnerability of each segment of shoreline in response to erosion, overtopping due to extreme tides, storm surges, and future SLR. Vegetated and unvegetated shorelines at elevations between 0.6 to 0.9 m attained a combined VRATE of 7 and 8 (high vulnerability) and shorelines lacking cover at elevations of 0.9 to 1.2 m received a high VRATE of 7. The same staggered VRATE was also applied at 1.2 to 1.5 m and 1.5 to 1.8 m due to shoreline cover causing higher vulnerability than expected compared to only elevation.

Statistical Analyses

Standard statistics.—All statistical tests used the R-suite of statistical programs (R Core Team 2022). The Anderson-Darling (AD) test statistic (Stephens 1986) showed that each environmental metric used to generate vulnerability ratings were not normally distributed (Structure type: D = 2,474; Cover type: D = 1,795; Marsh type: D = 853; Vulnerability index (VINDEX): D = 449; for all variables $P < 0.001$, n = 9,437). Non-normality in relative elevation (continuous variable) was also verified using theoretical density plots of histograms versus fitted density functions as a measure of goodness-of-fit (Delignette-Muller and Dutang 2015). Goodness-of-fit information criteria showed a 50:50% split in the environmental parameters that most closely fit a “normal” versus “Gamma” distribution (Akaike’s Information Criterion [AIC], Akaike 1973; Bayesian Information Criterion [BIC]; Schwarz 1978; Burnham and Anderson 1998). Thus, all subsequent univariate and multivariate statistical analyses used non-parametric or semi-parametric statistical methods for both non-normal continuously distributed and ranked attributes (McDonald 2014; Tsiatis et al. 2006).

We used the Kruskal-Wallis Chi-square (χ^2) rank sum test to evaluate each environmental variable accompanied by follow-on (post-hoc) planned pairwise comparisons between each designated wildlife area (group) using the Dunn test statistic (Z). P-values were adjusted using the Benjamini-Hochberg method (Benjamini and Hochberg 2000). Principal components analysis (PCA) identified variable selection, examined the extent of association among wildlife areas, assessed the comparative ability of attributes to explain variation among sites, and minimized multicollinearity between model predictors, with the goal of identifying a smaller subset of variable components that capture the majority of variance in predictors (Everitt and Hothorn 2011). We used the nonparametric Spearman’s rank correlation (r_s; 2-tailed test) to calculate the strength and direction of the relationship between any two variables expressed as a monotonic relationship, whether linear or not (Corder and Foreman 2014).

We used Generalized additive models (GAM) in all regressions (Wood 2017). This method: 1) is a semi-parametric extension of Generalized Linear Models (GLM) that is less restrictive in assumptions about the underlying distribution of data, 2) is effective for assessing non-linear relationships between response and explanatory variables (Hastie and Tibshirani 1990; Madsen and Thyregod 2011), 3) generally gives the best mean square error performance and optimal smoother of any given basis dimension, and 4) avoids the need to make prior assumptions about the shape of the function (Schluter 1988). A Gamma error-structure was used to establish the relationship between response variables and the smoothed functions of predictor variables (Wood et al. 2017). Statistics reported from each GAM included F-statistic, P-value, 99% confidence bands for spline lines, adjusted regression coefficient (R^2) for the model, and proportion of null deviance explained (DevExp; Nychka 1988). We used Spearman’s rank correlation coefficient as a follow-on statistic to assess strength and significance of trends in data delineated by smooth terms (Diankha and Thiaw 2016).

Results

Evaluation of Environmental Parameters Used to Model

Vulnerability

Shoreline elevation and vulnerability index.—Our study showed that the density distribution of elevation in 1-m shoreline segments at FSWA and MRSWA (**Fig. 4C and 4E**) were mostly “bimodal” in their exposure to high-water inundation and vulnerability to future SLR, compared to the diked shoreline at ERWA (**Fig. 4A**).

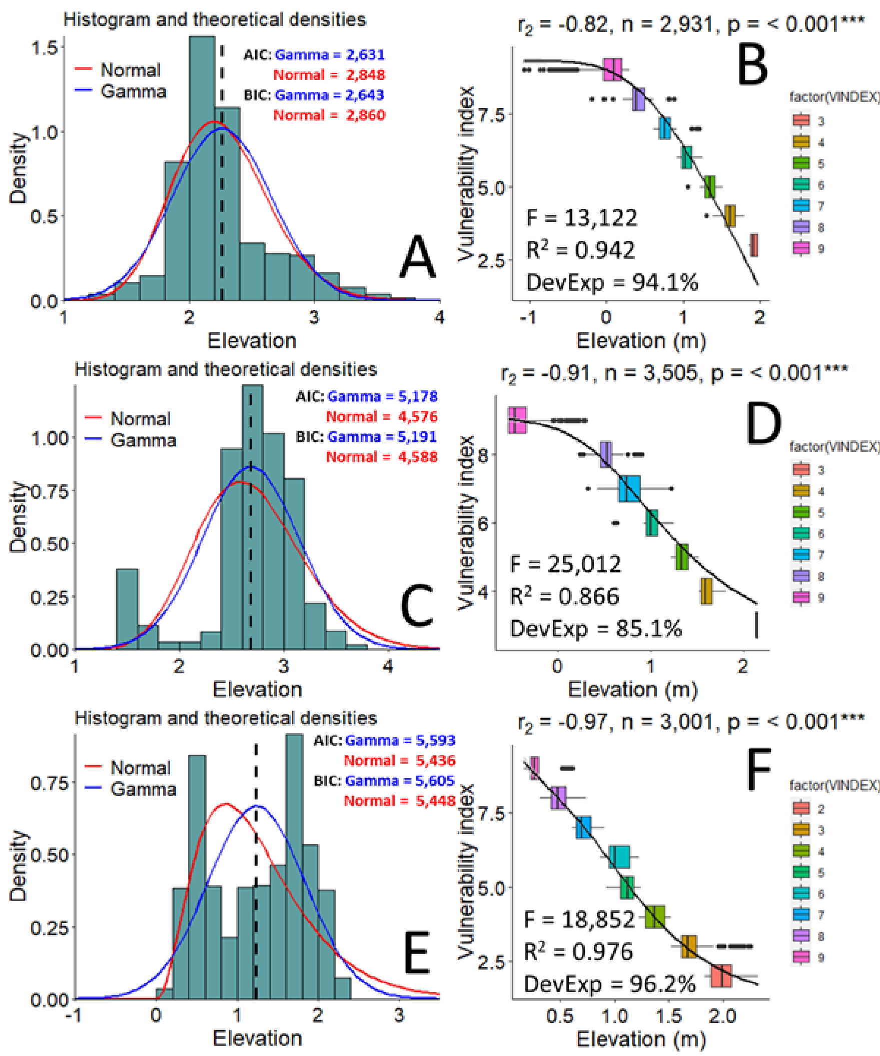

Figure 4. Generalized Additive Modeling (GAM) of the relationship between the Vulnerability Index (VINDEX) and relative elevation (m) of 1-m shoreline segments surrounding the boundary of each wildlife area. A) Elk River Wildlife Area, B) Fay Slough Wildlife Area, C) Mad River Slough Wildlife Area. For Elk River Wildlife Area the GAM regression of VINDEX against elevation used family = gaussian (link = log) because several segments had a negative in elevations; all other regressions used family gamma (link = log).

Shoreline segments at the MRSWA ($\bar{x}$ = 1.23 m) followed by FSWA ($\bar{x}$ = 0.68 m) averaged higher in elevation than diked segments at ERWA ($\bar{x}$ = 0.26 m; **Appendix I (PDF)**; **Table 2**).

Table 2. Summary of total shoreline length (1-m segments) and average elevation in relation to Vulnerability index (VINDEX: ranks = 2–9) for each rank in the VINDEX by wildlife area. No shoreline segments that had a vulnerability index of 10. Wildlife areas: Elk River (ERWA), Fay Slough (FSWA), Mad

River Slough (MRSWA).

Table 2a. Total shoreline segment

Wildlife area	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
ERWA (n = 2,931)	0	4	19	51	169	242	458	1,988
FSWA (n = 3,505)	0	2	36	184	744	1,396	735	408
MRSWA (n = 3,001)	515	782	332	281	59	249	649	134

Table 2b. Average elevation of shoreline segment by each rank in the VINDEX

Wildlife area	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
ERWA	0.000	1.916	1.598	1.343	1.041	0.766	0.413	0.050
FSWA	0.000	2.140	1.616	1.344	1.012	0.791	0.521	-0.378
MRSWA	1.998	1.695	1.368	1.103	1.030	0.714	0.474	0.297

However, in the development of their VINDEX Powell et al. (2013; **Table 1**) did not show the relationship between elevation based on their sampling of shoreline GIS data and the corresponding VINDEX values. This relationship is an integral component of the logic and process associated with modeling vulnerability of each shoreline segment. To address this issue, we evaluated the relationship between elevation and the ranked order of the VINDEX. As expected, our regression analyses showed a highly significant ($P < 0.001$) correlation between elevation and the VINDEX metric for all wildlife areas, which validated use of this measure as a surrogate for elevation in composite modeling of the rate of vulnerability of shoreline segments for each refuge (**Fig. 4B, 4D, and 4F**).

Kruskal-Wallis Chi-square (χ^2) rank sum tests of parameters used in the modeling of vulnerability ratings revealed significant overall differences for each wildlife area for each parameter (Table 3). Post-hoc pairwise comparisons also showed significant differences between wildlife areas for all shoreline elements used as model parameters. Thus, each wildlife area had its own unique suite of environmental parameters in reference to the potential threat of current high-water inundation and future SLR. Use of ranked correlation analyses to test the extent of association between shoreline attributes within the GIS database indicated that except for the relationship between structure and marsh types (r_s = -0.02, P = 0.12) all other shoreline attributes were significantly ($P < 0.001$) correlated. This was primarily because of the large sample size for each pair-wise comparison (n = 9,437). however, except for the relationship between elevation and VINDEX (r_s = -0.97) the correlation between all attributes was not particularly strong (r_s = < 0.51 > –0.61).

Bridge abutments were rare and only found only on the ERWA where they were associated with 0.1% of the total shoreline but ranked high on the VINDEX (**Appendix II (PDF)**, **Fig. 5A**).

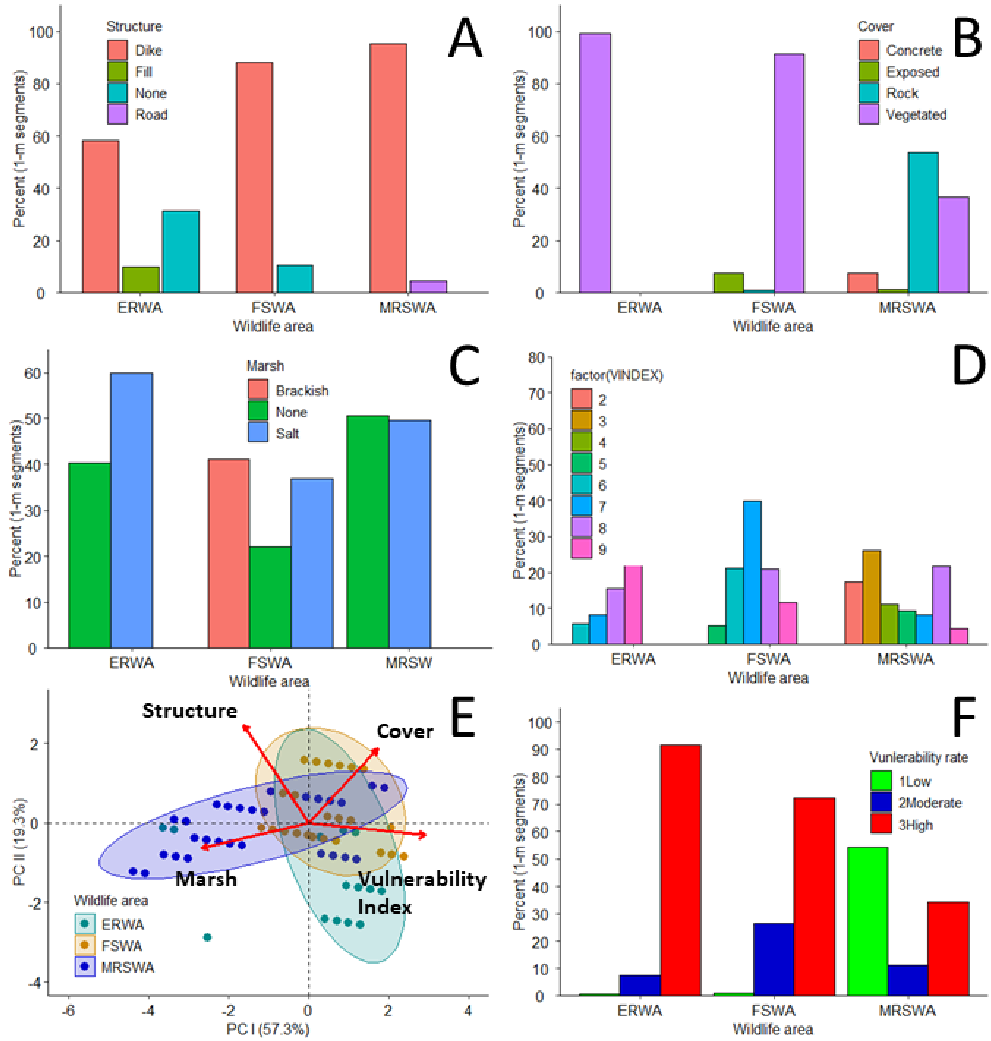

Figure 5. Bar graphs of the percent of total 1-m segments of shoreline associated with: A) structural, B) cover, and C) marsh types, and D) vulnerability indices (VINDEX) for each wildlife area. E) Results of the Principal Components Analysis (PCA) of environmental variables measured at each 1-m segment of shoreline along the first two vectors; and F) shows the percent overall Vulnerability Rating (VRATE) for each wildlife area. ERWA = Elk River Wildlife Area, FSWA = Fay Slough Wildlife Area, and MRSWA = Mad River Slough Wildlife Area. Each PC ellipse is based on a multivariate normal distribution with a 95% confidence level; red arrows indicate the direction and loading of each attribute along each vector. Diked shorelines were common on all wildlife areas (Elk River = 58.3%, Fay Slough = 88.2%, Mad River Slough = 95.4%). Here vulnerability indices were highest for ERWA and FSWA but more evenly spread across all vulnerability indices along the diked section of Mad River Slough adjacent to MRWA. Cover type at ERWA was comparatively sparse as there were few shoreline segments covered in concrete (0.1%), which ranked low on the VINDEX (Appendix II (PDF); Fig. 5B); whereas most segments were vegetated (99.3%) and ranked at the upper end of the VINDEX scale. Similarly, at FSWA most shoreline segments were vegetated (91.5%) and ranked within the mid to upper end of the vulnerability scale. MRSWA had a significant amount of shoreline covered in rock rip-rap (53.7%) that ranked at the low end of the VINDEX, while vegetation covered 36.6% of the shoreline and ranked at the upper ends of the VINDEX scale.

Saltmarsh habitat dominated (59.8%) the shoreline at ERWA (Appendix II (PDF); Fig. 5C). The only documented areas of brackish marsh (41.1%) were found along the shoreline at Fay Slough along with salt marsh (36.8%). Both marsh types spanned the mid to upper range of the VINDEX scale. Salt marsh habitat was found along 49.5% of the shoreline at Mad River Slough of MRSWA and it was distributed rather uniformly along the entire range of vulnerability indices. A summary of the total number of shoreline segments showed that the ERWA and FSWA had the largest percentage of highly vulnerable shoreline segments (VINDEX = 7, 8, and 9), compared to the MRSWA, which had the least vulnerable number of shoreline segments (VINDEX = 2, 3, and 4; **Fig. 5D**).

Principal components analysis of environmental variables merged with plot loadings showed considerable overlap in the spatial relationships among wildlife areas even though Kruskal-Wallis rank sum tests and post-hoc differences were significantly different between wildlife areas (**Fig. 5E**). A total of 75.1% of the variation among wildlife areas was explained on the first two PCs. As shown by the loading, relationship, and direction of each arrow, marsh type (0.54%) and VINDEX (0.91%) loaded heavy and positive along PC I (57.3%), whereas the structure (-0.502%) and cover type (-0.83%) of shoreline segments loaded negative along this vector. Because of the strong correlation between elevation and VINDEX for all shoreline segments, irrespective of wildlife area, this variable was not included in the PCA analysis to reduce collinearity.

Shoreline Vulnerability Ratings Applied to Wildlife Areas

Application of overall vulnerability criteria to potentially impacted diked shoreline segments indicated that the ERWA had the greatest percentage of shoreline rated as highly vulnerable (91.7%, 2.7 km), followed by FSWA (72.4%, 2.5 km), and MRSWA (34.4%, 1.0 km; **Fig. 5F**). Thus, the total length of diked shoreline potentially impacted by SLR at a high vulnerability rating was 6.3 km, a moderate viability rating encompassed 2.8 km of shoreline, and a low vulnerability rating equated to 0.4 km. This estimate is likely somewhat small because at several locations, both the front and back sides of the diked shoreline system were mapped and measured due to the potential for differential erosion on opposite sides of the dike along Fay Slough and some shoreline segments at the ERWA (Laird 2013; Sullivan 2013). At ERWA, the specific locations of diked shoreline potentially impacted by SLR occur along the southern branch of Elk River Slough that runs along and in-between the northern and southern segments of the wildlife area (**Fig. 6A**).

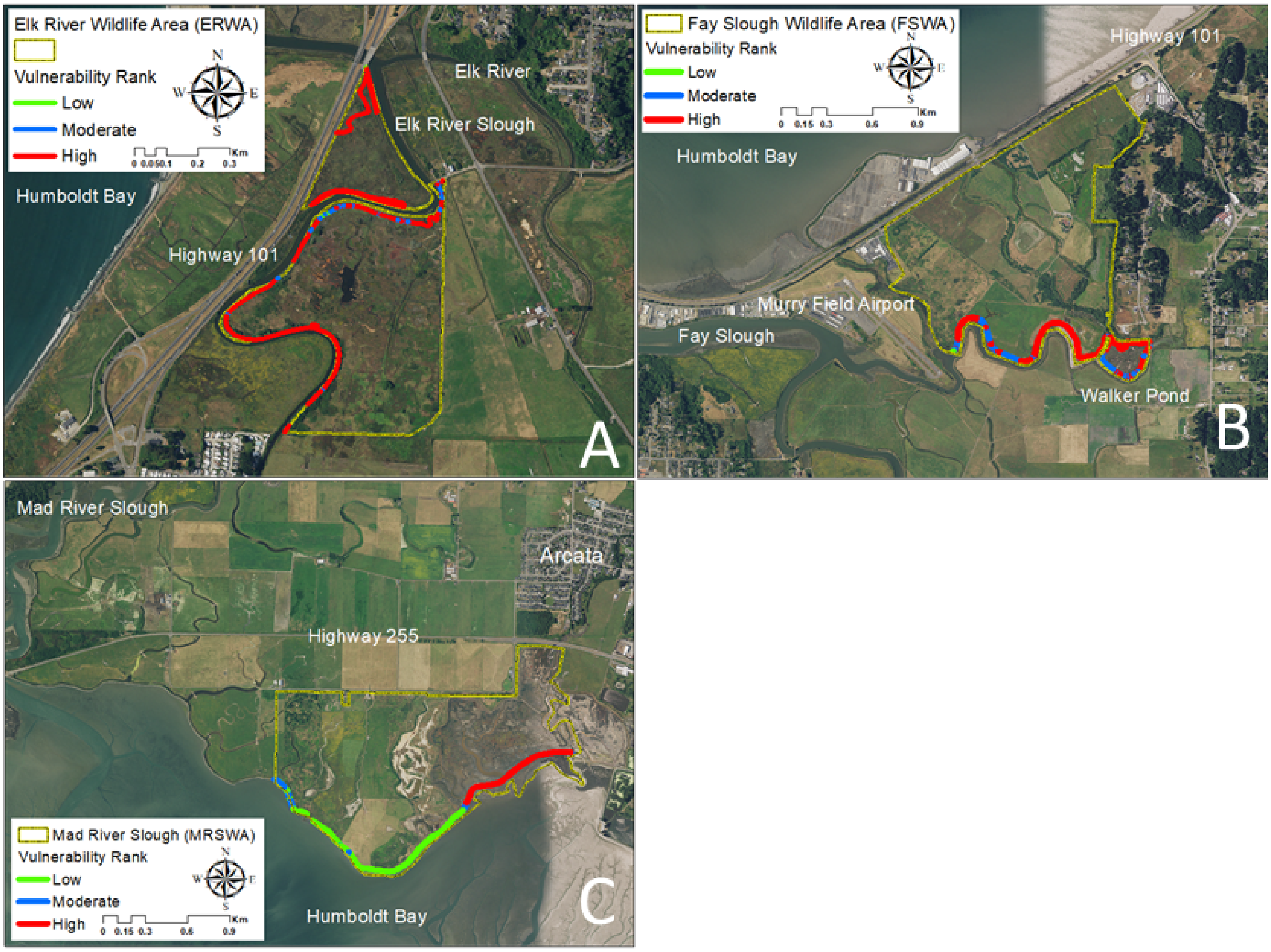

Figure 6. National Agriculture Imagery Program (NAIP) digital ortho quarter quad photographic satellite imagery (2020; **https://naip-usdaonline.hub.arcgis.com/(opens in new tab)**) of the 1-m survey segments of the shoreline and the surrounding the landscape at: a) Elk River Wildlife Area, A) Fay Slough wildlife Area, and C) Mad River Wildlife Area. Perimeter colors show the extent and Vulnerability Rating (VRATE) to sea level rise.

At FSWA the shoreline segments most susceptible to SLR are located along the outer margin of Walker Point Pond, in the extreme southeast quadrant of the property (**Fig. 6B**). At MRSWA, the diked shoreline most vulnerable to the impacts of SLR occurs along the southeastern half of the property bordering North Humboldt Bay in the vicinity of south Arcata, Arcata Marsh, and Arcata Oxidation Ponds at the eastern edge of McDaniel Slough (**Fig. 6C**).

Discussion

Back to the Future

Based on the tidal record from the North Spit of Humboldt Bay, Laird (2013) hypothesized that a conservative estimate for California is a 0.31-m rise in SLR by 2050. Exacerbating this expectation is the fact that Humboldt Bay is also subsiding, resulting in the highest rate of SLR in California. Yet because of the effect of subsidence and other simultaneous tidal and storm surge events, Humboldt Bay could realize a SLR of 0.31-m sooner than 2050. Future projections suggest that these diked shorelines will be breached or overtopped by 0.30 to 0.60 m rise in sea level this century (Russell and Griggs 2012; **Appendix III (PDF)**). Further, vulnerability mapping of the tidal inundation footprint of the bay at MMMW could expand by 52% (3,609 ha) if highly vulnerable shoreline structures are breached (NHE 2014a; NHW 2014b; Laird 2015). Shoreline segments that are most vulnerable occur along the Eureka, Mad River, Fay, and Elk River sloughs (Laird 2015). At risk are shoreline structures and assets that border or are interior to all State wildlife areas that occupy property lower in elevation than MMMW (i.e., utilities, transportation, agricultural, hydrologic, infrastructure, and natural resource areas).

Since 2000, Humboldt Bay has experienced periods of rising water elevations ranging from 0.3 to 0.5 m during annual EHTs combined with winter storm water runoff and wave surges, known as extreme high-water levels or events. In 2003, during EHT and a storm surge, water levels were elevated to 0.54 m above MMMW. This caused a breach of 71 m of dike along Mad River Slough that flooded 243 ha of agricultural land. During the 2005 to 2006 New Year's storms and EHT's, water elevations of 0.53 to 0.55 m overtopped the Eureka Reclamation District dikes in North Humboldt Bay at several locations (Laird 2013). Currently, Elk River, east of the entrance to the bay, regularly floods the lower valley reaches of Elk River Slough during EHT events. In January 2014 many existing nonfunctional and leaking diked shoreline segments put thousands of acres at risk from flooding had there been simultaneous or catastrophic shoreline failures during future El Nino and King Tide events.

Earthen dikes that surround much of each wildlife area are actively eroding, unmaintained, or have surfaces that are highly vulnerable to overtopping by a rise in the MMMW or EHT events. A King Tide can raise water elevations 0.31 m to 0.46 m and El Nino conditions would add another 0.3 m (Storlazzi and Griggs 2000). In Humboldt Bay, the 1% annual (100-yr) extreme high-water level is approximately 0.7 m (2.3 ft) above MMMW (NHE 2015).The tipping point for most dikes is 0.61 m above MMMH (2.4 m at North Spit of Humboldt Bay). At ~1 to 2 million dollars per 1.6 km to rebuild dikes, potential future funding from State or the Federal Emergency Management Agency may not provide for the kilometers of dikes that are vulnerable now (Laird 2013). Although former tidelands have been and continue to be productive areas for agriculture, at some time in the future rising tides and continued subsidence of the land within and around Humboldt Bay may elevate groundwater to the point that existing tide gates will no longer fully drain on ebbing tides (Laird 2013; Laird 2015). Eventually, rising tides and groundwater, and subsiding land may reclaim much of the nearly 3,642 ha of former tidelands as the Bay returns to its historical footprint (e.g., **Fig. 2**).

A further consideration for land managers is that increasing the amount of fortified shoreline along the margins of wildlife areas and the bay may not conform to future coastal resource protection policies regarding: 1) sediment recruitment and deposition; 2) continued existence of shoreline habitats like salt marsh; or 3) the rapid spread of the invasive cordgrass that frequently forms dense colonies within coastal salt marshes and unvegetated shorelines (Pickart 2001; Pickart 2006). Thus, the general consensus among regional scientists is that communities, infrastructure, utilities, freshwater wells, and natural resources surrounding Humboldt Bay are living on "borrowed time" given the lack of dike maintenance, available space for upslope migration of marsh habitat, and lack of abundant fine-sediment needed for salt marsh growth in most areas (Laird 2013; Laird 2015).

Natural Resources at Risk

Historically (1854 forward), Humboldt Bay occupied 10,441 ha, of which 59.3% were tidal channels and inter-tidal mudflats, and 40.7% were inter-tidal wetlands and salt marsh (Laird 2007). Since 1870, ~90% of all salt marsh habitat has been diked and drained for agricultural uses or walled off from tidal inundation with construction of rail and highway rights-of-way (Pickart 2006). Currently, salt marsh habitat in Humboldt Bay is estimated at < 364 ha (Barnhart 1992; Pickart 2001). Estimates of marsh accretion short-term rates are 2.19 ± 1.36 mm/year (Curtis et al. 2019) but analysis of marsh cores suggest historical accretion rates of 3.5 to 5.7 mm/year (Thorne et al. 2016).

Future SLR projections suggest that all wildlife refuges along the bay may evolve into saltwater-brackish marsh ecosystems, greatly altering the current management strategies, which may result in the complete loss of all properties as they currently exist. However, Thorne et al. (2016) appeared to have lumped all marsh accretion estimates into one data set, which included historic un-leveed marshes and leveed marshes that have breached but have a muted tide. Currently, historic marshes in North Humboldt Bay appear to be keeping pace with SLR, which is about 4 to 5 mm/year (J. Anderson, pers. obs.). In contrast, the so-called restored marshes, such as McDaniel Slough that have undersized breaches and muted tides are not keeping pace with SLR and would bias average results.

Refuge landscapes also face threats from SLR, which shrinks marsh habitats, destroys riparian vegetation over time, and facilitates the spread of ecologically-damaging invasive plants (i.e., cordgrass) within coastal salt marsh and unvegetated shoreline habitats (Pickart 2006). Chord grass depresses native plant biological diversity, displaces both invertebrate and vertebrate species (Pickart 2021), and facilitates the loss of key trophic support for fishes and migratory birds by shifting dominance to species not widely consumed by taxa at higher trophic level (Levin et al 2006). Retention and protection of salt marsh habitat from SLR also provides habitat for listed species (Table 4). Combinations of open water, mudflats, and marshes offer refuge and forage for abundant wildlife, fishes, and invertebrates. Shallow ponds and seed-producing vegetation provide overwintering habitat for both resident and migratory waterfowl, shorebirds, and wading birds annually. Foraging success of these species is inextricably linked to water levels in freshwater marsh when prey is concentrated in shallow waters during the annual drawdown. Reduction in the level of freshwater in marsh habitats may also alter bird use if changes in timing or duration of water levels are outside of the range required by foraging species (Galbraith et al. 2002). Rising sea levels and high tides combined with climate-mediated flooding of tidal marshes tends to isolate and fragment these populations. These shifts in community structure and demographics in tidal marsh ecosystems are known to increase vulnerability to predation of tidal marsh wildlife and obligate salt marsh species (Roberts et al. 2019; Thorne et al. 2019).

Ecological Consequences of SLR

To continue to provide ecological functions, marsh types must maintain their elevation in pace with SLR by moving inland where they are subject to erosion and accumulation of fine sediment at the seaward landscape edge (Curtis et al. 2021). Increasing elevation of a diked system requires an abundant and nearby supply of fine-sediment rich in organic material. However, sediment cores in marshes analyzed in North Bay have shown low organic content (J. Anderson, pers. obs.). Sensitivity analysis modeling of San Francisco Bay showed that sediment accumulation and the rate of SLR had the greatest influence over salt marsh sustainability for resident endangered species (Swanson et al. 2013). Marshes associated with sloughs, shoreline, and the interiors of wildlife areas surrounding Humboldt Bay also require a geomorphological substructure of uplift or low subsidence to survive the projected rise in sea level (NRC 2012; CG 2013).

Results of our study and the expanded bay-wide assessments of Humboldt Bay suggest that marsh types and mudflats rank high on the index of coastal vulnerability (Powell et al. 2013; Laird 2013). Although vulnerability may vary from location to location most wetlands are considered resilient to SLR over the next 50 to 70 years before converting to intertidal mudflats as SLR outpaces the capacity of salt marsh to adapt (Thorne et al. 2015). Intertidal mudflats tend to transition to marshes only when the land surface reaches an elevation that supports salt- or flood-tolerant emergent vegetation in the absence of abundant fine-sediment (Curtis et al. 2021). Nonetheless, transitioning from intertidal flats to marshes is especially sensitive to changes in sea level (Pestrong 1965; Swanson et al. 2013).

Viewed collectively, many projects fail to meet their habitat rehabilitation or restoration goals owing to an insufficient understanding of the physical processes involved in shaping tidal wetlands, resulting in seasonal freshwater wetlands being converted into mudflats to the detriment of sensitive species and reduced biological diversity (Knuuti 2006). Failure to understand the synergistic relationships among physical factors (i.e., elevation, extent of muted tidal exchange restricting sediment delivery with the bay, and availability of abundant fine-sediment) are in large measure why restoration actions at the McDaniel Slough Unit (MRSWA) failed to restore this marsh type in response to SLR (i.e., **Fig. 6C**; Sullivan 2014b). In this specific example, the lack of abundant fine-sediment was likely due to the implementation of undersized breaches and muted tide conditions facilitating expansion of mudflat to the exclusion of salt marsh.

Current Conditions and Management Options

Currently, most of the existing tidal wetlands in North Humboldt Bay that have not been leveed historically appear to be keeping pace with SLR (e.g., they are all around MHHW in elevation; J. Anderson, pers. obs.). However, these conditions are not met in most areas along the eastern edge of Humboldt Bay, between and including the towns of Arcata and Eureka. This is because of: 1) a lack of available space for upslope migration and steep topography surrounding the eastern elevated regions of the bay; 2) a deficit in the supply of fine-sediment combined with a low-level annual accretion rate that would have to be supplemented by nearby external sources; and 3) the tectonic subsidence characteristics of the bay (Barbier et al. 2011; Klein and Anderson 2012; Curtis et al. 2021). Although coastal regions with abundant fine-sediment supply may be more resilient to SLR (Komar et al. 2011; Curtis et al. 2021), resiliency is totally dependent on the availability of upslope terrestrial habitat for marshland migration. Thus, land and refuge managers responsible for maintaining the overall integrity, extent, and biological diversity of wildlife areas need to consider sediment-based solutions to combat SLR and mitigating extreme events through wave attenuation, shoreline stabilization, and floodwater retention (Shepard et al. 2011; Leonardi et al. 2016; Nicholls 2018; Curtis et al. 2021).

At ERWA, there appears to be an adequate supply of fluvial sediment from Elk River to maintain marsh elevations in face of SLR, once the site is restored to accommodate overbank flows when they occur, and to allow a full tidal exchange of high sediment concentration water when overbanking does not occur. However, we do not know how much sediment is available from the bay to ERWA, but much less than is available from the Elk River source (CalTrout et al. 2022). At FSWA, because a potential breach or bay connection, would likely occur in Fay Slough and not North Bay, sediment delivery to FSWA may be the most questionable. The most likely source would be from Freshwater Creek during flood events, and the delivery of the sediment plume from repeated tidal excursions between the bay and Fay Slough. The second source of sediment would be from North Bay during wind events that resuspend bed sediment. This is also an important source that could reach FSWA. Thus, it would be important to have a large breach that provides full tidal exchange. An increased tidal prism would also drive circulation processes that would deliver higher sediment concentration water to FSWA.

Currently Walker Point Pond (6.5 ha; FSWA) is a former diked area to the south of Walker Point where the dike was breached after being overtopped and was allowed to revert back to intertidal wetland habitat. This was done because land managers and local residents were concerned that the flooded area without any tide gates would become a breeding ground for mosquitoes, which being next to a residential area was considered it might become a public nuisance. The north side of this subunit consists of natural shoreline at the base of Walker Point. In response to future SLR some levees could be built higher, pulled, or redeployed to allow landward migration of salt marsh habitat to enhance the natural shoreline (i.e., **Fig. 6B**). Removal of diked shoreline segments of Fay Slough surrounding Walker Point Pond would also eliminate highly vulnerable segments of the diked shoreline that are expensive to maintain. This would leave the remaining (31%) diked shoreline to be managed through natural and fortified efforts to prevent erosion from future SLR. The result would be that in addition to Walker Point Pond other low-lying areas associated with Fay Slough may convert to tidal marshland, mudflat, or even subtidal ecosystems habitats sooner than currently predicted by estimates of SLR depending upon the abundance and supply of sediment and space. Although not specifically included herein the adjacent Highway 101 and railway corridors between the edge of Humboldt Bay and the west facing boundaries of ERWA and FSWA are also subject to overtopping as a function of these processes (i.e., **Fig. 6A and 6B**; Laird 2013, 2015).

At MRSWA, the only source of sediment is the accumulated sediment in North Bay. According to Curtis et al. (2021), the fine-sediment sediment supply to Humboldt Bay should increase into the future with climate change. This sediment would be delivered to MRSWA during higher tides and storm surge events. As with the other sites, restoring full tidal exchange will be critical. In our opinion, there is enough sediment locked up in North Bay for restored marshes to keep pace with SLR, as long as we do the restoration correctly. The drivers are there and have been for eons.

Natural shorelines can provide partial protection against sea-level rise and tidal surge (Dare 2005). Such architecture may be an important tool for managing coastal erosion, enhancing intertidal habitat, and enhancing the resilience of ecosystems against damage caused by intense storms, wave erosion, and SLR (**https://www.habitatblueprint.noaa.gov/living-shorelines**). Where feasible, use of living shorelines and setback segments may stabilize vulnerable sections of diked lagoon-front property bordering Humboldt Bay. Additionally, spring tide or MMMW can be used as an indicator of upper marsh edge, or perhaps the transition from salt to brackish marsh. Importantly, use of MMMW as a vulnerability threshold for levee failure is conservative (on the low end; J. Anderson, pers. obs.), whereas use of an extreme high-water event, such as a 10-year or 100-year coastal flood, could breach a levee well before MMMW would. These methods along with reducing the length of highly vulnerable shoreline when replacing eroding dikes by cutting off meander segments may also function to retain and restore marshland habitats and their ecosystem services at the land-water interface. For example, recent habitat restoration efforts at McDaniel Slough were originally designed to enhance freshwater marsh and create a brackish marsh component interior to the current diked system (Pickart 2009).This effort would in theory provide connectivity of habitats using “eco-levees” to create a gradation between salt marsh and mudflat habitats, while enhancing existing estuarian, freshwater, riparian, and upland habitat connectivity as a buffer to SLR.

We believe that all three wildlife areas have the potential for viable restoration to occur that would lead to a more SLR resilient property. However, any decision to restore these areas to salt marsh cannot be made lightly because of infrastructure (HWY 101, Samoa Blvd), private lands, wetland and land use conversion issues, and wildlife-related habitat and species impacts. For example, if the intent is to maintain the “status quo” at each site restoring ERWA to full tidal will require removing the existing man-made levees on the upriver end of the Elk River and constructing new interior “eco levees” or “green dike systems” (i.e., made of natural material natural materials like soil, pebble, gravel in terms of allowable velocity and shear stresses; SRK 2013) along the ERWA east and north property boundary to protect adjacent private property and agricultural lands. Additionally, the same interior levees are going to be needed at FSWA and MRSWA if full tidal restoration is proposed to occur.

Recommendations for Future Adaptive Planning

Because all three wildlife areas are located within high impact zones for SLR, there is a need to develop a proactive land-resource management planning strategy while there is still time to improvise and adapt to future SLR (Sullivan 2013). Without long-term intervention planning over the next half century, as SLR accelerates, marshland habitats surrounding Humboldt Bay may convert to mudflats and subtidal habitats that abut upslope topography to the demise of marshlands and valued wildlife habitats. In the interim, supervisors that oversee management of lands adjacent to Humboldt Bay require SLR data customized and available at a local scale to concisely communicate local SLR scenarios and identify potential impacts to goals and objectives unique to each managed refuge. Protecting coastal access and resources requires developing a sea level rise policy. A proactive approach can help alleviate the need for managers to deal with anticipated lengthy permit, administrative, and economic issues, and extended timeframe scheduling associated with emergency flooding along the North Coast in the foreseeable future. The timeframe identified for future management projects is particularly important for SLR assessments, which may affect timelines for funding, permitting, and the approach taken to assess, implement, and mitigate impacts (Laird 2013, 2015; Sullivan 2013).

In addition to specific infrastructural and natural resources at risk from SLR in combination with other climatic factors (Table 4), adaptive planning for each State wildlife area may involve: 1) risk analyses to assess the level and extent of sensitivity of wildlife area land uses practices, infrastructure, and natural and agricultural resources uses; 2) an economic analysis of specific areas and assets associated with each wildlife area; 3) assessments of the adaptive capacity of CDFW and upper management to respond and cope with the overall and complex effects of SLR, and its economic impacts on regional wildlife areas; and 4) reevaluation and vetting of adaptive management goals, objectives, strategies, and specific actions for confronting and mitigating impacts of SLR on wildlife refuges, including site abandonment (Sullivan 2013; Czech et al. 2014; Nicholls et al. 2018; Nicholls et al. 2021). Our vulnerability assessment provides the initial effort in the process of proactively planning for conservation of natural resources in support of ecosystem processes and retention of biological diversity on State wildlife refuge lands surrounding Humboldt Bay threatened by future SLR.

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Literature Cited

- Akaike, H. 1973. Information theory and an extension of the maximum likelihood principle. Pages 267–281 in B. N. Petrov and F. Csáki, editors. 2nd International Symposium on Information Theory, Tsahkadsor, Armenia, Budapest, USSR.
- Anderson, J. K. 2012. Technical memorandum: estimates of mean monthly maximum water surface elevations in Humboldt Bay, Humboldt County, CA. Northern Hydrology and Engineering, McKinleyville, CA, USA.
- Anderson, J. K. 2015. Humboldt Bay: sea level rise, hydrodynamic modeling and vulnerability mapping. Report prepared for the State Coastal Conservancy and Coastal Ecosystems Institute of Northern California. Northern Hydrology and Engineering, McKinleyville, CA, USA.
- Barbier, E. B., S. D. Hacker, C. Kennedy, E. W. Koch, A. C. Stier, and B. R. Silliman. 2011. The value of estuarine and coastal ecosystem services. Ecological Monographs 81:169–193. **https://doi.org/10.1890/10-1510.1**
- Barnhart, R. A, M. J. Boyd, and J. E. Pequegnat. 1992. The ecology of Humboldt Bay, California: an estuarine profile. U.S. Fish Wildlife Service, Biological Report No. 1 Available from: **https://www.semanticscholar.org/paper/The-Ecology-of-Humboldt-Bay%2C-California%3A-An-ProfileBarnhart-Boyd/03176f3154529d7552204f9b5b43e1da0b473344**
- Burnham, K. P., and D. R. Anderson. 1998. Model Selection and Inference: A Practical Information-Theoretic Approach. Springer-Verlag, New York, NY, USA.
- Cascadia Geosciences (CG). 2013. Tectonic land level changes and their contributions to sea-level rise, Humboldt Bay region, Northern California. Cascadia Geosciences, McKinleyville, CA, USA.
- Clarke, S. H., and G. A. Carver. 1992. Late Holocene tectonics and paleoseismicity, southern Cascadia subduction zone. Science 255:188–192. **https://doi.org/10.1126/science.255.5041.188**
- Colwell, M. A., and E. J. Feucht. 2018. Humboldt Bay, California is more important to spring migrating shorebirds than previously recognized. Wader Study 125:1–7.
- Corder, G. W., and D. I. Foreman. 2014. Nonparametric Statistics: A Step-by-step Approach. John Wiley and Sons, Inc., Hoboken, NJ, USA.
- Curtis, A., C. Freeman, and K. Thorne. 2019. Early results—salt marsh response to changing fine-sediment supply conditions, Humboldt Bay, CA. State and Federal Reports and Publications, Humboldt State University Sea Level Rise Initiative. Available from: **https://digitalcommons.humboldt.edu/cgi/viewcontent.cgi?article=1020&context=hsuslri_state (PDF)**
- Curtis, J. A., L. E. Flint, M. A. Stern, J. Lewis, and R. D. Klein. 2021. Amplified impact of climate change on fine-sediment delivery to a subsiding coast, Humboldt Bay, California. Estuaries and Coasts 44:2173–2193.
- Czech, B. S., S. Covington, T. M. Crimmins, J. E. Ericson, C. Flather, M. Gale, K. Gerst, M. Higgins, M. Kaib, E. Marino, T. Moran, J. Morton, N. Niemuth, H. Peckett, D. Savignano, L. Saperstein, S. Skorupa, E. Wagener, B. Wilen, and B. Wolfe. 2014. Planning for climate change on the national wildlife refuge

system. U.S. Fish and Wildlife Service, National Wildlife Refuge System, Washington, D.C., USA.
- Dare, J. 2005. Coastal Erosion and Armor Database for California, California Coastal Commission, San Francisco, CA, USA.
- Delignette-Muller, M. L., and C. Dutang. 2015. Fitdistrplus: an R package for fitting distributions. Journal of Statistical Software 64:1–34.
- Diankha, O., and M. Thiaw. 2016. Studying the ten years variability of *Octopus vulgaris* in Senegalese waters using generalized additive model (GAM). International Journal of Fisheries and Aquatic Studies 2016:61–67.
- Everitt, B. S., and T. Hothorn. 2011. An introduction to applied multivariate analysis with R. Springer, New York, NY, USA.
- Galbraith, H., R. Jones, R. Park, J. Clough, S. Herrod-Julius, B. Harrington, and G. Page. 2002. Global climate change and sea level rise: potential losses of intertidal habitat for shorebirds. Water birds 25:173–183.
- Griggs, G. 2012. Symposium on Sea-Level Rise in California. Western Governors Alliance on Ocean Health, San Francisco, CA, USA.
- Griggs, G. B., K. B. Patsch, and L. E. Savoy. 2005. Living with the Changing California Coast, University of California Press, Berkeley, CA, USA.
- Hastie, T., and R. Tibshirani. 1990. Generalized additive models. Statistical Science 1:297–301.
- Klein, R. D., and J. K. Anderson. 2012. Declining sediment loads from Redwood Creek and the Klamath River, north coastal California. Proceedings of the Coastal Redwood Forests in a Changing California: A Symposium for Scientists and Managers. USDA Forest Service General Technical Report PSW-GTR-238.
- Komar, P. D., J. C. Allan, and P. Ruggiero. 2011. Sea level variations along the U.S. Pacific Northwest coast: tectonic and climate controls. Journal of Coastal Research 27:808–823.
- Knuuti, K. 2006. Effects of regularly reversing energy gradients on sediment transport in a tidal wetland system. Proceedings of the 8th Federal Interagency Sedimentation Conference, Reno, NV, USA. Available from: **https://pubs.usgs.gov/misc/FISC_1947-2006/pdf/1st-7thFISCs-CD/8thFISC/Session%203B-2_Knuuti.pdf (PDF)**
- Laird, A. 2007. Historical atlas of Humboldt Bay and Eel River Delta. Humboldt Bay Harbor, Recreation and Conservation District, Eureka CA, USA.
- Laird, A. 2013. Humboldt Bay Shoreline Inventory, Mapping, and Sea Level Rise Vulnerability Assessment. Prepared for the State Coastal Conservancy by Trinity Associates, Arcata, CA, USA. Available from: **http://scc.ca.gov/webmaster/ftp/pdf/humboldt-bay-shoreline.pdf (PDF)**
- Laird, A. 2015. Humboldt Bay seal level rise adaptation planning project: phase II report. Trinity Associates, Arcata, CA, USA.
- Leonardi, N., N. K. Ganju, and S. Fagherazzi. 2016. A linear relationship between wave power and erosion determines salt-marsh resilience to violent storms and hurricanes. Proceedings of the National Academy of Sciences 113:64–68. **https://doi.org/10.1073/pnas.1510095112**
- Levin, L., C. Neira, and E. D. Grosholz. 2006. Invasive cordgrass modifies wetland function. Ecology 87(2):419–432. **https://pubmed.ncbi.nlm.nih.gov/16637367/**
- Lester, C. F. 2006. California's coastal hazards: theory and practice. Pages 138–162 in G. Griggs, K. Patsch, and L. Savory, editors. Living with the Changing California Coast. University of California Press, Berkeley, CA, USA.
- Lewis, J. 2013. Salmon Forever's 2013 annual report on suspended sediment, peak flows, and trends in elk river and freshwater creek, Humboldt County, California. State Water Resources Control Board Agreement No. 07-508-551-0. Available from: **https://www.waterboards.ca.gov/northcoast/water_issues/programs/watershed_info/eureka_plain/pdf/RCAA_2013_report_Salmon_Forever.pdf (PDF)**
- Madsen, H., and P. Thyregod. 2011. Introduction to General and Generalized Linear Models. Chapman

and Hall/CRC, Boca Raton, FL, USA.
- McDonald, J. H. 2014. Handbook of Biological Statistics. Sparky House Publishing, Baltimore, MD, USA.
- Mitsch, W. J., and J. G. Gosselink. 2000. The value of wetlands: importance of scale and landscape setting. Ecological Economics 35:25–33. **https://doi.org/10.1016/S0921-8009(00)00165-8**
- Montillet, J. P., T. I. Melbourne, and W. M. Szeliga. 2018. GPS vertical land motion corrections to sea-level rise estimates in the Pacific Northwest. Journal of Geophysical Research, Oceans 123:1196–1212. **https://doi.org/10.1002/2017JC013257**
- Northern Hydrology and Engineering (NHE). 2014a. Estimates of local or relative sea level rise for Humboldt Bay region. Prepared for the California State Coastal
- Conservancy, McKinleyville, CA, USA.
- Northern Hydrology and Engineering (NHE). 2014b. Data release for the Humboldt Bay sea level rise vulnerability assessment: Humboldt Bay sea level rise inundation
- mapping. Prepared for the California State Coastal Conservancy, McKinleyville, CA, USA.
- Northern Hydrology and Engineering (NHE). 2015. Humboldt Bay sea level rise
- hydrodynamic modeling and inundation vulnerability mapping. Prepared for the
- California State Coastal Conservancy, McKinleyville, CA, USA.
- Nicholls, R. J. 2018. Adapting to sea-level rise. Pages 13–29 in Z. Zommers and K. Alverson editors. Resilience: The Science of Adaptation to Climate Change. Elsevier, Cambridge, MA, USA.
- Nicholls, R. J., S. E. Hanson, J. A. Lowe, A. B. A. Slangen, T. Wahl, J. Hinke, and A. J. Long. 2021. Integrating new sea-level scenarios into coastal risk and adaptation assessments: an ongoing process. WIREs Climate Change 12:e706:1–27. **https://doi.org/10.1002/wcc.706**
- National Research Council (NRC). 2012. Sea-level rise for the coasts of California, Oregon, and Washington: past, present, and future. Committee on Sea Level Rise in California, Oregon, and Washington. Board on Earth Sciences and Resources, Ocean Studies Board, Division on Earth and Life Studies, National Research Council, Washington, D.C., USA.
- Nychka, D. 1988. Bayesian confidence intervals for smoothing splines. Journal of the American Statistical Association 83:1134–1143.
- Pestrong, R. 1965. The development of drainage patterns on tidal marshes. Publications in Geological Science 10. Stanford University, Palo Alto, CA, USA.
- Pickart, A. 2001. The distribution of *Spartina densiflora* and two rare salt marsh plants in Humboldt Bay, 1998-1999. U.S. Fish and Wildlife Service, Arcata, CA, USA.
- Pickart, A. 2006. Vegetation of diked herbaceous wetlands of Humboldt Bay National Wildlife Refuge: classification, description, and ecology. U.S. Fish and Wildlife Service, Arcata, CA, USA.
- Pickart, A. 2009. Vegetation monitoring plan for McDaniel Slough estuarine restoration project. Unpublished report, U.S. Fish and Wildlife Service, Arcata, CA, USA.
- Pickart, A. 2021. *Ammophila* invasion ecology and dune restoration on the west coast of North America. Diversity 13:629. **https://www.mdpi.com/1424-2818/13/12/629**
- Powell, B., S. McBain, W. Trush, and A. Laird. 2013. Humboldt Bay shoreline inventory, mapping and sea level rise vulnerability assessment addendum: shoreline vulnerability ratings. Prepared for the State Coastal Conservancy by Trinity Associates, Arcata, CA, USA.
- Roberts, S. G., R. A. Longenecker, M. A. Etterson, C. S. Elphick, B. J. Olsen, W. G. Shriver. 2019 The Condor 121:1–14. **https://doi.org/10.1093/condor/duy024**
- Russell, N., and G. Griggs. 2012. Adapting to sea level rise: a guide for California's coastal communities. For the California Energy Commission Public Interest Environmental Research Program, University of California, Santa Cruz, CA, USA.
- Schlosser, S., and A. Eicher. 2012. Humboldt Bay and Eel River estuary benthic habitat project. California Sea Grant College Program Publication No. T-075, University of California, San Diego, CA, USA.
- Schluter, D. 1988. Estimating the form of natural selection on a quantitative trait. Evolution

42:849–861.
- Schwarz, G. 1978. Estimating the dimension of a model. Annals of Statistics 6:461–464.
- Shepard, C. C., C. M. Crain, and M. W. Beck. 2011. The protective role of coastal marshes: a systematic review and meta-analysis. PLoS ONE 6(11):e27374. **https://doi.org/10.1371/journal.pone.0027374**
- Stephens, M. A. 1979. Test of fit for the logistic distribution based on the empirical distribution function. Biometrika 66:591–5.
- Storlazzi, C. D., and G. B. Griggs. 2000. The influence of El Niño-Southern Oscillation (ENSO) events on the evolution of Central California's shoreline. Geological Society of America Bulletin 112:236–249.
- Sullivan, R. M. 2013. Back to the future: programmatic sea level rise vulnerability assessment with recommendations for Fay Slough, Mad River Slough, and Elk River Slough wildlife areas. Unpublished report prepared for the California Department of Fish and Wildlife, Sacramento, CA, USA.
- Sullivan, R. M. 2014a. Fay Slough Wildlife Area land management Plan. Unpublished report prepared for the California Department of Fish and Wildlife, Sacramento, CA, USA.
- Sullivan, R. M. 2014b. Mad River Slough Wildlife Area land management plan. Unpublished report prepared for the California Department of Fish and Wildlife, Sacramento, CA, USA.
- Sullivan, R. M. 2015. Avian monitoring, resource assessment, and management implications of the McDaniel Slough restoration project, Mad River Slough Wildlife Area land management plan. Unpublished report prepared for the California Department of Fish and Wildlife, Sacramento, CA, USA.
- Swanson K. M., J. Z. Drexler, D. H. Schoellhamer, K. M. Thorne, M. L. Casazza, C. T. Overton, J. C. Callaway, and J. Y. Takekawa. 2013. Wetland accretion rate model of ecosystem resilience (WARMER) and its application to habitat sustainability for endangered species in the San Francisco Estuary. Estuaries and Coasts 37:476–492. **https://doi.org/10.1007/s12237-013-9694-0**
- Takekawa, J. Y., K. M. Thorne, K. J. Buffington, C. M. Freeman, K. W. Powelson, and G. Block. 2013. Assessing marsh response from sea-level rise applying local site conditions: Humboldt Bay National Wildlife Refuge. Unpublished data summary report. U.S. Geological Survey, Western Ecological Research Center, Vallejo, CA, USA.
- Thorne, K. M., G. MacDonald, G. Guntenspergen, R. Ambrose, K. Buffington, B. Dugger, C. Freeman, C. Janousek, L. Brown, J. Rosencranz, J. Holmquist, J. Smol, K. Hargan, and J. Takekawa. 2018. U.S. Pacific coastal wetland resilience and vulnerability to sea-level rise. Science Advances 4(2). **https://doi.org/10.1126/sciadv.aao3270**
- Thorne, K. M., K. A. Spragens, K. J. Buffington, J. A. Rosencranz, and J. Takekawa. 2019. Flooding regimes increase avian predation on wildlife prey in tidal marsh ecosystems. Ecology and Evolution 9:1083–1094.
- Tsiatis, A. A. 2006. Semiparametric theory and missing data. Springer Series in Statistics. Springer, New York, NY, USA.
- Valentine, D. W., E. A. Keller, G. Carver, W. H. Li, C. Manhart, and A. R. Simms. 2012. Paleoseismicity of the southern end of the Cascadia subduction zone, northwestern California. Bulletin of the Seismological Society of America 102:1059–1078. **https://doi.org/10.1785/0120110103**
- Van Kirk, S. 2007. Fay Slough tributaries enhancement project historic resources report. Redwood Community Action Agency, Eureka, CA, USA.
- Wood, S. N. 2017. Generalized Additive Models: An Introduction with R. 2nd edition. Chapman and Hall/CRC Press, Boca Raton, FL, USA.