KACHEMAK BAY RESEARCH RESERVE AND THE UNIVERSITY OF ALASKA, FAIRBANKS

Assessing Coastal Uplift and Habitat Changes in a Glacially Influenced Estuary System: Kachemak Bay, Alaska

Relative Sea-level Rise

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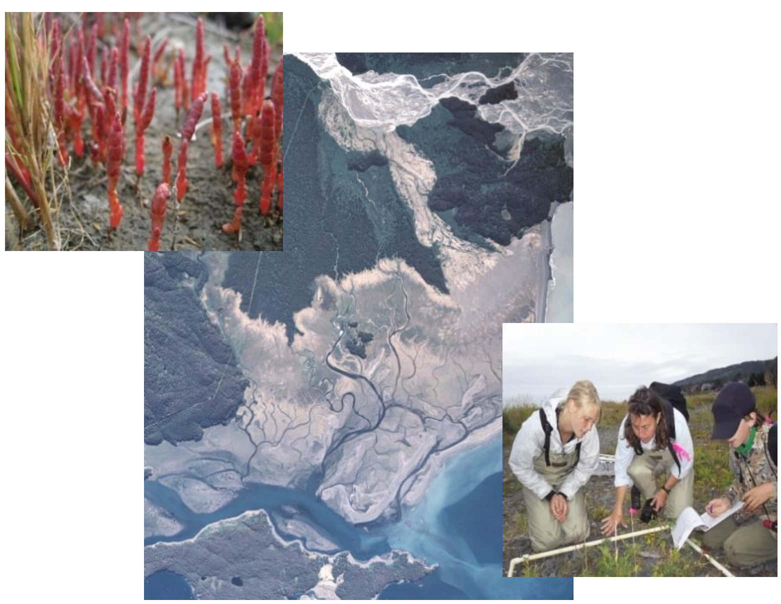

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Executive Summary

Coastal communities surrounding Kachemak Bay, Alaska depend on near-shore fisheries for food and safe harbor infrastructure for transportation. Climate change impacts to the coastal communities surrounding the Kachemak Bay Research Reserve (Reserve) will involve complex interactions among diverse processes such as: changes in sea level, shifts in salt marsh extent and plant community structure, shoreline erosion, sedimentation, water quality, and uplift or subsidence of the land. In 2009, local residents noticed “more land showing at low tides” in the Bay. Local observations, in addition to relevant news articles on isostatic rebound from melting glaciers, led the community to approach the Reserve and ask for help to understand what was happening in the Bay.

The community requested information on how changes in land and sea-level will affect coastal habitat, harbor and other infrastructure, and local food resources. The central research question to be answered was distilled to: what is the rate of relative sea -level change for this region? Finding an answer to this question would help interpret related questions on coastal processes in the region. The scientific approach aimed to provide accurate vertical land level rates of change due to tectonic and isostatic adjustment over a meaningful time frame for the end-users of the information. The scientific approach also laid the ground work necessary to monitor biological changes in salt marsh habitats over time. An overarching goal of the study was to facilitate the integration of science into coastal decision-making processes. In this study, we refined relative sea-level rise predictions, initiated a monitoring framework for salt marsh habitat in Kachemak Bay, and used multiple methods of communicating these results and information on coastal processes to decision-makers and the community.

In our region, coastal uplift is due to three main factors: after-effects from the 1964 earthquake, the steady buildup of strain for the next big earthquake (strain accumulation), and rapid melting of heavy ice contained in local glaciers and ice fields (isostatic re-adjustment). During 2011-2013, we updated existing models of vertical and horizontal land-level changes in the Kachemak Bay area with data from this study. In the analysis of vertical land movements, we found that the longer time series data ($\geq$10years) suggest a fairly uniform uplift rate around Kachemak Bay independent of the substrate type. By utilizing data from monitoring sites with $\geq$ 10yrs of data, the average coastal uplift rate was 8.6mm/year (+/-0.5mm) or 0.34in/year for Kachemak Bay with the exception of the Homer Spit. This study indicates that the Homer Spit, a geographical feature in Kachemak Bay with economic relevance, is uplifting significantly less (at 5.6 mm/year or 0.22in/year) than other areas of similar substrate around Homer. This is important because the Homer Spit will have a different trajectory relative to global sea level rise than the surrounding landscape. Having established these rates of vertical land level change, we can map relative sea level changes for the region. We utilized published global sea level rise estimates of 3.2mm/year (0.13in/year) for the study. In collaboration with our coastal decision-makers, we elected to project out to 20 years into the future which will reduce uncertainty in the relative sea level rise estimates.

Vegetation community structure in salt marsh habitats range from freshwater to salt-tolerant plants and the long-term mapping of vegetation cover types can provide a site-specific indicator of sea-level rise. When paired with the GPS and digital elevation data, mapped vegetation plant communities provide valuable information on relative shifts in sea-level rise and land-level change over time. During 2010-2013, we established four long-term monitoring salt marsh sites, Beluga Slough, Fox River Flats, China Poot Bay, and Sadie Cove in Kachemak Bay. At each site, systematic monitoring of emergent vegetation, marsh elevation relative to vertically stable benchmarks, water elevation and soil temperature monitoring were established. We created a baseline for the biological diversity utilizing methods similar to the National Geographic Bioblitz; using trained members of the community to participate in data collection. This resulted in an additional 576 vegetation plots sampled to refine vegetation cover types determined from the systematic sampling and provided updated plant and animal (bird, mammal, fish, and infaunal invertebrate, and insect) lists unique to each site. Using existing aerial photography and data collected in this study, we assessed directional shifts in marsh vegetation relative to historical aerial-based photography. All sites have photographs pre and post subsidence from the 1964 earthquake; these can provide insight into salt marsh migration for future changes in our region.

During 2011-2013, we developed several communication strategies for information from this study on relative sea-level change and about coastal processes. Communication methods included NERRS Coastal Training Program workshops, educational *Discovery Labs*, radio, newspaper, and newsletter stories, and presentations at science conferences. During 2011-2013, we conducted 12 public *Discovery* Labs (*Our Landscape Over Time / Salt Marsh Plants & Wildlife* / *Citizen Science*), reaching a total of 974 people of all ages from Alaska and internationally. We taught the *Our Landscape Over Time* to 26 school groups and overall worked with 641 students and their teachers. We also reached out to some of the smaller coastal communities and were able to host 40 students from Kenai and the Russian Old Believer community of Kachemak Selo.

An active, participatory approach was used in this study to support community dialogue and enhance the use of science in coastal decision-making. Coastal decision-makers in the community had agreed to participate through the life of the study; we termed this group the Core Intended Users (CIU). We met with the CIU group quarterly and employed a collaborative learning model approach to our meetings. During 2010-2013, 11 CIU meetings were held. Collectively, we benefited from the collaborative learning approach by having established a clear and tangible process at the beginning of the study, which alleviated potential conflicts within the group. The method provided a new and valuable way of working together and created a shared understanding and appreciation for scientific and management processes and their respective strengths and limitations. Through the collaborative process, we developed tangible feedback loops to refine and reformulate information needs which lead to the identification of data gaps and ideas about fulfilling them.

Project Introduction

Climate change impacts to the coastal communities in Kachemak Bay will involve complex interactions among several diverse processes such as: changes in sea level, shifts in salt marsh extent and community structure, shoreline erosion, sedimentation, water quality, and isostatic and geostatic rebound. In 2009, local residents noticed "more land showing at low tides" in the Bay. Local observations coupled with recent articles from SE Alaska on isostatic rebound from melting glaciers, led the community to approach the Reserve for help to identify and understand relevant processes that may impact the community. We employed participatory approach to maintain continued community dialogue and to create opportunity for community members to have input to the study as it progressed so that the results were presented in useful formats that will aid in decision making.

Like much of coastal Alaska, glaciers on the Kenai Peninsula are melting at a fairly rapid rate. The weight released from the earth's surface as glaciers retreat has caused significant isostatic rebound or uplift in some areas in Alaska (Larsen et al. 2005). In our region, coastal uplift also is due to after-effects from the 1964 earthquake and the steady buildup of strain for the next big earthquake (strain accumulation). The waters in Kachemak Bay are fed by 14 glaciers from the Grewingk/Yalik glacier complex and the Harding Ice field on the Kenai Peninsula. The increased melt water is rich in nutrients and sediments which influence the community ecology in the Bay (Kachemak Bay Ecological Characterization 2001). Coastal Alaska is also prone to earthquakes and active volcanoes, and this active tectonic environment produces significant vertical motions of the earth's surface due to these deep-seated processes. A total of ~60cm (24 inches) of uplift occurred near Homer in the first 35-40 years after the Great Alaska earthquake in 1964, based on repeated measurements of leveling benchmarks (Cohen and Freymueller, 2004) and tide gauge measurements at Seldovia and Nikiski (Larsen et al., 2003). The measured uplift results from a combination of geophysical processes, including a substantial component of postseismic uplift following the earthquake (Freymueller et al. 2008; Suito and Freymueller, 2009). Much of the infrastructure for the Kenai Peninsula Borough (inclusive of Kachemak Bay) is not built on bedrock but rather a range of compacted substrate types. We explored how well the geophysical models for land level changes functioned for differing substrate types (bedrock versus consolidated sediments and salt marsh sediments).

Models developed to assess ecological changes to relative sea level rise, such as the Sea-Level Affecting Marshes Model (SLAMM), require vertical elevation data, land cover maps, marsh accretions measurements, and tidal datum (Clough 2010). In Alaska, these data are not available or are available with lower precision than is needed for coastal communities to plan with and to be meaningful for studies of salt marsh ecology. In this study, we developed an extensive monitoring network of vertically stable benchmarks monitored with high-precision Global Positioning System units and Continuously Operating Reverence Stations (CORS) to obtain regional data on land level movements in Kachemak Bay. These data were used to evaluate models of tectonic deformation and ice loss or isostatic adjustment for this region. Specifically, we set out to evaluate patterns of vertical land motion from these models based on location and substrate type and to evaluate relative sea-level change for the region. We paired the vertical land level change model projections with intensive baseline monitoring of four salt marshes in Kachemak Bay to provide a base for understanding and predicting changes from glacier loss or other environmental perturbations to the local community ecology (Fig 1).

In this study, we recognize there are many complex coastal processes that are relevant to coastal decision-making in the local community (City of Homer 2007; Baird 2009). We approached the problem by addressing the question of relative sea-level rise and how that is predicted to change in this region over time.

Glossary of key geophysical terms

Term	**Definition**
CORS	Continuously Operating Reference Station. These instruments record GPS date continuously, either on a data card or over the internet. These data can provide very precise daily estimates of horizontal and vertical positioning.
Static GPS	Static GPS surveys use high precision Global Positioning System receivers used to collect data for daily average positions of benchmarks. This contrasts with kinematic GPS surveys, which use the same equipment but are processed to provide positions continuously, for example for moving receivers.
NGS geodetic	National Geodetic Survey is a branch of the National Oceans and Atmospheric Administration that provides official and legally authoritative 3D positions for benchmarks and CORS stations. This also requires monitoring or modeling the motions of these points.
Benchmark	A benchmark is a survey marker that can be temporary or permanently placed to record the point for which the position is known. Most permanent benchmarks use a small survey disk or a rod or pin with a punchmark to indicate the exact location of the measurement. To collect data on the vertical and horizontal position, the benchmark must be established to be stable in both of those positions for the measurements to be accurate.

Subsidence	Subsidence indicates the sinking or lowering of the earth's crust (or surgical layers), which can result from a variety of processes ranging from sediment compaction to deep-seated crustal movements. GPS measures positions relative to the center of mass of the earth, so rates of uplift or subsidence are measured relative to the center of the earth. Because the ellipsoid is fixed relative to the center of the earth, uplift or subsidence rate measured by GPS are also changes in ellipsoid height. The geoid can change due to changes in mass, so changes in geoid height may differ from changes in ellipsoid height.
Isostatic rebound	More accurately stated as isostatic adjustment of the earth when the weight is changed. In most cases, this term is used for glacial loads, which are being reduced as glaciers lose mass. There are short and long wave effects from this process.

Land-level Projections

Introduction:

In our region, coastal uplift is due to after-effects from the 1964 earthquake, the steady buildup of strain for the next big earthquake (strain accumulation), and rapid melting of heavy ice contained in local glaciers and ice fields (isostatic adjustment). We measured vertical motion of the land using repeated, precise GPS surveys. These included repeated surveys of pre-existing GPS survey points, surveys of new benchmarks, and new Continuously Operating Reference Sites (CORS) that make daily position measurements. Rates of uplift or subsidence were measured from the time series of GPS position estimates. These rates were then compared to geophysical model predictions to determine causal factors of change. Relative sea level, such as that measured by a tide gauge, is the difference between (absolute) sea level and land level. Thus the land level changes measured by GPS, sea surface height changes measured by satellite altimetry, and tide gauge measurements should all be consistent.

Methods:

During this study, we established 15 new benchmark sites at four salt marsh study sites (Beluga Slough, Sadie Cove, China Poot, and Fox River Flats) in Kachemak Bay. Of these benchmarks, 12 were in salt marsh sediment substrates and 3 in bedrock adjacent to the salt marsh benchmarks. We repeated surveys of all pre-existing benchmarks previously measured by the University of Alaska, Fairbanks (UAF) around Kachemak Bay (seven sites), and we added three benchmarks that had been first surveyed during the 2009 “Hydropalooza” bathymetric mapping effort. Our plan was to use the Hydropalooza measurements to gain a long enough time span of data to compute precise velocities; unfortunately, we later found out that NOAA had discarded the original GPS data from that survey, so only the measurements we made for this project could be used. This makes the precision of the data from these benchmarks comparable to that of the salt marsh sites. We used data from the static GPS campaigns and the CORS sites to analyze site velocity estimations and evaluate existing models of land-level changes (Freymueller *et al*. 2008).

During the first and second years of the project, we established five new CORS in the region. Four used Trimble Net-RS and Net-R9 GPS receivers with Zephyr Geodetic or Zephyr GNSS antennas, and one used a Javad Sigma receiver and Javad choke ring antenna. These sites were established with the cooperation of the City of Homer, the local elementary school, and private landowners. These CORS sites provided a measure of vertical land-level change for compacted sediments in contrast to the existing bedrock sites in the region. The Peterson Bay location is the exception as it is situated on bedrock, and filled a data gap on the south side of Kachemak Bay. Data from the CORS sites are publically available on the web, and all data have been archived at the UNAVCO archive (http://www.unavco.org).

We established a minimum of three vertically stable benchmarks in each of the salt marsh study sites (Beluga Slough, China Poot, Fox River Flats, and Sadie Cove) and new bedrock monuments in two of the four sites (China Poot and Sadie Cove). These benchmarks were used to create an elevation network for the vegetation monitoring by surveying ground-surface elevations relative to permanent benchmarks. Newly established benchmarks were placed in the supratidal fringe of each salt marsh study locations to begin a time series of measurements in the salt marsh habitats. We established benchmarks utilizing National Geodetic Survey (NGS) guidelines (Smith 2007) by driving 9/16” stainless steel rods to the point of refusal. A gas-powered driver was used to drive the rods into the ground in 4’ sections. Near the surface, the end of the rod was encased in a grease-filled sleeve, which was within a 6” plastic pipe with the space between filled with sand. We then poured concrete into an area around the plastic pipe and placed hinged access covers on the benchmarks. New bedrock benchmarks were established in proximity to the marsh sediment benchmarks by drilling holes into bedrock and epoxying 5” long 0.5” diameter stainless steel pins into the holes.

During 2010-13, we made a series of static 2-3 day GPS measurements to determine rates of coastal uplift in our study area (Fig. 2), using a mixture of new and pre-existing (NGS geodetic and tidal benchmarks) measurement benchmarks. We monitored most benchmarks in the study area annually and the benchmarks in (or associated with) salt marsh locations biannually. Most sites were surveyed using Trimble 5700 GPS receivers and Trimble Zephyr Geodetic antennas (owned by UAF) mounted on tripods or spike mounts, with the exception of the marsh sites. Those sites were surveyed almost exclusively with Sokkia GRX1 receiver units (owned by the Reserve) mounted on fixed-height poles. The tripods and spike mounts used with the Trimble 5700 GPS receivers should be capable of achieving 1mm or better accuracy in the antenna setup. However, while the vertical accuracy for the fixed height poles is equivalent to the tripods and spike mounts, the horizontal position measured is less accurate, depending on the accuracy of the level bubble used.

There were two primary types of models considered when assessing land-level changes for the study area: i) regional tectonic uplift including postseismic effects and ii) isostatic uplift caused by loss of glacier ice, based on the latest ice mass loss estimates. Modeling methods followed those described in Larsen *et al.* (2005) and Freymueller *et al*. (2008). The models we used provided land-level change contours (based on static GPS measurements and CORS sites data) to provide a higher-level of precision than existing predictions for the region.

Regional sea surface changes were estimated from the rate of global sea-level rise published in the latest Intergovernmental Panel on Climate Change (2013) report, corrected for the change in the sea surface shape caused by the local area ice loss. The changes in sea surface shape results from the small changes in gravity caused by removing mass from the local glaciers and icefields and, when distributing that mass around the world’s oceans, and it can be predicted from the same models that predict isostatic uplift. We cross-checked our measurements using the rate of relative sea level change measured by the Seldovia tide gauge and the regional rate of sea surface rise estimated by satellite altimetry.

GPS data were analyzed following the approach described in Fu et al. (2012). All GPS data for a given day (0-2400 hours, defined by UTC time) were consolidated and analyzed together, producing a set of site coordinates in the ITRF2008 reference frame. Details of the GPS analysis are not given here, but are described in full in Fu et al. (2012). The analysis accounts for sub-daily motions due to solid earth tides and ocean tidal loading, and path delays due to atmospheric refraction of the GPS signals. Given a full 24 hours of data, the typical formal uncertainty for the position is approximately 1 mm for each horizontal component and 3 mm for the vertical. These uncertainties are known to be too small, based on the observed measurement scatter. Based on past experience, these values need to be multiplied by a factor of 2.2 (square root of 5) to reflect short-term scatter of the measurements.

We estimated uplift or subsidence rates using a model for the station positions as a function of time that included linear terms (position at a reference time plus velocity), and for the CORS sites we estimated periodic (annual and semi-annual) terms to account for seasonal surface loading. For the sites surveyed only a few times each year, we applied seasonal terms determined from a surface loading model based on data from Gravity Recovery and Climate Experiment (GRACE) satellites. Parameter values were estimated using a standard weighted least squares fit, and parameter uncertainties were determined by scaling the covariance matrix (for each benchmark site) by a variance factor so that the reduced chi square statistic was equal to zero. For most sites, this variance factor was close to 1.0 after the initial scaling of the formal errors described above. In addition, errors in GPS positions show correlations in time, which means that especially for the CORS sites we must apply additional analysis to determine a reliable estimate of the uncertainty. Based on the extensive analysis of Sanatamaría-Gómez et al. (2012), we add in quadrature an additional uncertainty of (1 mm/T) for the horizontal components and (3 mm/T) for the vertical components of the trend, where T is the total duration of the observations at the site in years. We also add a correction to all velocities for motion of the ITRF frame relative to the geocenter (~1 mm/yr, Argus et al., 2010), and include the uncertainty in this estimate.

Taking the data noise and all of the uncertainty factors mentioned above into account, we can give some general statements about the precision of the vertical land level change rates for different sites. For sites with long measurement histories (10-15 years of campaign measurements), uplift rate uncertainties are typically 0.5-1.0 mm/year. Regional CORS sites with >6 years of continuous measurements (sites from the Plate Boundary Observatory) have similar uncertainties, typically 0.5-0.6 mm/year. In contrast, the CORS sites set up for this project have uncertainties of 1.0-1.5 mm/year due to their shorter time span of measurements, and uncertainties for the marsh sites still exceed 2.5 mm/year.

Results

During 2011-2013, we updated existing models of vertical and horizontal land-level changes in the Kachemak Bay area with data from this study. In the analysis of vertical land movements, we found that the longer time series data (≥10years) suggest a fairly uniform uplift rate around Kachemak Bay independent of the substrate type. By utilizing data from monitoring sites with ≥ 10yrs of data, the average coastal uplift rate was 8.6mm/year (+/-0.5mm) or 0.34in/year for Kachemak Bay (Fig.2) with the exception of the Homer Spit. This study indicates that the Homer Spit, a geographical feature in Kachemak Bay with economic relevance, is uplifting significantly less (at 5.6 mm/year or 0.22in/year) than other areas of similar substrate around Homer. This is important because the Homer Spit will have a different trajectory relative to global sea level rise than the surrounding landscape. Having established these rates of vertical land level change, we can map relative sea level changes for the region. We utilized published global sea level rise estimates of 3.2mm/year (0.13in/year) for the study (IPCC 2013; Fig. 3). In collaboration with our coastal decision-makers, we elected to project out to 20 years into the future which will reduce uncertainty in the relative sea level rise estimates.

There was an unexpected side benefit of one of the CORS sites. The site at Peterson Bay (PBAY) is located on a small rock that is an island at high tide, but connected to the mainland by a spit at low tide (Fig. 4). Thus it is nearly surrounded by water. We provided the data from PBAY to Dr. Kristine Larson of the University of Colorado, who analyzed the GPS receiver's recorded signal to noise ratio for variations in multipath, which is the effect of interference of reflected signals that are received in addition to the direct signal from the satellite. Because the PBAY antenna is mostly surrounded by water, the dominant reflector is the sea surface. The frequency of the multipath variations depends on the height of the antenna about the reflector, which makes the PBAY site an effective tide gauge (Fig. 5). Over the course of one year, the root-mean-square (RMS) difference between tide levels determined by the PBAY GPS site and tide levels measured at the Seldovia tide gauge was only 2.3 cm (Larson et al., 2013).

Salt Marsh Monitoring

Introduction

Kachemak Bay, within the Kachemak Bay National Estuarine Research Reserve (Reserve), hosts diverse watersheds and marine habitats. Marine waters in Kachemak Bay range from depths over 160 meters (525 ft) to shallow tidal flats, of which there are 15 major and several minor tidal marshes. The fresh water inputs (ground and surface water, snow melt, and glacier melt water) to these marshes vary by location; several marshes have glacial melt water input during the late summer and early fall months. The tidal marshes of Kachemak Bay are highly productive, and provide important habitat for a wide range of species, including juvenile salmon and other fish, shorebirds, waterfowl, moose, and bears (Kachemak Bay Ecological Characterization, 2001).

A baseline monitoring framework of salt marshes is important to detect changes in plant community composition and species distributions over time. Such information, in combination with other ongoing studies in these marshes, will allow us to begin investigating the relationships between plant communities and fish, bird, and mammal use of the marshes relative to environmental changes. In this report, we present species diversity information for emergent vegetation, fishes, insects, birds, and mammals in four salt marshes sampled in the study area.

Site Description

To assess changes in vegetation as an indicator of sea-level change, we established a vertical control network and permanent vegetation plots within four salt marsh sites in Kachemak Bay. The salt marsh sites were selected based on their accessibility and sources of fresh water input, which extend across a gradient of no glacier melt water input to seasonally high contributions (Table 1). During 2010-2013 at each of these sites, we systematically monitored emergent plant vegetation, soil temperatures, water level, and created elevation profiles annually.

Methods

Vegetation Monitoring: Vegetation sampling methods followed the NERRS protocols (Moore 2009, Roman *et al.* 2001, and Jorgenson 2009). To monitor emergent saltmarsh vegetation we established transects from high to low marsh and placed permanent vegetation plots along those transects. The sampling design was developed using ArcGIS (ESRI), by placing parallel transects over each marsh land layer; the initial transect was haphazardly placed near one end of each marsh and the remaining transects were uniformly spaced across the marsh. We then used a stratified random sampling method to select transects for monitoring from each location. The initial vegetation plot along each transect was placed randomly at the lowest end of the marsh and the remaining plots were spaced evenly along the transect until the uppermost portion of the marsh was attained; vegetation plots that were located in open water were omitted. We drove a wooden stake into the ground to mark the location of each vegetation monitoring plot along a transect. We used a one-meter square quadrat (constructed of ABS plastic pipe) to vertically displace each plot one-meter from the transect. Plots were marked at diagonally opposite corners with 18" lengths of ½-inch rebar. The rebar was driven into the ground so that approximately 1" remained visible. We recorded a GPS waypoint over the center of each 1x1m vegetation plot. To assess plant diversity at each site, we collected the following data: an estimate of percent cover by species, stem densities, and maximum canopy height (the latter two were a subsample of the upper left corner of the plot). At each sampling event, we collected digital photos that were archived with the data. We also monitored the physical characteristics of the salt marshes relative to plant diversity. At each salt marsh location, we deployed the following instruments: two water level loggers (high and low marsh), one barometric logger (uplands immediately adjacent to the marsh), 12 soil temperature loggers (six high and six low marsh) and a minimum of three benchmarks. To develop a network of elevation monitoring, we surveyed annually ground-surface elevations of all vegetation plot markers and water level loggers relative to permanent benchmarks at our sites (Jorgenson 2009). To assess salt marsh migration, we used existing aerial photography and data collected in this study to validate recent salt marsh plant community maps. Future directional shifts in marsh vegetation cover types can be assessed relative to this historical aerial-based photography.

Biomonitoring: Each of the salt marsh study sites were extensively sampled one time during the course of the study by trained community monitors and KBNERR staff with methods patterned after the National Geographic Bioblitz (http://education.nationalgeographic.com/education/program/bioblitz/) community monitoring program. All personnel collecting data completed a two-day training on the study methods (see Education and Outreach Section). Sampling methods at all salt marsh sites followed the same sampling scheme described herein. At each salt marsh, we randomly selected six of the long-term monitoring transects using ARC GIS, and placed a 100mx100m plot at the high and low marsh end of the transect. Within each of the 100mx100m plots, we randomly placed 12- 1x1m vegetation plots where plant composition and percent cover data was collected. For each transect we sampled: insects, infaunal invertebrates, bird, and mammals sightings in the upper and lower marsh. Fish were sampled in the fall during 2011 and 2012 at each salt marsh location by Reserve staff following the sampling methods listed below.

Insect Fall Out Traps (FOT's): During each sampling effort, fallout traps were set at high and low marsh plots. The fallout trap apparatus consisted of a clear plastic tub (approximately 26.5L total capacity, 58.4 x 40.6 x 15.2cm), bordered by four guide poles (approximately 2.5cm diameter, 1.5m tall) which kept the tub in place while allowing it to rise and fall with the tide level. The tub was loosely secured to one of the PVC poles with a monofilament loop which was attached to the tub through a hole drilled in one end. On uneven ground, a stand was set in the ground (under the tub) to provide a level surface for the tub to set down on at lower tide levels. A quarter-sized portion of soap was placed in the bottom of the tub before filling it approximately one-quarter full with water. The trap was left to sample for 2 tidal cycles (approximately 24 hours). The insect sample was collected by sieving the water in the tub through a 106μm sieve, washing sieve contents into a sample jar with a garden sprayer and funnel, and then fixed in 70% Ethyl alcohol (50-70% concentration was approximated by adding 100% alcohol to the water already in the jar with the sample).

Insect Sweeps: One side of the 100x100m plot was selected haphazardly, from which the person collecting the sample took 25 (approximately 1m) paces, sweeping the net from side to side. Insects residing within the upper portion of the vegetation were swept into the net. The net was a heavy duty sweep net made from rugged sail cloth with a 2ft handle and 15in diameter hoop. Insects were shaken down to the bottom of the net, and the net then inverted into a large-mouthed jar. Insects were anesthetized with a small amount of fingernail polish soaked into a cotton swab.

Benthic Core samples: Macroinfauna consisted of a wide variety of invertebrate organisms that could be retained on a 0.5 mm screen. To sample macroinfauna, we used a hand-coring device, which was 10cm in diameter cylinder with a small hole on top. The corer was set in the sediment (in a vertical position) to a depth of 15 cm. The core contents were then placed in a large plastic bag, labeled, and refrigerated until sieving. We sieved the core samples using a 0.5 mm screen and preserved samples in buffered formalin for later species identification. Macroinfauna were placed in a jar and labelled with station location, sample number, and collection date.

Fish: We used a beach seine to conduct comparative instantaneous ("grab") samples of fish in the channel habitats by using multiple pass seines in 50m blocked sampling units of the upper and lower marsh habitats. Captured fish were enumerated and measured at each salt marsh site. We also tried a modified nylon mesh (0.6 cm) fyke net deployed across a discrete tide channel at high, slack tide (at Beluga Slough and China Poot sites in 2011). Pole seining was used to “herd” residual fish into the trap where marsh channels failed to dewater completely at low tide.

All fish captured were identified to species (where feasible), enumerated and, for juvenile salmon, measured the fork length (to the nearest 1.0 mm). Captured fish were placed in buckets and shaded from the sun. Battery- powered aerators and frequent water changes were employed for aeration to minimize stress to the fish. Fish were held no longer than 1 hour and water temperature was monitored throughout the sampling period. We anesthetized juvenile salmon in a 70-ppm solution of MS-222 to the point where handling was feasible (Walker *et al.* 2013). After measurements were complete the anesthetized fish was placed in a bucket of fresh (anesthesia-free) water for recovery. We released all captured fish at the site of capture.

To better describe fish distribution and relative abundance across study sites, we modified sampling methods in 2012. We restricted sampling to two 50m reaches, one each at upper and lower marsh (defined by vegetation cover types) for each salt marsh site. In the field, we blocked at the upper and lower ends with nets and used pole seining methods to take three passes of the channel and collected fish from pass. To account for annual variability among sites, we sampled all sites in August of 2012. We collected basic physical habitat data such as conductivity, salinity, temperature, channel depth and a physical description of the habitat. Where feasible, we sampled for fish in streams that had water level loggers (upper and lower marsh) throughout the summer months.

Bird and Mammal Sightings: In August of 2011 and 2012, bird and mammal sightings were recorded opportunistically during the course of the sample structure set up in the community monitoring methods. On a separated data sheet, each sampling team recorded bird and mammal species identified, a description of the sighting and behavior (tracks, scat, flying, vocalization only, number seen) and the location the sighting was made relative to the sampling plot(s). We used this information to develop species lists for each salt marsh surveyed but did not try to estimate relative abundance among salt marshes in the study.

Biomonitoring Results and Discussion

Water level and soil temp loggers: During 2011-2013, we had water level loggers at each marsh. We linked the location of each water level logger to our vertical control network through high-precision leveling. We were able to accurately calculate frequency and duration of inundation by tides at all vegetation plots. Very tight correlations ($R^2 \geq 0.99$)

between high tides recorded at our loggers and high tides at Seldovia tide gauge allow us to relate our measured elevations (for plots and benchmarks) to tidal heights (Fig. 6). Mean higher high water (MHHW) was near 4 meters orthometric height in NAVD88 in all marshes.   This corresponds very well with a recent FEMA Flood Insurance Study for the City of Homer (FEMA 2013), which reported mean lower low water (MLLW) to be equivalent to -4.90 feet (-1.49 m) in NAVD88. Using the 5.49 m observed difference between MLLW and MHHW at the Seldovia tide gauge, this would make MHHW in the FEMA study equivalent to 4.009 m (-1.490 + 5.499). The calculated NAVD88 equivalents to MHHW in our study range from 3.891 m to 4.171 m.

Soil temperature very likely influences salt marsh plant growth, as well as habitat suitability for infaunal invertebrates, insects, and fish. During 20011-2013, we measured soil temperatures at all four marshes (see methods). Averaging the temperature data from all loggers within a marsh and all years, it can be seen (Fig.7) that average soil temperatures were relatively similar between marshes, with the exception of Sadie Cove, which had soil temperatures nearly 3 degrees C cooler than the other marshes for most of the summer. In the fall, as air temperatures dropped, soil temperatures at Sadie Cove converged with those of the other marshes. Beluga Slough soil temperatures were somewhat cooler than those at Fox River and China Poot in the spring, but those three marshes had very similar soil temperatures from July onward.

Air temperature was recorded at all marshes by our barometric pressure loggers. Air temperature varied only slightly between marshes, with the main difference being that Sadie Cove experienced cold periods throughout the summer, where daily averages were colder than the other three marshes (as an example, Fig. 8 shows air temperature at all marshes in 2011).

Water temperature was recorded by our water-level loggers. Average daily water temperatures at the loggers in the lower part of each marsh show great differences between the four marshes in summer, with Sadie Cove having considerably colder temperatures than the other marshes. Figure 9 shows average daily water temperatures in 2011 at all four marshes, along with average daily sea-water temperatures at the Reserve’s water quality monitoring stations (at the end of the Homer Spit and at the Seldovia ferry dock). The differences in water temperature need to be interpreted with caution, however, since the loggers were placed in flowing streams in Sadie Cove and China Poot, while they were placed in dead-end tidal guts at Fox River Flats and Beluga Slough. Thus, while all loggers were likely measuring water temps from the Bay at high tides, the loggers at Beluga Slough and Fox River were measuring residual bay water in the tidal guts at low tide. Figures 10 and 11 show the relationship between water level and water temperature at Sadie Cove and Fox River (respectively) over a ten-day period in July, 2011 (as an example).

The placement of our soil temperature loggers (6 high and 6 low at each marsh), allowed us to look at soil temperature differences within each marsh from early spring to late fall. The average daily temperatures at China Poot and Sadie Cove varied very little between high marsh and low marsh. However, at Beluga Slough loggers in the low marsh showed warmer temperatures than those in the upper marsh (Fig. 12). The pattern at Beluga Slough was reversed at Fox River Flats, where high marsh was warmer than low marsh (Fig. 13). This pattern at Fox River may be partially explained by the fact that the low marsh is more frequently covered by cold glacial water than is the upper marsh. Water temperatures were lower at the low marsh logger than at the high marsh logger at Fox River Flats (Fig. 14), where there was little or no difference in water temperatures between high marsh and low marsh at the other marshes.

Leveling: During 2011-2013, we were able to obtain precise elevation measurements for 255 of 269 vegetation plots (see methods). Plots were placed from high marsh (with a few plots in freshwater fringing marsh) to the lowest extent of vascular vegetation. Most of the plots with salt-tolerant vegetation occurred in the same elevation zone in all the marshes (3.5 to 5.0 meters in NAVD88 orthometric heights). However, vegetated plots occurred at elevations up to a meter lower in the two south-side marshes than in the north-side marshes (Fig. 15).

At each marsh, repeated elevation measurements were made each year at a subset of the plots. These generally showed little difference from year to year. However, differences of up to 9 cm were seen at some plots. As an example, the elevation data for plots along transect 5 in Fox River Flats are shown in Figure 16. The variation at plot FR45 (approximately 7 cm between 2011 and 2012-2013), makes sense given our observations at this plot. When this plot was established in 2010 (in a tidal gut), and again in 2011, the plot corner markers were extending several cm above the marsh surface. However, in both 2012 and 2013, these same markers were buried under several cm of accumulated silt.

Emergent Salt Marsh Vegetation: Plant community maps were created for the marshes included in this study in 2004, using base imagery from 1996 and field work from 2003 and 2004 (Reserve unpublished data). Mapping was done following methods used mapping several marshes in Lake Clark National Park (Tande 1996). The imagery used in that mapping effort was monochrome and lower resolution than imagery that is currently available. The fieldwork (and number of vegetation plots) was also less extensive in each marsh in the earlier mapping effort.

The plant community maps created for this project (see Appendix A) are based on well-rectified high-resolution color imagery, and should allow us to detect significant marsh migration using future mapping efforts, assuming the availability of similar imagery. Key features to track will be upper limit of salt-tolerant vegetation communities, and high-marsh to low-marsh transitions.

We used data from our vegetation plots to calculate importance values for each plant species in each marsh. Importance values incorporate both frequency of occurrence and percent cover for each species, and were calculated as the sum of the relative frequency and relative cover divided by two (Swarth et al 2012). Importance values can be used to examine differences between marshes, as well as differences in vegetation within the same marsh between different years or different parts of the marsh.

Examining the data from the permanent plots, and combining all years, the relative importance of most species varied considerably between marshes (Fig.17). While *Puccinellia nutkaensis* and *Triglochin maritima* were relatively important at all marshes, *Puccinellia phryganodes* was an important species at only the north-side marshes, while *Plantago maritima* was a more important species in the south-side marshes.

Importance values calculated using the community monitoring data (collected on temporary plots in just a single year) generally agrees quite well with the data from the permanent plots (collected for 3 or 4 consecutive years on the same plots). As an example, Figure 18 shows the two types of data compared for Beluga Slough. The higher diversity shown by the community monitoring data reflects the placement of some of those plots on berms dominated by less saline-tolerant species. The similarity of importance values calculated from data collected in two very different ways helps illustrate the value of this metric in analyzing vegetation patterns.

Since field work was conducted on the permanent plots for 3 or 4 consecutive years, these data can be used to look at short-term interannual variability within a marsh. As an example, Figure 19 shows the importance values of the most important species at Fox River Flats by year. While there are obvious small differences from year to year, there is no apparent directional increase or decrease in importance of any of these species. It will be important to understand this short term variability when examining data for longer term directional change in the future.

Because the community plots were located in separated high-marsh and low-marsh areas, we can use these data to look at differences between these areas of each marsh. In general, high marsh areas had a greater number of important species than low marsh areas (Figure 20). *Puccinelllia nutkaensis* had much higher importance values in low marsh plots in all marshes.

While some plant species occur over a wide-range of elevations within each marsh, other species are restricted to a much narrower elevation. *Puccinellia nutkaensis* is distributed broadly from low marsh to high marsh, as can be seen in Figure 21.

However, *Salicornia maritima* is restricted to a much narrower range of elevation, especially where it occurs at high percent cover values (Figure 22). Changes in relative sea level should be able to be detected in the future by shifts in the distribution of such species within each marsh.

The 1964 earthquake provided us with a natural experiment to see how marshes responded to a sudden change in relative sea-level. All marshes migrated landward immediately following the earthquake, as can be seen by a region of dead spruce trees at the upper end of each marsh that were killed by salt water inundation when the land level dropped. While immediate response was entirely due to land-level change, ongoing seaward migration is a result of both land-level change and sedimentation patterns. Figures 23 and 24 show these changes in low marsh at the Fox River Flats study area.

At the upper edge of our marshes, evidence of seaward migration can be inferred by the presence of young spruce and other saline-intolerants species like willows.

We are fortunate in Kachemak Bay NERR that most of our marshes are relatively unconstrained by human development (with the exception of Beluga Slough), and thus have the capability to migrate in response to relative sea level changes. The combination of accurate high-resolution plant community maps with permanent vegetation plots will enable us to detect changes in the future as the balance between land-level and sea-level changes.

Biomonitoring

Insects: In 2011 and 2012 during peak vegetation, we identified 93 taxa of insects in four sampling events: one each in Beluga Slough, China Poot, Fox River Flats, and Sadie Cove. Of these, 57 families representing 9 orders were preserved as reference specimens and were contributed to the University of Alaska, Fairbanks archives.

In general, but not exclusively, insect diversity was higher for the upper marsh sampling locations for insect sweeps and for insect fall out traps. The Beluga Slough site had the greatest insect diversity but the lowest number of insects of all four sites (Table 2; Figs. 25-26). Dominant taxa were also variable between sampling type and among study sites (Figs. 27-29). Peak counts that were common to more than one sampling site were: Beluga Slough (FOT) and Fox River Flats (SWP) had high numbers of *Cicadellidae* (leaf hoppers); Fox River Flats (SWP) and China Poot (FOT) had high numbers of *Ephydridae* (shore flies); and sweep samples of *Acari* (mites and ticks) were high at both Sadie Cove and China Poot sites.

These data help provide a baseline for insect diversity but it's difficult to ascertain trends in relative abundance. In Fox River Flats, more extensive insect sampling occurred for insects in association with juvenile salmon rearing habitat studies (Walker et al. 2013). Walker et al. (2013) sampled across the estuary gradient from saline to fresh water plant communities from July through September with insect fall out traps. Generally, insect densities declined over the season, with the exception of a few taxa including *Cicadellidae*, species richness was highest in the upper marsh where there was a greater influence of fresh water in the system. Based on Walker et al. (2013), it is clear that timing of sampling, proximity to fresh water, and site-specific characteristics can all play a role in insect diversity and relative abundance in salt marsh habitats.

Infaunal Invertebrates: The high and low marsh sampling structure was set up irrespective of sources of water and regular water saturation of the soil was an important factor for the presence of infaunal invertebrates at these locations. Because of the sampling design, it is likely that fewer infaunal invertebrates were detected in this study. In China Poot, there were no infaunal invertebrates in the upper salt marsh samples, in Fox River Flats, only one taxa was found; these are the largest of our salt marsh study locations and perhaps greater definition between high and low marsh habitats exists. In sampling locations, the lower marsh had a higher diversity and abundance of infaunal invertebrates. Beluga Slough was the exception where numbers of taxa were nearly equal. In Table 3, we show the diversity and relative abundance of each taxa encountered in our sampling.

Fish: We present the diversity, relative abundance, and size classes of fish captured (2012 only for all species) in Tables 4 and 5. In Figures 30-31, we show the tidal gut features in the upper and lower marsh habitats sampled in Fox River Flat. In Figure 32, we highlight the differences in relative abundance of fish species in the upper and lower tidal guts of each study site. For Beluga Slough and China Poot salt marsh sampling there were shifts in the dominant species captured between years. In 2011, threespine stickleback were the most abundant species captured at these sites. The remaining species (17% of the total) were: starry flounder (*Platichthys stellatus*), Pacific staghorn sculpin (*Leptocottus armatus*), ninespine stickleback (*Pungitius pungitius*), coho salmon (*Oncorhynchus kisutch*), and dolly varden (*Salvelinus malma malma*).

In 2012, starry flounder and staghorn sculpin dominated in Beluga Slough and China Poot marshes, respectively. By standardizing the sampling to tidal guts rather than fresh water stream sources, we markedly reduced the capture of salmon species in 2012. Rare species encountered in the sampling during year two which were not observed in year one were: gunnels (family, *Pholidae*), pacific herring (*Clupea arengus)*, halibut (*Hippoglossus stenolepis*), and Pacific sand lance (*Ammodytes hexapterus*). Of the four sampling sites, Beluga Slough had the greatest abundance fish in both sampling years and Fox River Flats had the fewest fish captured; average water temperatures at these sites were 17°F and 12.4°F, respectively, during our sampling in August of 2012.

In 2011, we sampled Beluga Slough and China Poot salt marsh sites for fish diversity. The fyke net did not function well for sampling the tidal guts in the two habitats it was used. In Beluga Slough, the channel did not de-water with the dropping tide; therefore, several passes with a pole seine were made to capture fish in the cod end of the net. In China Poot marsh, the tidal gut channels were very broad and subject to rapid flooding of the incoming tide. In 2011 the net was inundated before it could be retrieved resulting in no sampling of that habitat type.

There are many factors that influence fish species diversity and relative abundance, including inter-annual variability, seasonality, and physical factors, such as temperature, salinity, turbidity, and tidal state. The fresh water sources and underlying hydrology, which differ at each of the four salt marsh sites, also are important. Without being able to quantify those differences, we cannot directly compare fish sampling results across fresh water inputs to each of the salt marshes in the study.

Birds and Mammals: Bird and mammal observations have been summarized in Kachemak Bay Research Reserves Salt Marsh Habitats: Citizen Science Monitoring 2011-2012 Appendix B and will not be summarized here.

Education and Outreach

Introduction

During 2011-2013, we developed several communication strategies for information from this study on relative sea-level change and about coastal processes in general. We used a combination of methods such as NERRS Coastal Training Program workshops, educational *Discovery Labs*, radio, newspaper, and newsletter stories, and presentations at science conferences. In this study, we had a unique opportunity to educate the community on the geomorphic processes associated with relative sea-level change in advance of communicating the results of this study. We explored the role of outreach and education on building a common vocabulary about the issues related to relative sea-level rise in our region.

Methods

Our goal was to develop a standardized vocabulary in our community about the processes that shape and influence the landscape that supports communities in this region. We employed several methods to reach decision-makers, the public, and students in the surrounding communities with information relevant to this study. While the data collection was ongoing in this study, we developed outreach materials on the physical processes that related to earth movements and relative sea level rise.

We developed K-16 marine and estuarine lab & field classes, *Discovery Labs*, and Coastal Training Program (CTP) workshops to provide an outlet to share project goals, methods, and results. One method of information delivery we used extensively was *Discovery Labs*. *Discovery Labs* are open to the public and offer educational opportunities for school-age children and adults in our fully-equipped lab classroom. *Discovery Labs* are typically conducted in one of two ways: 1) for the public as a two-hour stand-alone event or 2) for a class of K-12 students as a 90-minute or two-hour science education / field trip program. Both of these formats are designed to introduce targeted science content and inspire an interest in the scientific process by providing hands-on and inquiry-based information and activities.

Each Discovery Lab presents a topic of interest, such as “Earthquakes”, “Coastal Processes in Kachemak Bay”, and “Influences of Glaciers on Ecology”. Topics are subdivided into eight different tables. Each table contains interesting factual information, and scientific investigations presented in multiple ways to appeal to a variety of ages and learning styles. Most tables include hands-on activities, and incorporate the use of dissecting scopes, close-up examination of live marine invertebrates, experiments that learners can conduct, and craft activities. *Discovery Labs* offered in the summer had a new topic each week, presented on Wednesdays, Fridays and Saturdays. Winter labs focused on one research topic per month. Winter *Discovery Labs* are open to the public on the first Wednesday of the month and, with adjustments as needed to meet grade requirements, continue to be available for three weeks to accommodate K-16 students. Additional educational programming such as lectures, local news articles, and outdoor family programs build upon the topic of the month. Winter labs and associated activities attract families, home school groups, and inquisitive residents. All programs were free to the public.

Other audience members for this project include coastal decision-makers. To reach this audience several methods were used, including informational one-pagers, science articles for local and state-wide newspapers, and figures disseminated appropriately during various educational opportunities. Coastal decision-makers attendance and participation in the outreach events hosted by this project were encouraged to increase understanding, integration, and use of study information.

During CTP workshops and other outreach activities, results from this study were presented by project scientists'.

Results

Public Discovery Labs: In 2011, 2012, and 2013 we delivered a total of 12 Discovery Labs associated with this Science Collaborative project for the general public, reaching a total of 974 individuals of all ages and from locations ranging from Homer and other Alaskan locales to places beyond Alaska in the U.S., Europe, and Japan. Three of these public labs - in February 2011 and April 2012 and 2013 - reached primarily Homer area residents. The other nine labs occurred during summer months when our visitor center and its public events attract both a local and worldwide audience.

Each public Discovery Lab focused on Science Collaborative-related topics – *Our Landscape Over Time* / *Salt Marsh Plants & Wildlife* / *Citizen Science* – and featured eight learning stations offering resources and activities related to the natural forces that shape our landscape, sea/land level change research and data, salt marsh biodiversity, citizen monitoring efforts, and a wide array of specifics about this project. Materials at these stations included tabletop audio-visual displays, touchable objects and organisms, research updates, and interactive games/activities. Lab stations were hosted by KBRR staff, agency partners, community volunteers, and at least one of this project's Core Intended Users (CIUs).

Three of the summer 2011 public labs also offered an opportunity for attendees to share, in a video interview with TIDES student Kenny Daher, their opinions on the value of community monitoring to the scientific process. Kenny produced a series of video vignettes selected from these interviews that are used as outreach material for this project. The vignettes were made available on touch-screens in our exhibit hall for free-choice viewing by the public.

Student Discovery Labs: We also delivered *Our Landscape Over Time* Discovery Labs to 26 school groups during the three years of this project. Most of the 641 students participating in these 90-minute to two-hour labs were from Homer and in the 4^{th}, 5^{th}, and 6^{th} grades. We also taught students in preschool and kindergarten through 3^{rd} grade and reached 40 students from Kenai and the Russian Old Believer community of Kachemak Selo, which borders the Fox River Flats salt marsh in Kachemak Bay. A total of 116 adults (classroom teachers and parent chaperones) participated in the student labs, as well.

At each of these Discovery Labs (2011, 2012, and 2013), students participated in three learning stations related to this Science Collaborative research project. We incorporated into these stations the basics of plate tectonics and glaciation and highlighted the impacts of glaciers, sea level rise, earthquakes, tsunamis, and volcanoes on the Kachemak Bay landscape. We also shared information with the students on both the process and progress of this Science Collaborative project. And we received tremendous praise and very appreciative comments back from teachers whose students joined us for these labs. Here are a few of the comments from teachers:

"*My students will use what they learned in this program by adding to their knowledge of volcanoes, tsunamis and the tectonic plates/shifts in the earth. This was a wonderful, enriching program!*"
– Mindy Hunter, $3^{rd}/4^{th}$ grade teacher

"*This was a nice follow-up to our study of volcanoes & earthquakes & plate tectonics (3 months previous to this field trip) – great for jarring recall of what was learned a 'long time ago'*."
– Lyn Maslow, 4^{th} grade teacher

"*Great interactive lessons that helped students make sense of how geologic time is so different from their time.*"
– Melissa Cloud, 5th grade teacher

"*This is a reinforcement for the 4th grade science curriculum on geology – keep this one next year! Very pertinent to local students.*"
– Carole Demers, 4th grade teacher

"*The activities were simply designed so all students could move from a concrete representation to the abstract concept.*"
– Patricia Moreth, 5th grade teacher

Community Monitoring Volunteer Training Discovery Labs: In July of 2011 and 2012 we conducted four-hour Discovery Lab training workshops (1 each year) for a total of 30 Science Collaborative community monitoring volunteers. These individuals - ranging in age from junior high students to senior citizens – were trained to assist our staff in the field by collecting data and samples for emergent salt marsh plants, insects, infaunal invertebrates, birds, and mammals.

Each community monitoring volunteer training event was offered over two evenings and led by KBRR staff. Data collection and sampling methods/protocols, species identification, and monitoring day logistics were covered during these trainings to prepare community volunteers for upcoming field work in the four salt marshes monitored as part of this project. Trainees also attended one or more of our public labs offered during the same week or following week as a self-directed, follow-up opportunity for review. Topics for these associated public labs included 1) *What Lives in Our Salt Marshes? Citizen Science in Kachemak Bay,* 2) *Salt Marsh Wildlife,* and 3) *Salt Marsh Plants*. All of our community monitoring volunteers expressed a great deal of gratitude for these training opportunities.

Post-monitoring surveys were conducted in 2011 and 2012 to determine the effectiveness of the pre-monitoring training, and to seek feedback on participant experiences during the fieldwork. Below are some highlighted responses from volunteer monitor about their experiences.

When asked to define the overarching goals of this Science Collaborative project volunteers replied:

> *"Monitoring changing sea levels and changes in ecology both locally and globally."*

> *"To gather database of knowledge that can be used in long- term studies to help us understand effect of climate/uplift change on our world and possible provide data that will help other communities too. Involving community members creates multiple stakeholders who appreciate more deeply the issues facing our environment."*

When asked what they enjoyed most about this experience we heard:

> "*Being out in the field working with inspiring scientists and other volunteers and getting to know my environment and understand local issues better."*

> *"Learning more about the science issues facing our community and expanding knowledge of local species and habitats."*

> *"Learning about the intricacies of the salt marsh from people who loved it and knew a lot. Loved tromping around in the tall tall grass, doing the square plots. Using the GPS to find the "spot"."*

> "*Seeing parts of Kachemak Bay that I otherwise may not get to visit; collecting scientific data for a long term project."*

And when asked to offer final comments we heard the following:

> *"Really enjoyed learning about salt marsh habitat from experts. Felt like I could contribute to a worthwhile project."*

> *"All of the information that staff provided during the training sessions was well thought out and necessary to understand for participating in the project. The time was used wisely and information was presented logically."*

"The staff did an excellent job of orienting and guiding the volunteers!"

"Thank you so much for including us in your work and training us so well."

"This is such a great project. Thanks to NOAA for funding it and the wonderful people at the Alaska Islands &Oceans Visitor Center and elsewhere who made it happen."

Discovery Labs as an Outreach and Education Tool: By utilizing *Discovery Lab* programming over the three years of KBRR's Science Collaborative, we have successfully communicated many aspects of this exciting project and its associated science concepts to over 1,000 adults and 641 pre-K to high school students. We've trained citizen scientists – some already trained as researchers, most with no or little background in science – to work professionally and efficiently side-by-side with KBRR staff in the field. Many of these individuals (especially the community monitoring volunteers and students), as a result of their interactive engagement with us, now understand local salt marsh dynamics intimately and fully grasp the importance of researching local land level changes in order to understand how sea level rise will impact our region. Through audio-visual materials (posters, videos, objects, specimens, demonstrations, games) and one-on-one discussions with KBRR staff and Reserve volunteers, *Discovery Lab* participants broadened their knowledge of sea-level rise, glacial retreat and its impacts on the landscape, land level changes, coastal biodiversity, the scientific method and, perhaps most importantly, how life exists and changes within their own natural environment.

Project Integration with Coastal Decision-makers

Introduction

In 2009, Homer, Alaska residents noticed "more land showing at low tides" in Kachemak Bay. This local observation coupled with mainstream media articles about rebounding land from melting glaciers in Southeast Alaska prompted then City Mayor, Jim Hornaday, to write a letter to the Kachemak Bay Research Reserve. In the letter, assistance was requested to better understand land and sea-level changes in the Kachemak Bay region. The Kachemak Bay Research Reserve (Reserve) is part of the National Estuarine Research Reserve System and is uniquely positioned to respond to community-driven questions. The structure of the Reserve integrates well-developed research with education, coastal decision-maker training, and a Community Council (formed by community and management agency members).

In scoping the problem, the Reserve recognized the need for better information on vertical land-level movements and sea-level rise in order to support informed decisions on land use planning and public safety. Prior to this study, we did not have detailed information for rates for the combined effects of uplift from the 1964 quake and isostatic uplift from the steady loss of icefields in the Kachemak Bay area. Further, the changing nature of sea-level globally presented additional complexity. Understanding the impacts of land and sea-level change to the coastal environment is important for creating resilient communities, yet access to sound technical information and use of that information for management was lacking.

The Reserve worked collaboratively with the Reserve's Community Council to identify an approach to address the issue through a joint proposal. The information need expressed by the community was for more information on how changes in land and sea-level will affect coastal habitat, harbor and other infrastructure, and local food resources in the future. The resulting research question to be answered was distilled to: what is the rate of relative sea -level change for this region? Finding an answer to this question would help interpret related questions on coastal processes in the region. The scientific approach aimed to provide accurate vertical land level rates of change due to tectonic and isostatic adjustment over a meaningful time frame for the end-users of the information. The scientific approach also laid the ground work necessary to monitor biological changes in salt marsh habitats over time. An overarching goal of the study was to facilitate the integration of science into coastal decision-making processes. An active, participatory approach was used in this study to support community dialogue and observations leading to the sound collection and use of technical information for coastal decision-making. We describe the methods, results, and lessons learned during this process.

Methods

We applied a Collaborative Learning approach in this study to facilitate the integration technical information gathered during the course of the study with local coastal decision-making processes. The model we employed was adapted from Feurt (2008), which is based on six collaborative learning principles designed to develop the shared understanding needed to support improved management decision-making. To guide the participants of this study, we followed a framework approach (Fig. 33) to promote participation and clear communication pathways among local coastal decision-makers (henceforth core intended users "CIU"s) involved in the project. The framework used was adapted from Allen *et al.* (2001) and was as follows.

Phase I. Assess and Identify Problem. In this initial phase of the project we identified the problem with the Reserve Community Council prior to submitting a proposal to the University of New Hampshire for funding. A comprehensive idea statement was collectively developed that framed the issue, research questions, and possible methods to address them. Additionally, a matrix of relevant coastal decision-makers (CIUs) from the region was developed that included their coastal decision-making authority and what types of information generated from this study might apply.

Phase II. Scope Goals and Objectives. In this phase we developed the study proposal with the Community Council and CIUs who wrote "letters of commitment" to participate in this study in a material way. The CIUs were identified based on their comprehensive perspective on the research question or impact of the findings, and they were considered as equal partners in this effort. The aim of this participatory approach to project scoping was to build relationships where all participants respected the backgrounds and perspectives that each brings to the group. As an example, while the project proposal was under development, one of the CIUs was in Washington D.C. and asked our Alaska Congressional Delegation for a letter of support, which was then included with the submitted proposal. Further stakeholders were also identified who were in the position to take action that would move toward the desired outcomes.

Phase III. Implement Collaborative Learning. In this phase we followed the cycle of experiential adult learning, which included issue assessment, design of an action strategy, implementation of strategy, evaluation of results, and incorporation of results into design of the next action. Stakeholders actively participated in this entire process and committed to these collective principles established. A forum for communications throughout the project was established at the onset that fostered respectful dialogue and shared understanding among the group.

To create a communication forum, we set up quarterly meetings with the CIUs for the duration of the project from 2010 to 2013. Quarterly meetings provided opportunity for joint review of the data and information gathered, and created participatory dialogue which facilitated a shared understanding of the technical information and decision-maker needs. In the first CIU meeting in 2010, the initial assumptions and levels of uncertainty by CIUs were addressed about the research, and a framework for future communications was set. The CIU group helped to define and implement the communication strategy at future meetings. By beginning with this open, participatory dialogue in which CIUs had collective responsibility for defining the communication framework and a process for vetting information, we believe a precedent was set for minimizing disagreements and potential conflicts during the course of the project.

Phase IV. Study Implementation. In this phase, technical information gained in the field was disseminated to CIUs as information became available. This frequent distribution of information helped support a learning-oriented approach, in which shared understanding of the technical information was developed though a participatory process. The CIUs also provided presentations to the group on how they use information in coastal decision-making. In this approach, a shared understanding and vocabulary was developed about the project. This phase of the collaborative learning process was iterative in which CIUs evaluated results and collectively refined, incorporated, or identified data gaps in the information needed. This was a critical stage for identifying the efficacy of the study in meeting CIUs decision-making needs. The matrix developed in Phase I was revisited as a touchstone to refine changes for each CIU in how the information might be used, to identify data gaps or additional information that would be needed for the science to be more applied, and to capture the desired outcomes of the study. The final matrix for the project is presented in Table 6.

Results and Discussion

Our quarterly meetings on the project with the CIUs were the primary venue for developing a participatory process to share the science and CIU information needs. During 2010-2013, 11 CIU meetings were held. Quarterly CIU meetings followed the communication guidelines set in Phase III of the project. To capture information and knowledge, shared agendas, meeting minutes, and any relevant project-related materials were circulated among the group. In the first meeting we developed the communication structure for future meetings. To facilitate the science teams' understanding decision-maker information needs, CIU members gave presentations to the group to frame their agency or organizations, professional decisions under their direct purview, and how data collected from this or other research projects could help inform their decision-making. The majority of these presentations were completed during CIU meetings held 2010 and 2011 and there was only one presenter during any one meeting time. This approach was important for establishing collective understanding of each other's decision-making authorities and to ensure better access to their knowledge among the group. During our quarterly meetings with coastal decision-makers, we discussed the differences between regional and global sea level rise estimates and their relative merits for coastal long-term planning processes. The result of these discussions was to select published global sea-level rise estimates of 3.2mm/year (0.13in/year) for the study (Fig. 3; IPCC Summary for Policy Makers 2013).

Alternate forms of meetings were also held, as necessary, during the study implementation phases in 2012 and 2013. These meetings often entailed one-on-one dialogue or small meetings between researchers and CIUs to better refine individual information needs, or to provide assistance in crafting messages or materials specific to their decision-making.

In June 2012, the project integration lead met with individual CIUs to discuss types of project deliverables. During these meetings, we were able to develop a better understanding of useful time scales for relative sea-level change projections that interfaced with budget and planning processes. Through collaborative dialogue, we were also were able to discuss and refine what other information needs were required by CIUs to integrate data from this study into regulatory and permitting processes. The information gathered in the meetings was later presented to the whole group to generate a shared understanding of other's information needs.

In 2013, CIUs provided feedback to draft product types that could be produced from the study. Feedback was provided in three ways: i) at a quarterly meeting where study results were reviewed and CIUs discussed draft products in small groups and provided written feedback on them, ii) via email where draft products were presented and feedback generated online via SurveyMonkey, and iii) in-person meetings with individual CIUs to collect impressions, feedback and concerns. All three formats yielded useful information. Although we found it was difficult to prevent feedback 'fatigue' and keep all participants engaged. We also found that the CIUs were more effective in providing direct feedback on draft products placed before them for evaluation, rather than generating innovative product ideas.

Feedback generated from the CIU product evaluations informed a list of project deliverables which were reviewed and voted on during a subsequent CIU meeting. The results from this poll determine the final products that would be produced for the project. The desired project deliverables include: publications of the relative sea-level rise projections and the collaborative learning model we employed, a geodatabase of the 20 year projections for relative sea-level change to be used in concert with other data layers for permitting and regulatory decisions, an online map viewer tool through the Kenai Peninsula Borough Parcel Viewer for data visualization that can be applied to permitting and land management, concise messages from the study to guide public communications, and education materials on salt marsh ecological and species identification (as developed from the community biomonitoring).

Also during 2013, the project integration lead met with individual CIUs to help craft project messaging specific to their decision-making and relevant stakeholders audiences with whom they communicate. The CIUs were interested having us develop supporting information about the study in the form of "proof points" to provide technical information or facts to support the messages. To that end, we've assembled a messaging document in Appendix C.

The quarterly meetings provided a venue for communication and facilitated participatory dialogue of the science and CIU information needs. Importantly, this approach created a common vocabulary about the technical aspects of this study, including relative sea-level change and factors that affect it in our region. Through familiarization with this technical information, the CIUs became more familiar with the strengths and limitations of science investigations and process.

By creating and open dialogue and joint review of technical information, researchers were able to gain a better understanding of how CIUs integrate information and what the barriers might be to incorporating new information into decision-making processes. Through this shared understanding information gaps and other supporting information needed by CIUs to fully utilize the information generated in the study was established. Through continued monitoring and evaluation, feedback loops to update the study information, and hence the collaborative learning process, was supported.

As an example, early on in the study a data gap was identified for information on sediment transport and how relative sea-level rise and sediment transport processes influence dredging of the Homer Harbor. To address this need, we brought in a speaker to a CIU meeting with expertise in sediment transport. The presenter outlined methods that would have utility for the CIUs needing the information (City of Homer and Army Corp of Engineers (ACOE)). We also worked with a NOAA intern to produce a scientific poster on relevant coastal processes that contribute to sediment transport in the local area. As a result, the group developed a more comprehensive understanding of these coastal processes and a more standardized vocabulary when discussing them. This was a data gap identified in Phase IV, resulted in problem reformation, and is ready to scope goals and objectives specific to this CIU problem (Phase II).

A second example of the collaborative process arose during Phase IV of the study, as interim results of the study became available. An anomalous result of land-level change specific to the Homer Spit (where the Homer Harbor is located) was identified; data from this study indicates a slower land-level rise for this region relative to the surrounding landscape which may make the area more vulnerable to sea-level rise and storm surges. In response, we engaged in shared dialogue with the community and CIUs as to whether the results were substantive enough to coastal decision-making to further expand this portion of the study. Utilizing in-meeting polling (key-pad polling) and an online survey (Surveymonkey) with the CIUs, the Reserves' Community Council, and other relevant coastal decision-makers, we learned that 70% of the participants indicated that more information about sea and land-level change on the Spit will be important to making decisions related to their work. This feedback informed a research proposal to expand the current Science Collaborative project to work collaboratively with CIUs and additional stakeholders to investigate of land-level changes on the Homer Spit (moving from Phase IV back to Phases I and II). The proposal was not successfully funded and no alternative funding sources have been identified to date, however, we were able to expand collaborations to help bridge the data collected in this study with ongoing monitoring regularly implemented by the ACOE. In serving to maximize knowledge and support CIUs decision-making in this study, new issues, such as sea-level rise interaction with sediment transport and the anomalous behavior of land-level change on the Homer Spit, were raised and the collaborative-learning process expanded.

In the first year of the project, we benefited greatly by having integration support from the University of New Hampshire's' Training for the Integration of Decisions and Ecosystems Science (TIDES) program. An integration specialist provided project interviews among a select group of CIU members and the Reserves integration and lead principal investigator. These early interviews (Phase III) were informative and clarifying to the project as we moved forward. It was helpful to have an approach that provided a very neutral inquiry from someone who did not live in the community being worked in. The second level of support was a graduate student intern who worked with the project for a six month period, serving as field support and taking an active role in the development of the collaborative learning process. The student, in collaboration with the integration lead, produced three video vignettes on the project that captured why the project was being conducted, interviews with local CIU members, and interviews with the citizen science component of the project. These vignettes served as part of their degree and have been a valuable for communicating about the project.

While there were clear successes with our approach to the collaborative learning model, there were also a few challenging areas in implementing the model. CIU fatigue on the project was evident for some of the participants, particularly the City of Homer Planning and the Kenai Peninsula Borough. When we discussed the project individually with them, it was clear they felt the project was important and they were interested in the information that would be generated in the study. However, the immediacy of applying the information was much less than many other issues they were responsible for during the time frame of the project. As a result, we lacked a close link with these CIUs and were not able to encourage regular dialogue or attendance the CIU meetings. In one case, this led to a lost opportunity to network with City of Homer during the development of updated flood zone maps (FEMA) for the City of Homer. The CIU representative felt that the land-level changes in millimeters per year were not relevant to the inundation maps which dealt with sea-level change at a scale of one to two feet increments. By not discussing his concerns and engaging in the participatory process, there was a lack of adaptive management to discuss and share case scenarios where these results could have been applied for Beluga Slough or in future revisions of the flood zone maps. We were able to engage a guest speaker from FEMA in a 2013 CIU meeting to discuss how they generate inundation maps for flooding and how land elevation data is incorporated. There was shared dialogue about the application of information from this study would have been beneficial to the inundation maps; however, the maps were in a final phase and unable to integrate any new information to their processing.

The communication and integration of a large project takes a lot of focus and creativity to keep the CIUs engaged throughout the process. We found the communication time during the CIU meetings invaluable to creating shared, bilateral understanding between the researchers and CIUs. The legal and management structures that many CIUs work within can be isolating and may not offer exposure to work being conducted by other agencies and departments. We did not have the opportunity to expand these collaborations or identified data gaps beyond this grant for a number of reasons. The first being the grant was only three years in duration, of which a complete three years of field work was involved. Another contributing factor was there was turnover (and a six-month vacancy) in the integration lead mid-way through the project. Fully implementing the collaborative learning model requires consistent and dedicated effort to manage stakeholder relationships and refine information needs. While the lead principal investigator fulfilled the primary responsibilities for the integration lead on the project, this was done on an already full workload. Without dedicated attention, collaborations and growth of the collaborative learning process was, at times, not fully realized due to time constraints. For the last year of the project, a new integration lead was added to facilitate the meetings and build rapport with the CIUs. This worked well but some momentum of the collaborative process, particularly in problem reformulation, was lost that could have developed from the early relationships built in the project.

In summary, this study benefited from the collaborative learning approach in several ways. Having established a clear and tangible process at the beginning of the study alleviated any potential conflicts within the group and provided a new and valuable way of working together. The collaborative learning model provided a process creating a shared understanding and appreciation for scientific and management processes, their respective strengths and limitations, and a common vocabulary for discussion. Working in this way also provided tangible feedback loops to refine and reformulate information needs and identify (and pursue filling) data gaps.

Future Directions

At the onset of the study, we recognized the complex nature of the question posed by the local community. We discussed the complex interactions among diverse processes such as: changes in sea level, shifts in salt marsh extent and plant community structure, shoreline erosion, sedimentation and sediment transport, water quality, and isostatic and geostatic readjustments. This study provided a baseline from which coastal decision-makers can use to guide local decision-making processes and to further address information needs identified in the community. In Alaska, this level of vertical land-level monitoring is unique and provides an excellent platform for future research and monitoring. We highlight a few of the data gaps identified in collaboration with our CIUs in this study and discuss the benefits of future monitoring.

One of the primary data gaps identified early in the study was the need for data on sediment transport processes associated with the Homer Harbor. The management issues are increased costs associated with the need for dredging and the volume of dredge materials to be transported. While having reliable estimates of relative sea-level change are important for the Homer Harbor, the more immediate management needs are for developing an interface with the land and sea-level changes along with sediment transport and accumulation on the Homer Spit.

A second data gap identified in this study was for more vertical elevation change data for the Homer Spit. We estimate that the Spit itself is rising relative to sea level but at a rate lower than the surrounding region. However, the data series indicating this trend is a single CORS on the Homer Spit and there is a need for further data collection to better understand the uplift trajectory of the entire Spit. We also a need for time to integrate the results of this study with the work the Army Corps of Engineers has done on the Spit to inform harbor dredging. The ACOE surveys were always confined to the Spit itself and thus could not measure uplift or subsidence of the Spit relative to the adjacent land.

In a year from now, it would be very beneficial to evaluate the results of this study in the community and obtain feedback on how the information was applied and identify unanticipated barriers to utilizing the information. The CIUs involved in the study suggested that information be in a peer review publication that could be cited in their permitting and other work. Publications require staff time to develop, submit, and revise and eventually be available to the public. We do not have time or funding in this study for that kind of follow through for our CIUs. Finally, there is a need to reassess the land-level change data at about a five year interval to update predictions and monitor salt marsh vegetation changes. The CORS sites will continue to collect high precision data beyond the life of the study and those data will be available through the web, however, there is not source of funding for their continued care and maintenance for the future. Routine operational costs for the CORS sites are minimal but they would cease operation in the case of equipment failure or if it became necessary to pay for ongoing power and internet access at these sites. Similarly, continuing static GPS campaigns for benchmarks that now have a valuable time series will increase the utility of the data in the models.

Acknowledgements

We are grateful to the Reserves' Community Council for being a sounding board for this project and their active participation in the study. We appreciated working with and are thankful to all of the Core Intended Users of the information from this study for their willingness to work through the process and build collaboration: Rick Thompson, Rick Abboud, Bryan Hawkins, Jim Hornaday, Walt Wrede, Bob Hartley, Sue Wilcox, Gary Williams, Kris Holderied, Julie Anderson, Ginny Litchfield, Tom Dearlove, and Paul Ostrander.

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We also thank the community of volunteers who participated in the citizen science portion of the study. It was a vital and vibrant group of people to work with and they reminded us how fun field work can be. Here are the people who helped in 2011 and 2012: Syverine Abrahamson , Donna Aderhold, Ericka Augustyn , Jason Baird, Taylor Bennett, Ed Berg, Mandy Bernard , Brittany Bobola, Heather Dalki, Raphaelle Descoteaux, Dave Eckwert, Janet Fink, Curtis Hightower, George Matz, George Maurer, Jasmine Maurer, Louie Maurer, Jenny Medley, Patrick Miller, Marilyn Moore, Jerri Nagaruk, Sue Pop, Melisse Reichman, Tadhg Scholz, Dots Sherwood, Kara Smith, and Jim Thiele.

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the project. Tim Blackmon produced the Citizen Science data summary, edited and produced bird, mammal, plant, fish, and insect guides for education and outreach, and assisted in development of figures and tables for the final report on the project. Conrad Field was our lead botanist during 2011-2013 and did an amazing job of plant identification, data preparation, and data archival for the project.

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Figures 1- 33

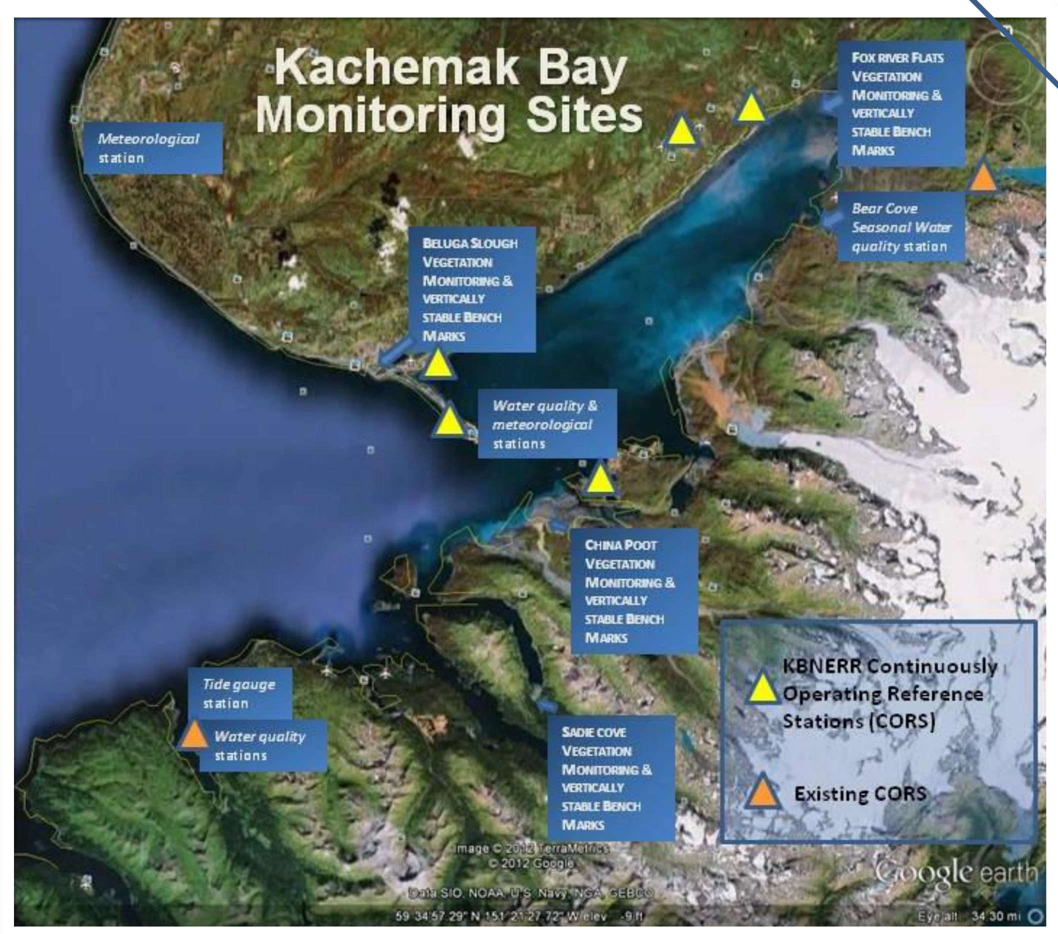


Figure 1. During 2011-2013, we monitored physical and biological parameters in four local salt marshes in Kachemak Bay: Beluga Slough, China Poot, Fox River Flats, and Sadie Cove. We also installed and maintained Continuously Operating Reference Stations to monitor vertical land-level changes.

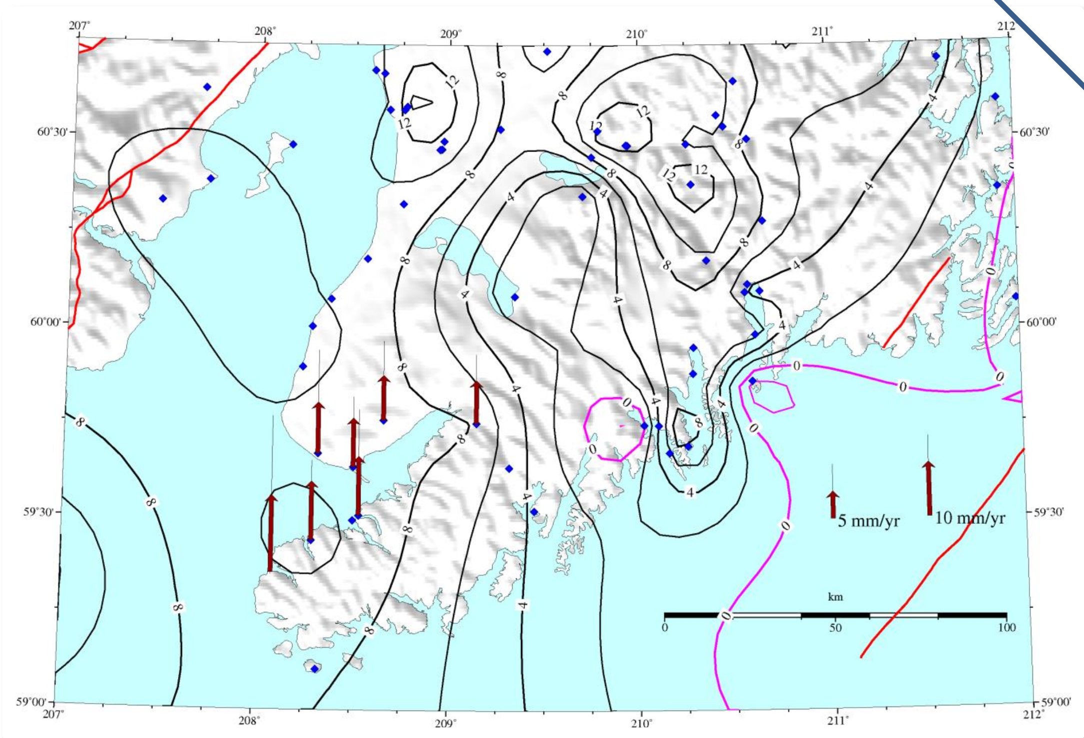


Figure 2. Detail of coastal deformation patterns (Freymueller *et al*. 2008) of Kachemak Bay and lower Cook Inlet. The red vectors show the actual observations with uncertainties (95% confidence) in the Kachemak Bay area. Contour interval is 2 mm/yr, pink contours are subsidence. The subsidence offshore is mainly tectonic. Blue diamonds are the sites used in deriving the contours, which weighted the data based on their uncertainties.

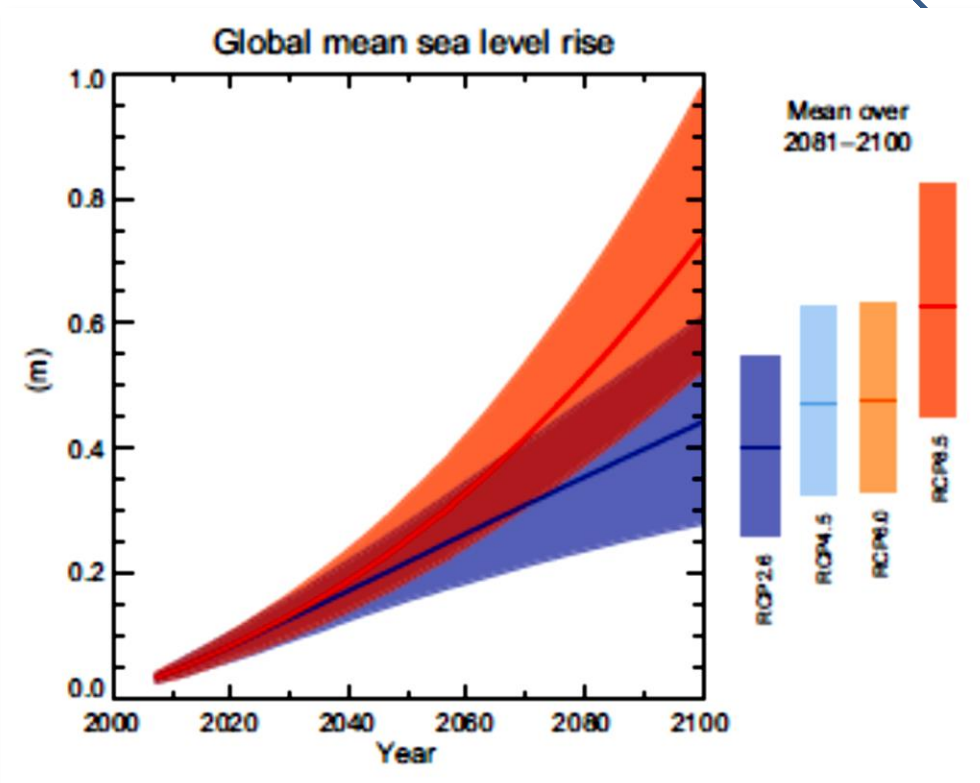


Figure 3. Projections of global mean sea level rise over the 21st century relative to 1986-2005 from the combination of the CMIP5 ensemble with process-based models, for RCP2.6 and RCP8.5. The assessed likely range is shown as a shaded band. The assessed likely ranges for the mean period 2081-2100 for all RCP scenarios are given as colored vertical bars, with the corresponding median value given as a horizontal line.

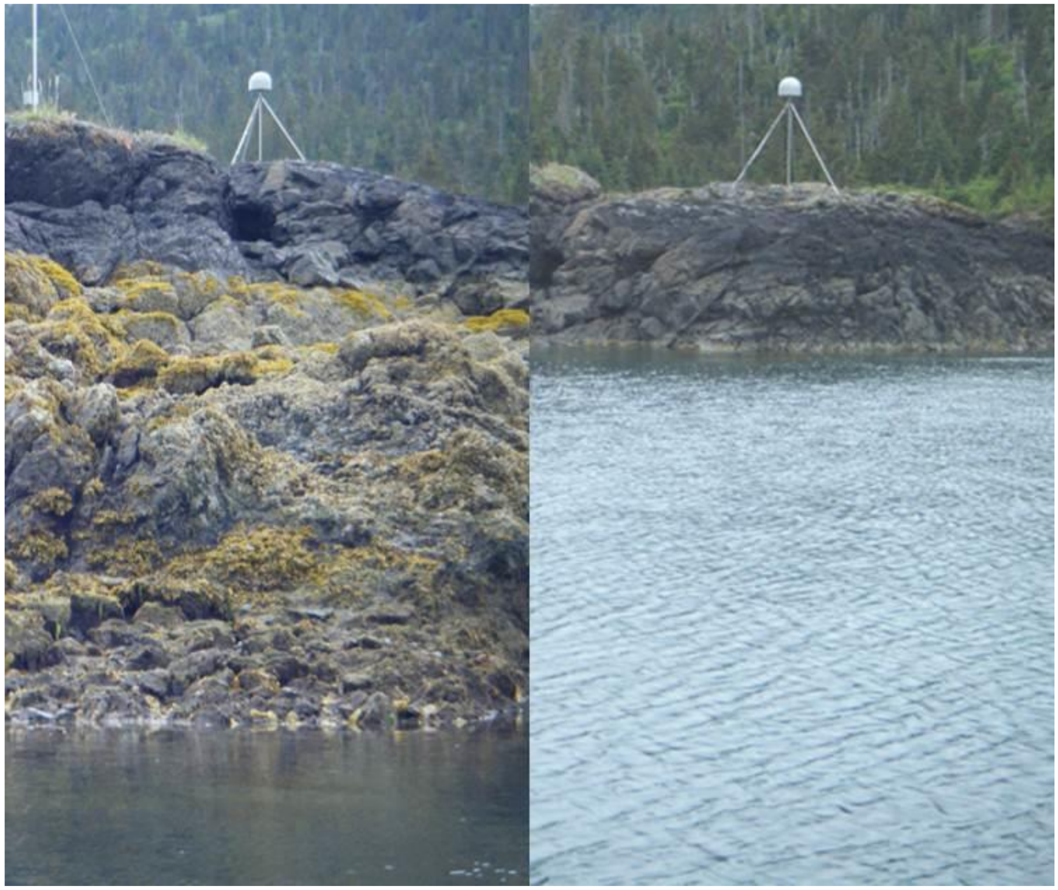


Figure 4. Photograph of Peterson Bay, Kachemak Bay Alaska, Continuously Operating Reference Station at low and high tide taken on July 5, 2012 at 10:30 and 3:30 local Alaska Time. The vantage point of the photographer is not identical in the two photos.

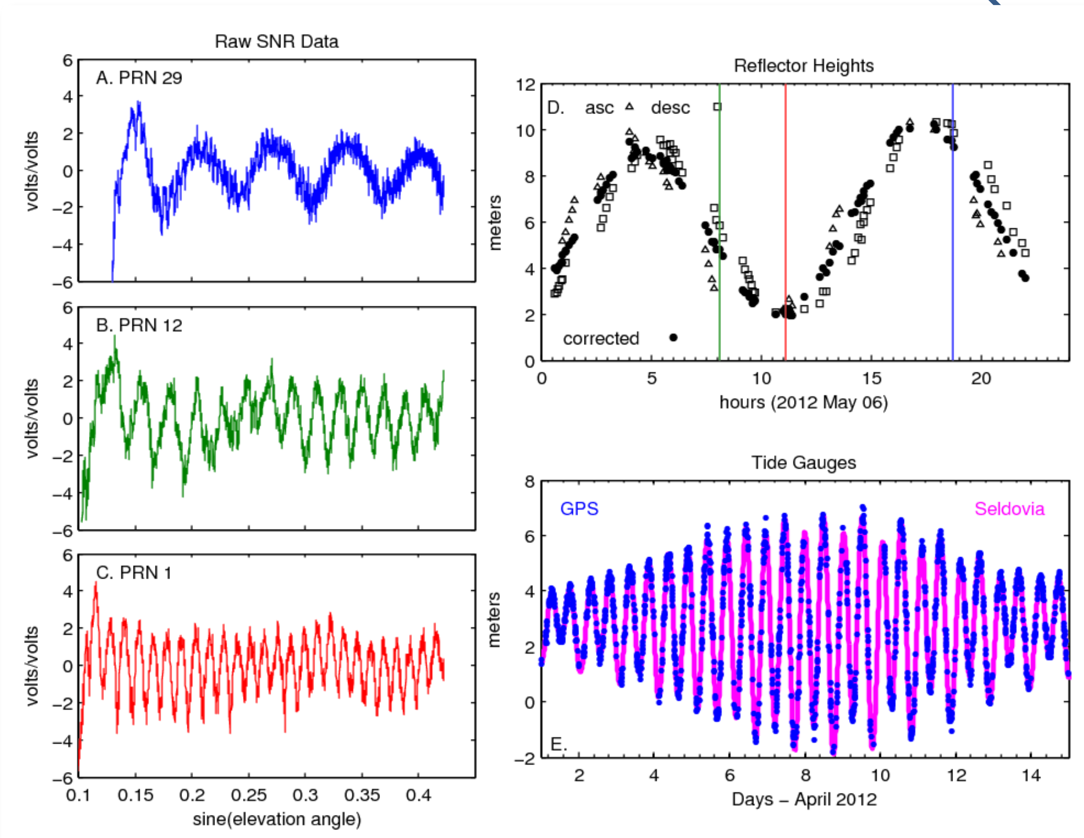


Figure 5 (A-E): GPS satellites are identified by their Pseudo Random Noise (PRN) numbers and in graphs A-C we show raw data (SNR) for three GPS satellite tracks with direct signal effects removed. Each track corresponds to approximately 48 minutes of time. In graph D, GPS reflector height retrievals of sea level on 2012 May 06 for ascending (triangle) and descending tracks (squares), superimposed on all tracks corrected for a sea- level rate term (closed circles). Times of satellite tracks in figures A-C are shown using the same colors. In graph E, we compare tide gauge measurements made at Seldovia (traditional) and Peterson Bay (GPS)

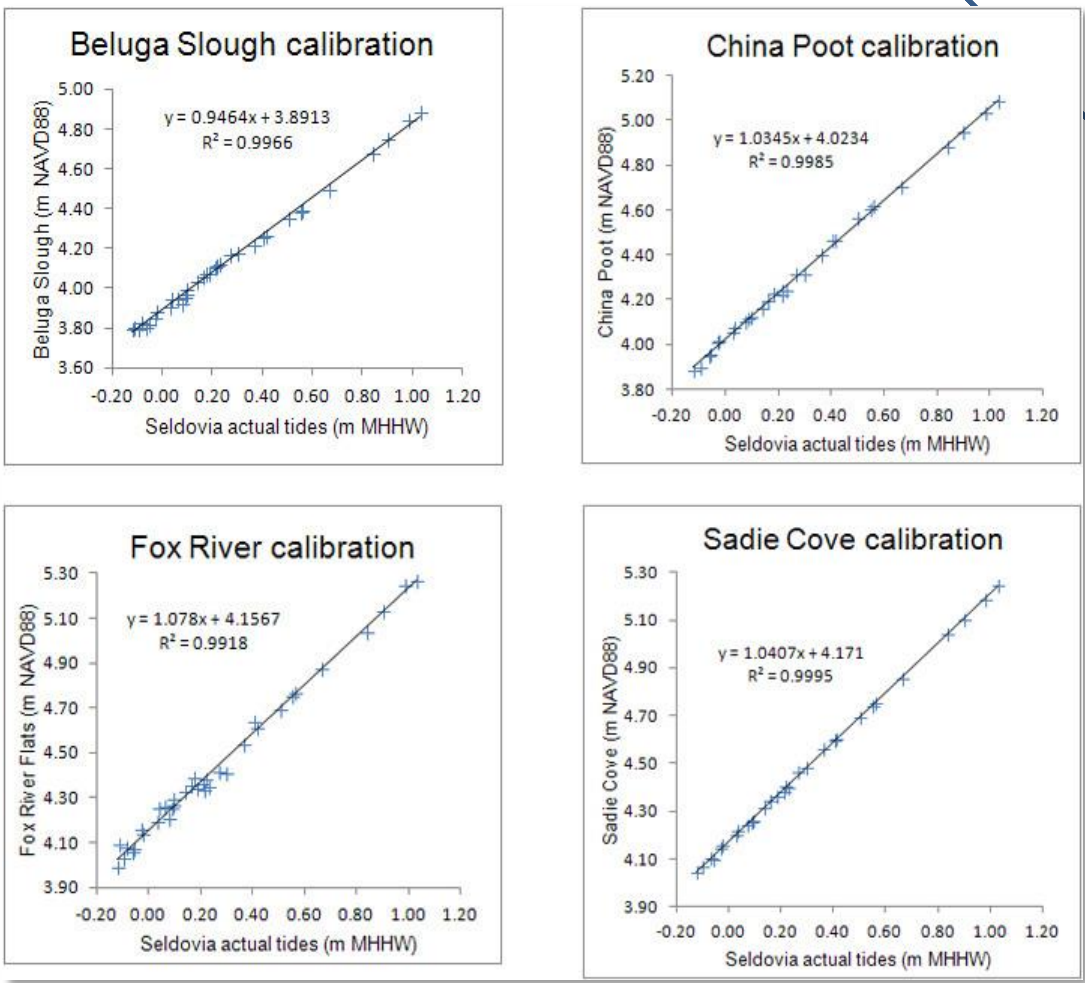


Figure 6. During 2011-2013, we monitored water level in four salt marsh sites, Beluga Slough, China Poot, Fox River Flats, and Sadie Cove; these graphs depict the correlations between the water level loggers placed in the marshes and the closest NOAA tide gauge in Seldovia, Alaska during high tides.

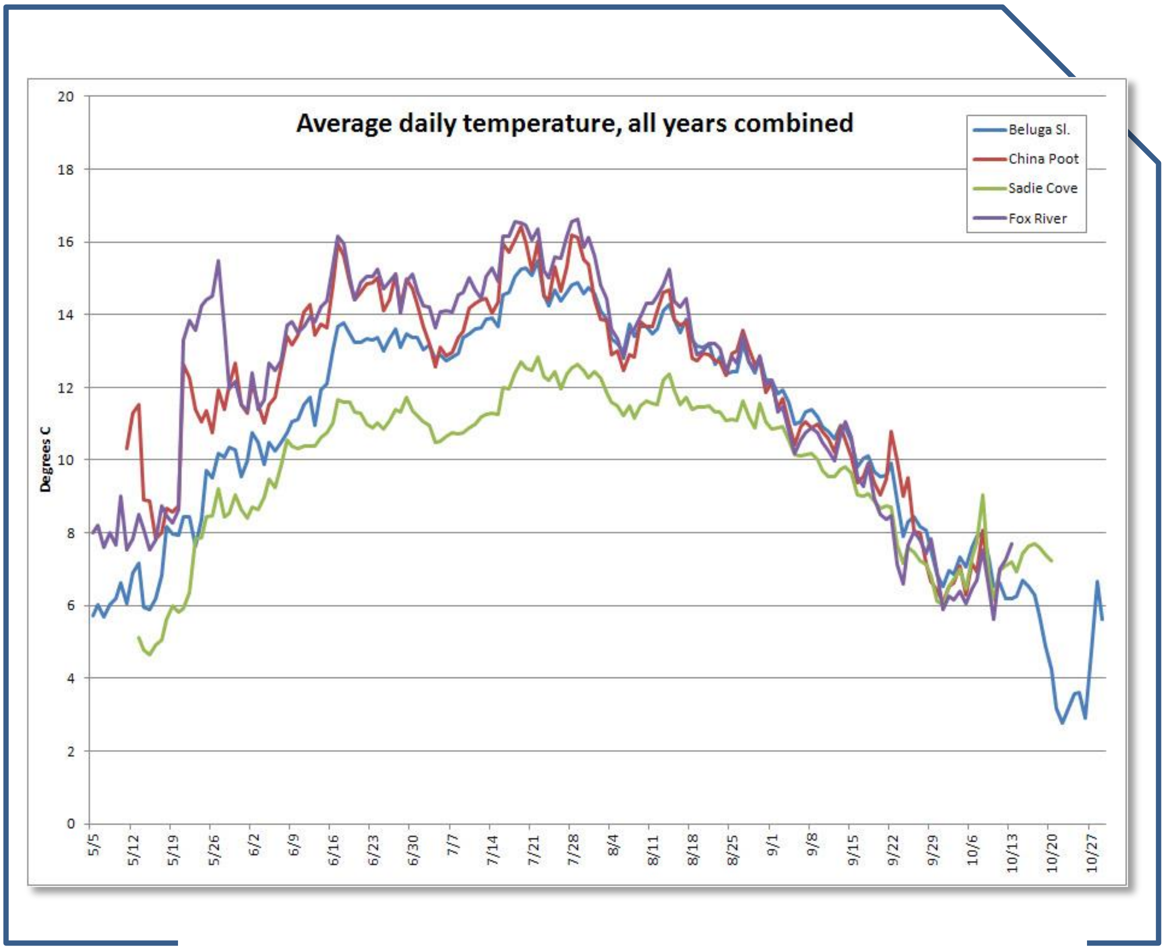


Figure. 7. During May- October, 2011-2013 these are the average soil temperatures (upper and lower marsh site temperature loggers combined) for Beluga Slough, China Poot, Fox River Flats, and Sadia Cove locations in Kachemak Bay, Alaska.

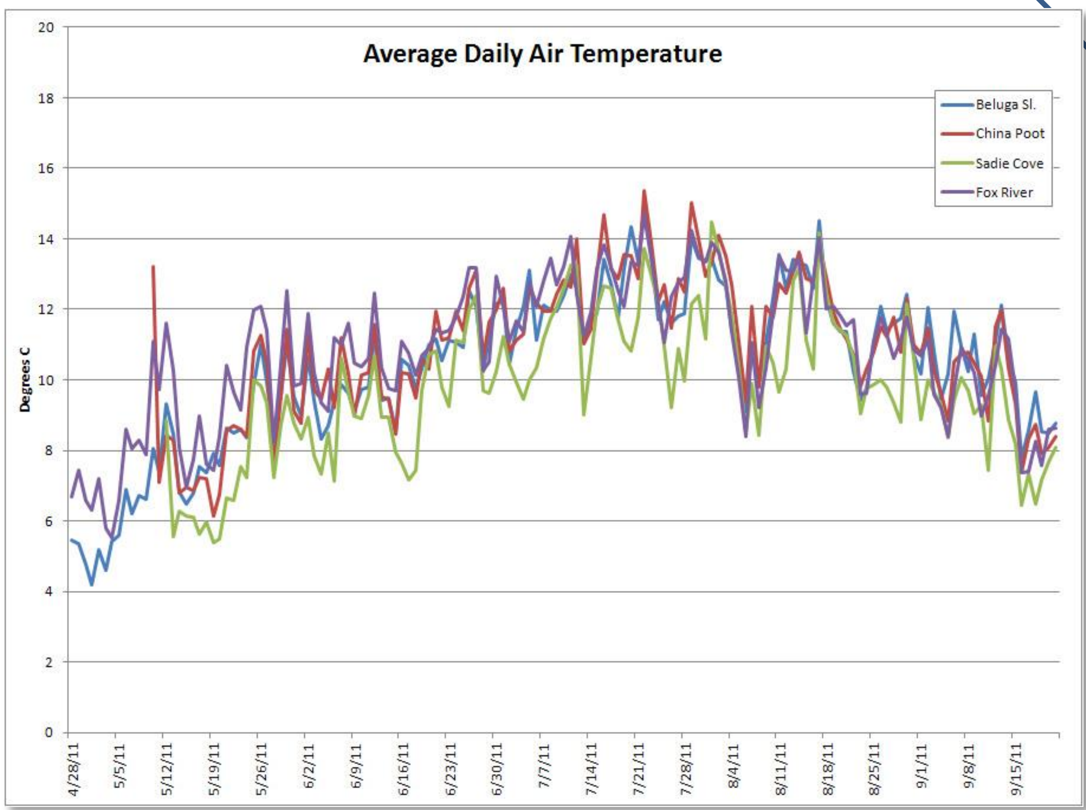


Figure 8. During April – September, 2011-2013 average daily air temperatures for Beluga Slough, China Poot, Fox River Flats, and Sadia Cove locations in Kachemak Bay, Alaska.

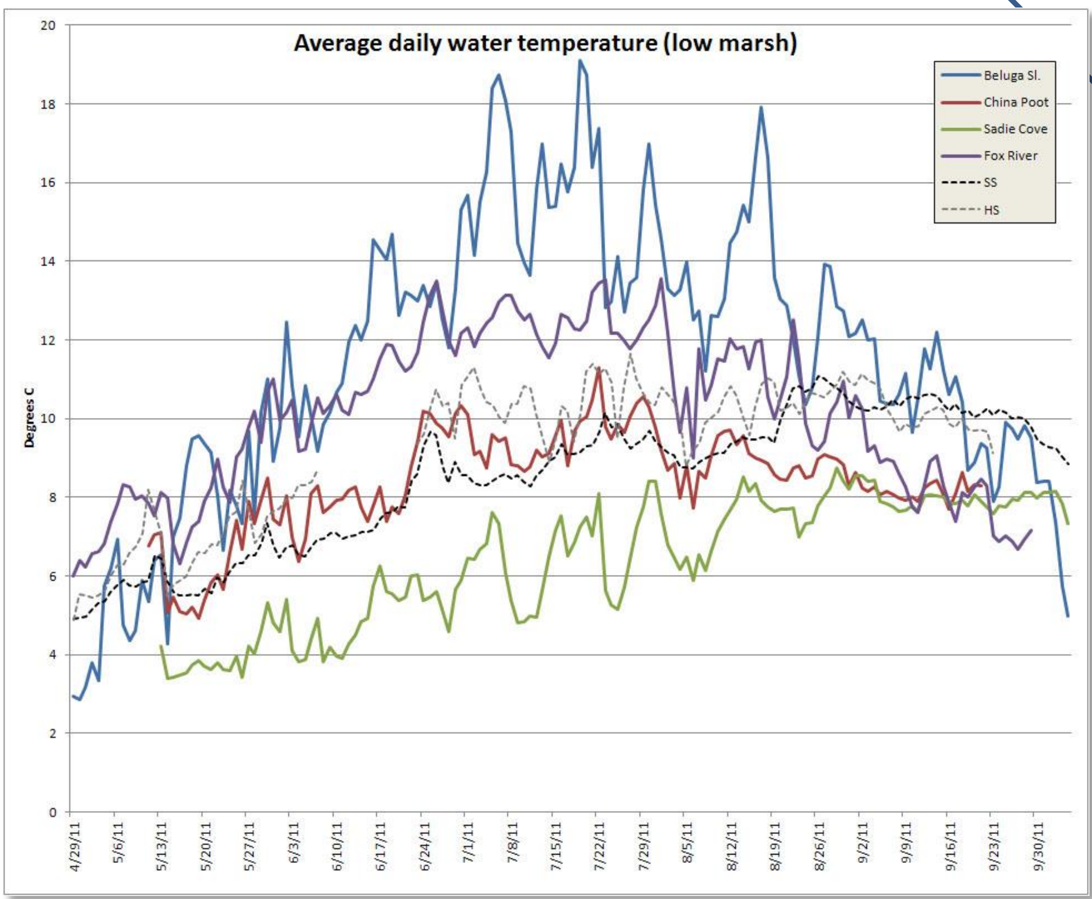


Figure 9. During April – September, 2011 average daily water temperature in the lower part of the marsh for Beluga Slough, China Poot, Fox River Flats, and Sadia Cove and average daily sea water temperatures at the Reserves' water quality monitoring locations in Kachemak Bay, Alaska.

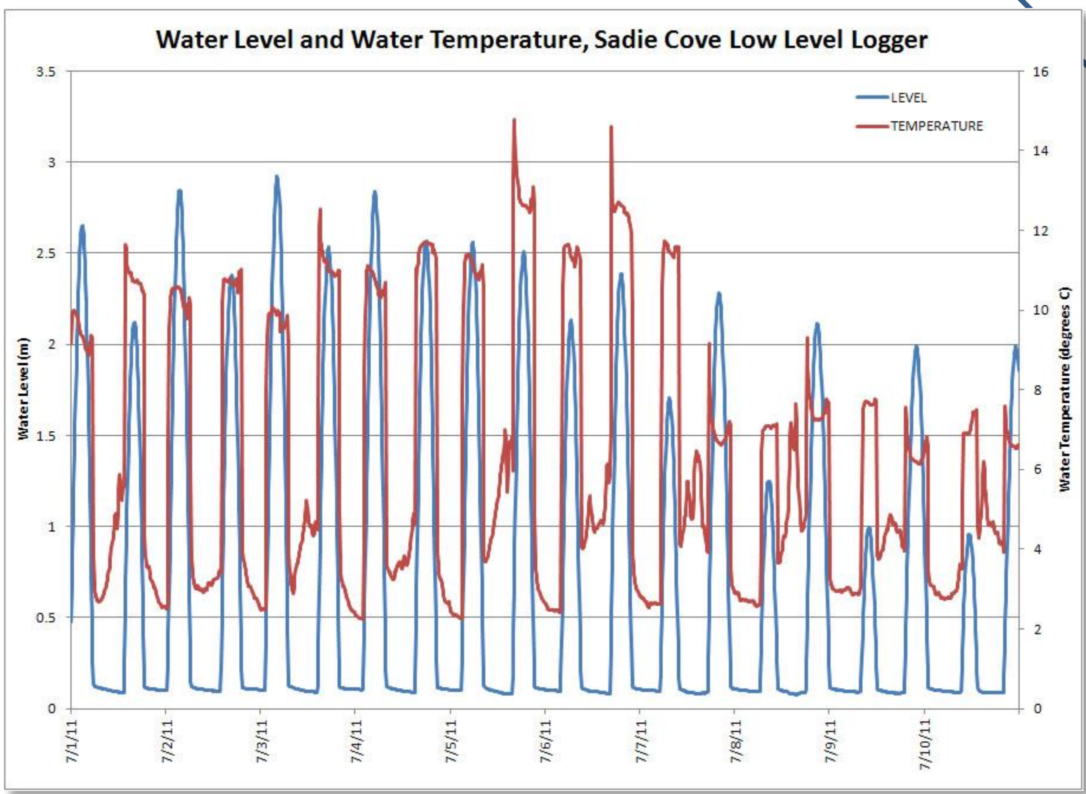


Figure 10. Water level and water temperature trends during July, 2011 collected in the lower marsh of Sadie Cove, Kachemak Bay, Alaska.

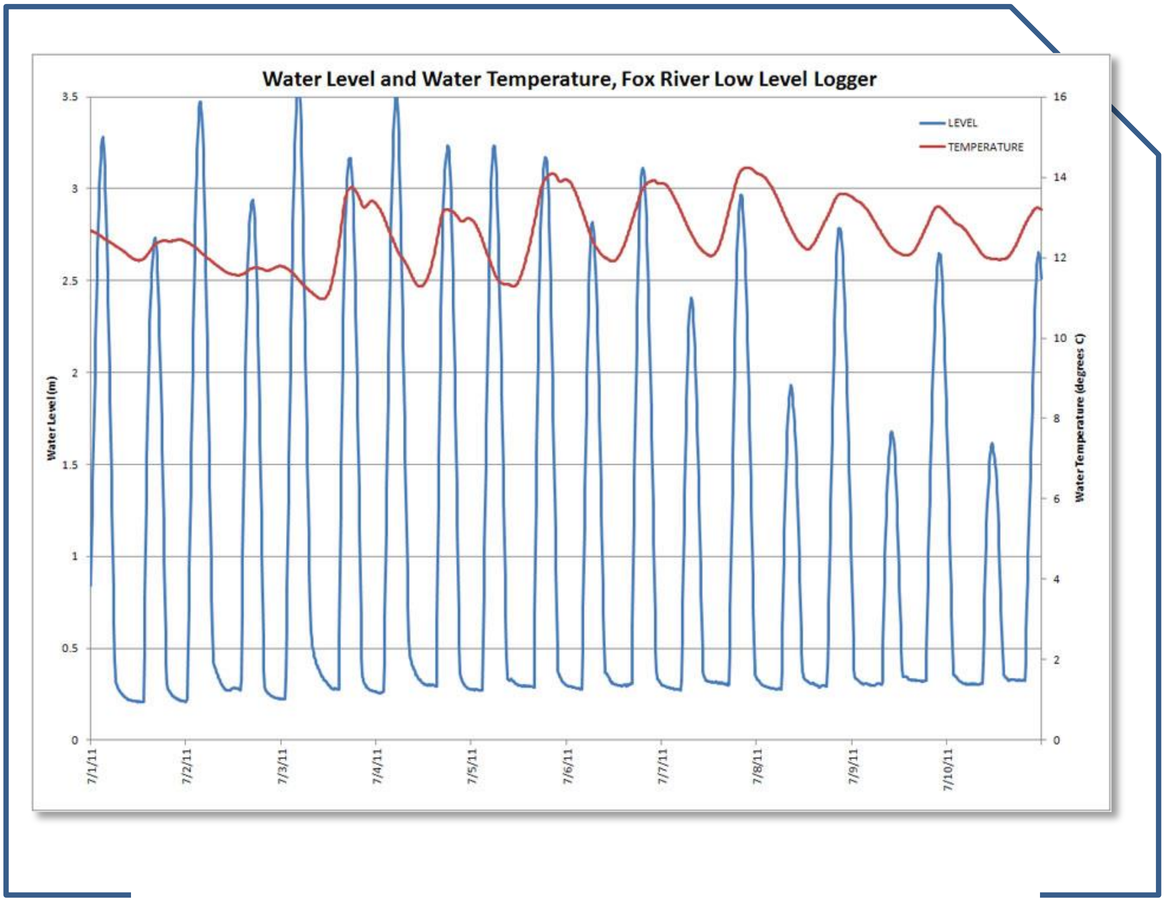


Figure11. Water level and water temperature trends during July, 2011 collected in the lower marsh of Fox River Flats, Kachemak Bay, Alaska.

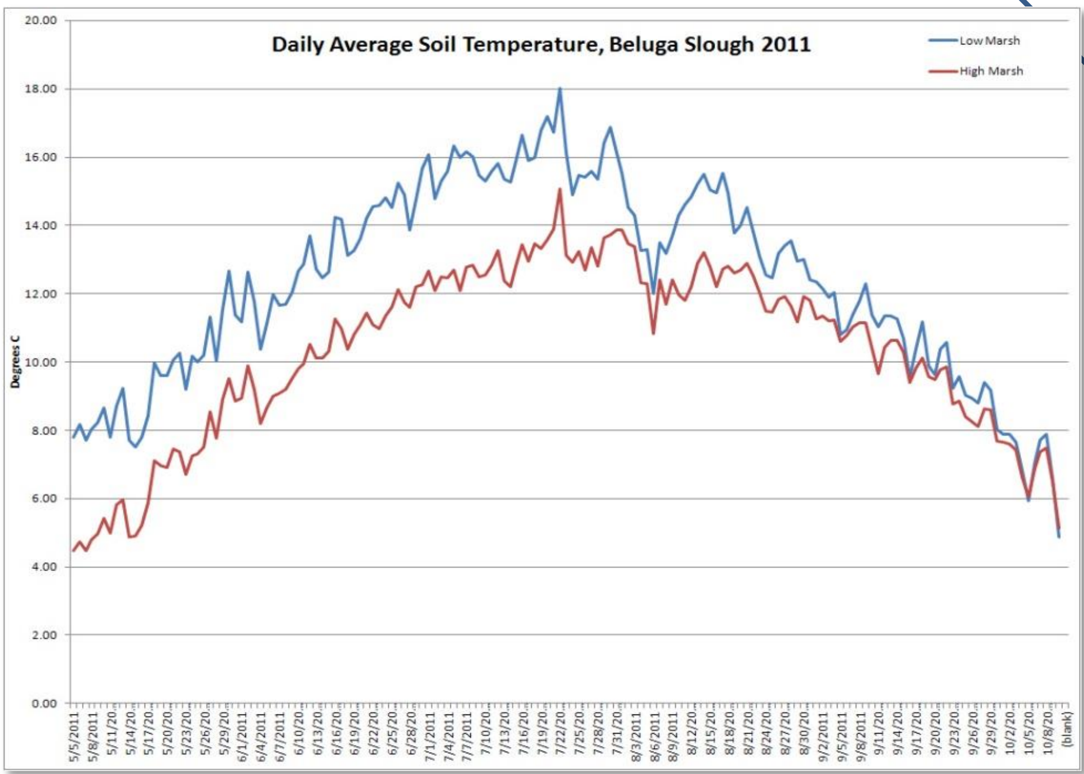


Figure 12. The average daily soil temperatures in the upper and lower marsh areas of Beluga Slough collected May-October 2011, Kachemak Bay, Alaska.

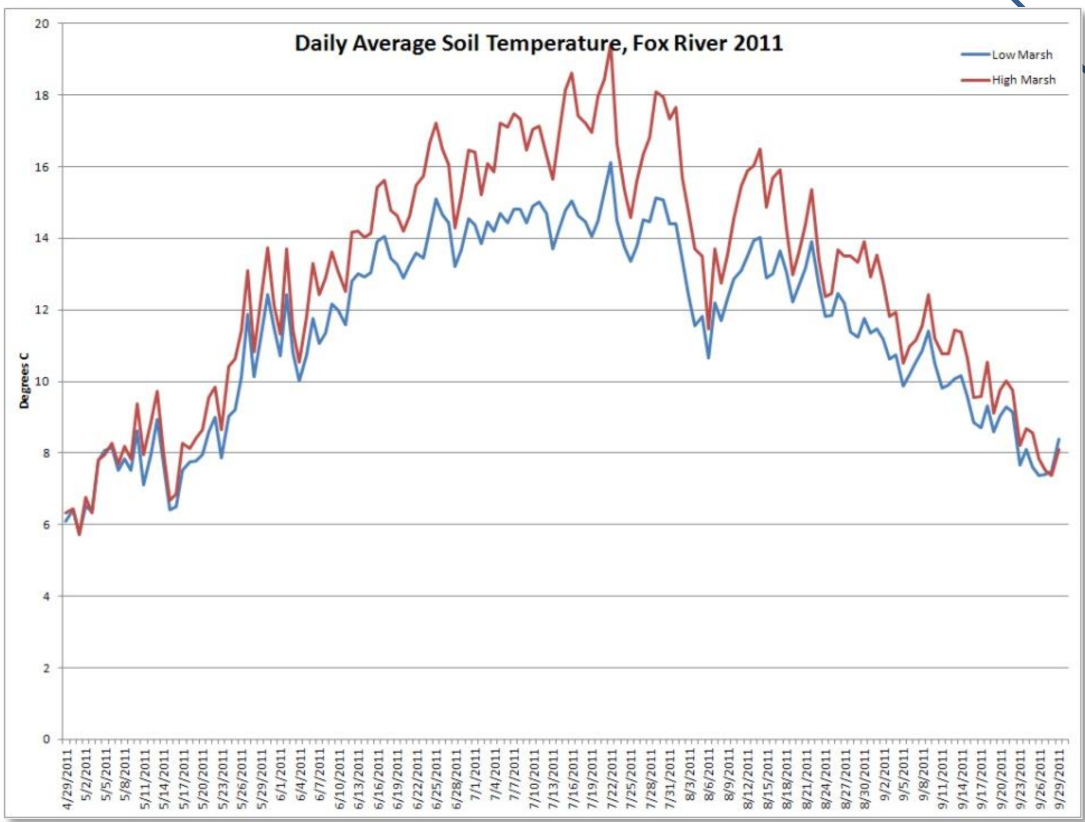


Figure 13. The average daily soil temperatures in the upper and lower marsh areas of Fox River Flats collected April-September 2011, Kachemak Bay, Alaska.

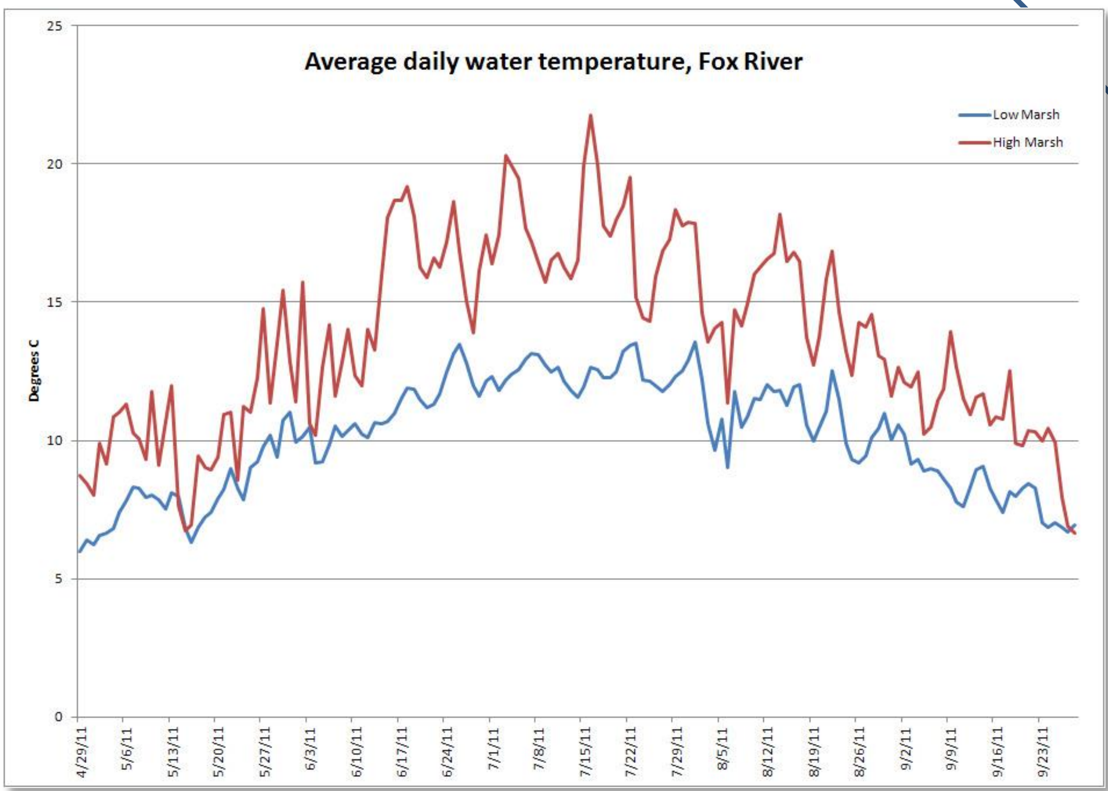


Figure 14. The average daily water temperatures in the upper and lower marsh areas of Fox River Flats collected April-September 2011, Kachemak Bay, Alaska.

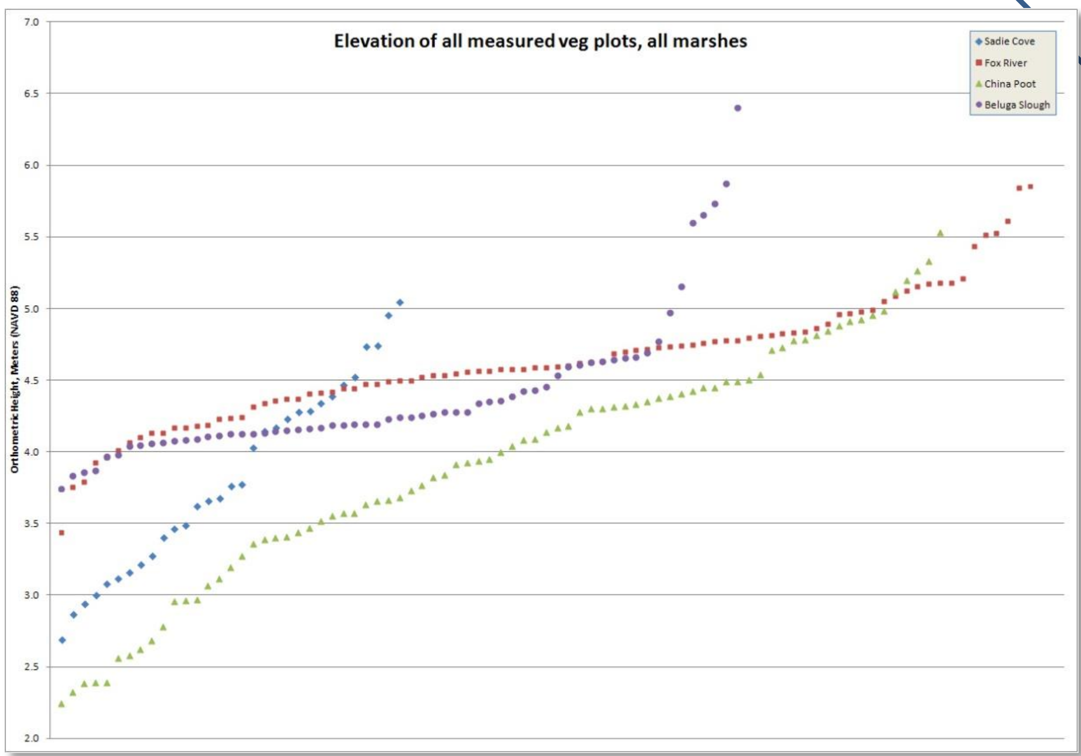


Figure 15. Average orthometric height (m) for all permanent vegetation plots established in Beluga Slough, China Poot, Fox River Flats, and Sadie Cove during 2011-2013 in Kachemak Bay, Alaska.

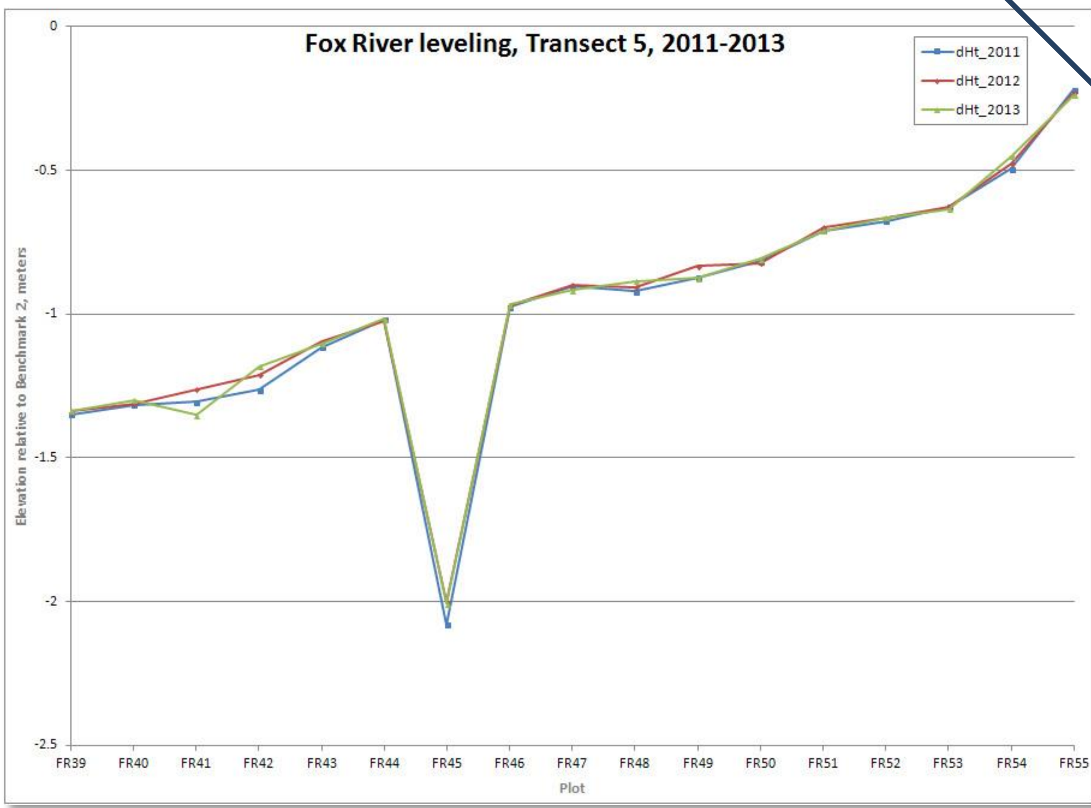


Figure 16. Orthometric height (m) for all permanent vegetation plots established along transect number 5 in Fox River Flats during 2011-2013 in Kachemak Bay, Alaska.

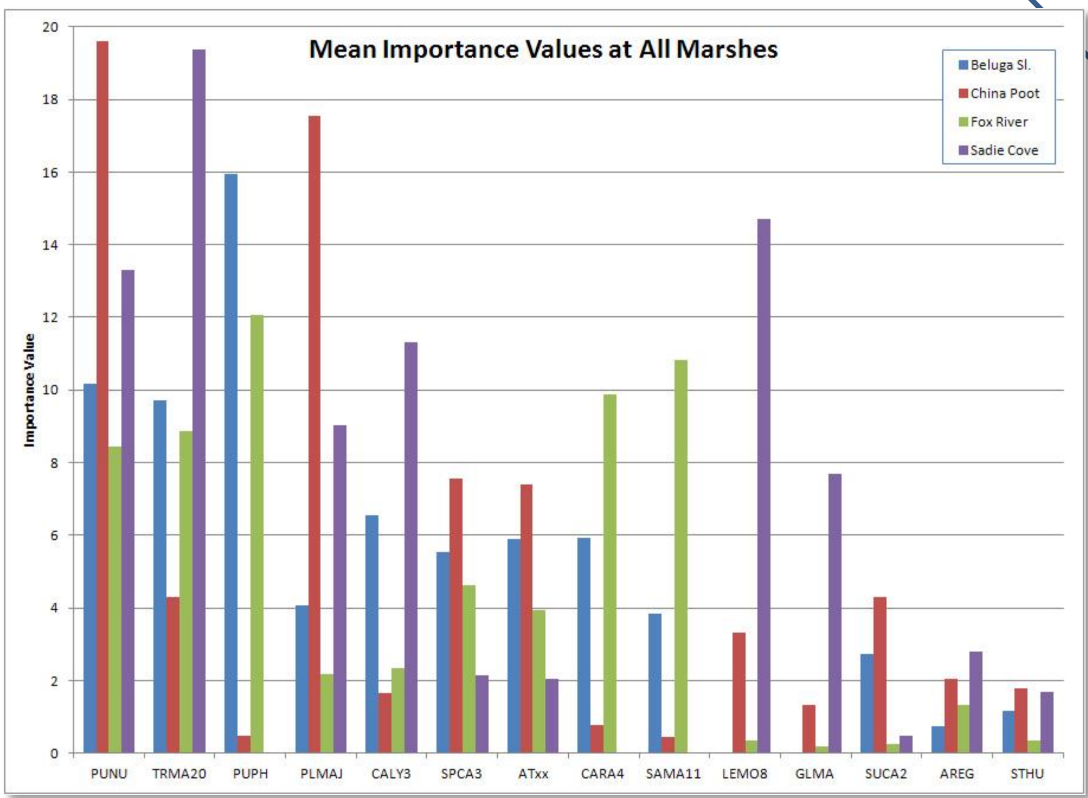


Figure 17. We monitored emergent salt marsh vegetation in Beluga Slough, China Poot, Fox River Flats, and Sadie Cove during 2011-2013 in Kachemak Bay, Alaska. This figure shows the relative importance of each plant species averaged across years within a marsh.

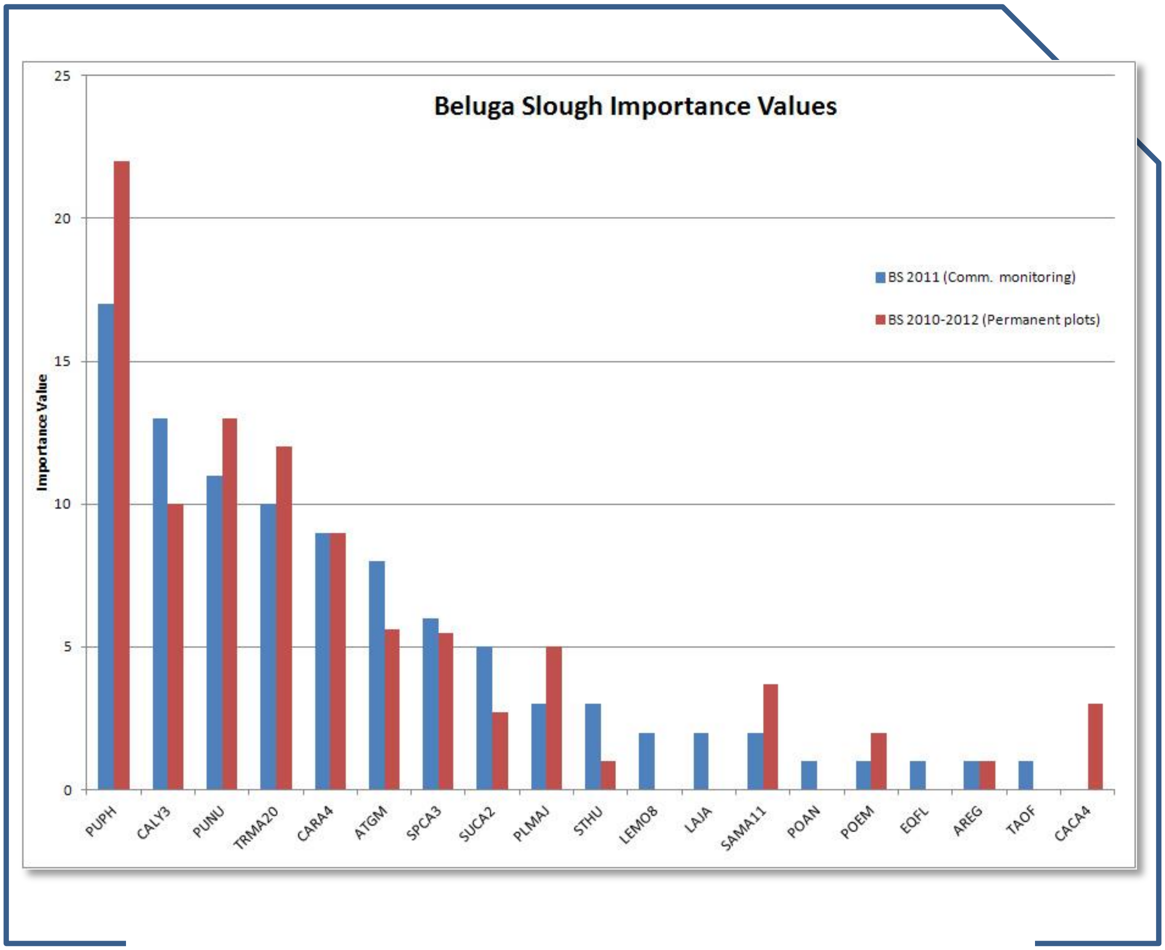


Figure 18. A comparison of emergent salt marsh vegetation sampling methods based on plant species importance values for Beluga Slough during 2010-12 in Kachemak Bay, Alaska.

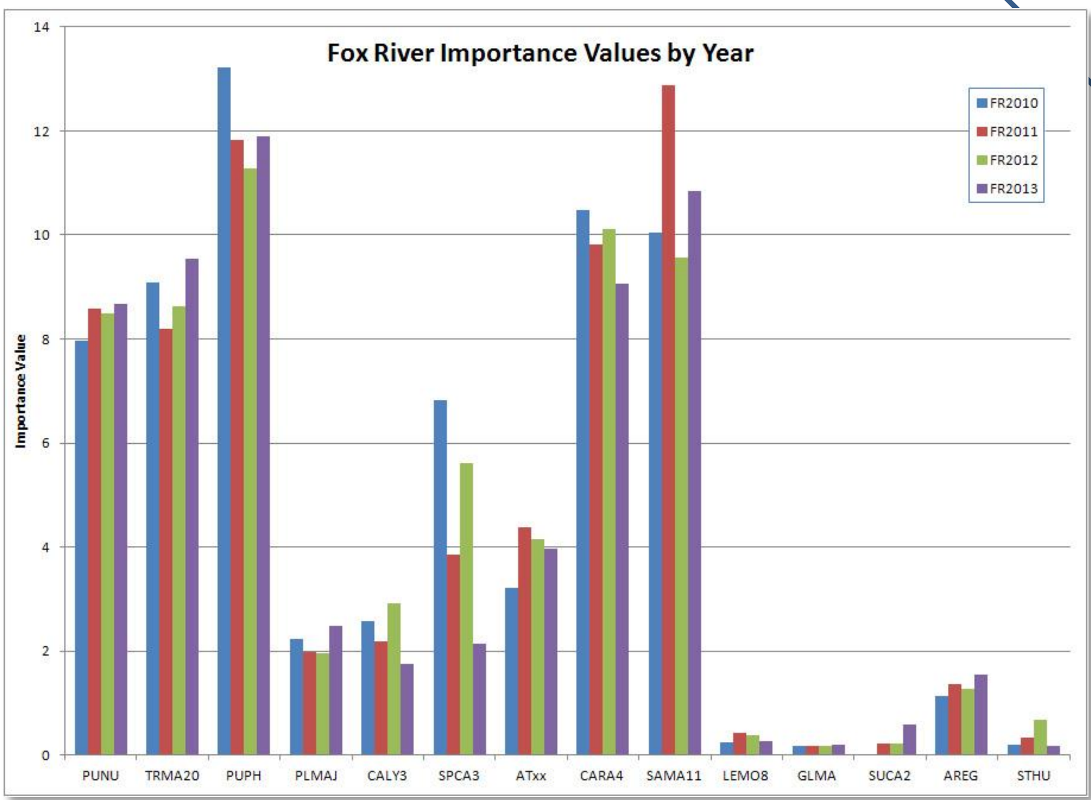


Figure 19. Interannual variability of emergent salt marsh vegetation importance values by dominant plant species in Fox River Flats during 2010-2013 in Kachemak Bay, Alaska.

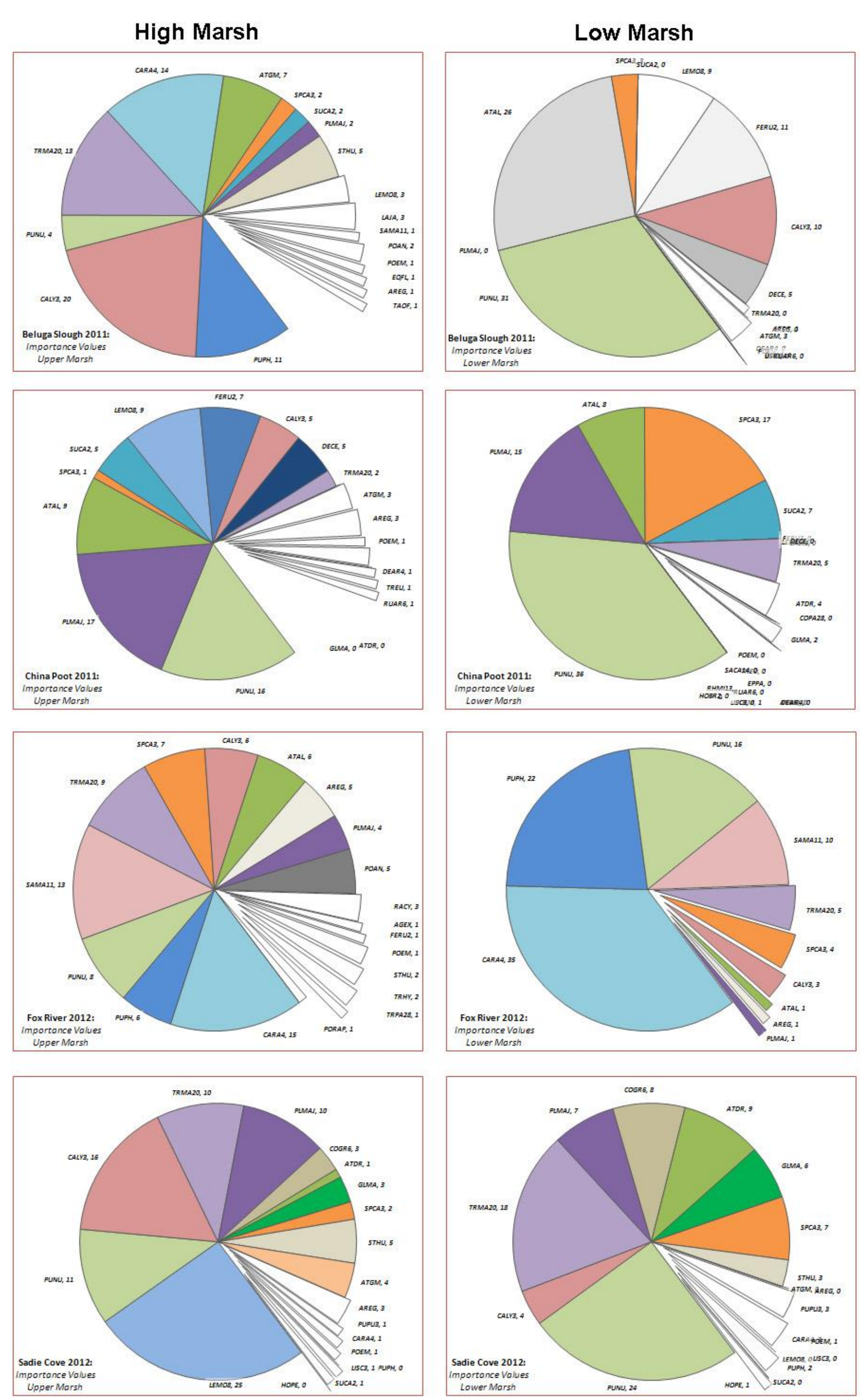


Figure 20. The relative importance values for emergent salt marsh vegetation in the upper and lower habitats in Beluga Slough, China Poot, Fox River Flats, and Sadie Cove during 2011-2013 in Kachemak Bay, Alaska.

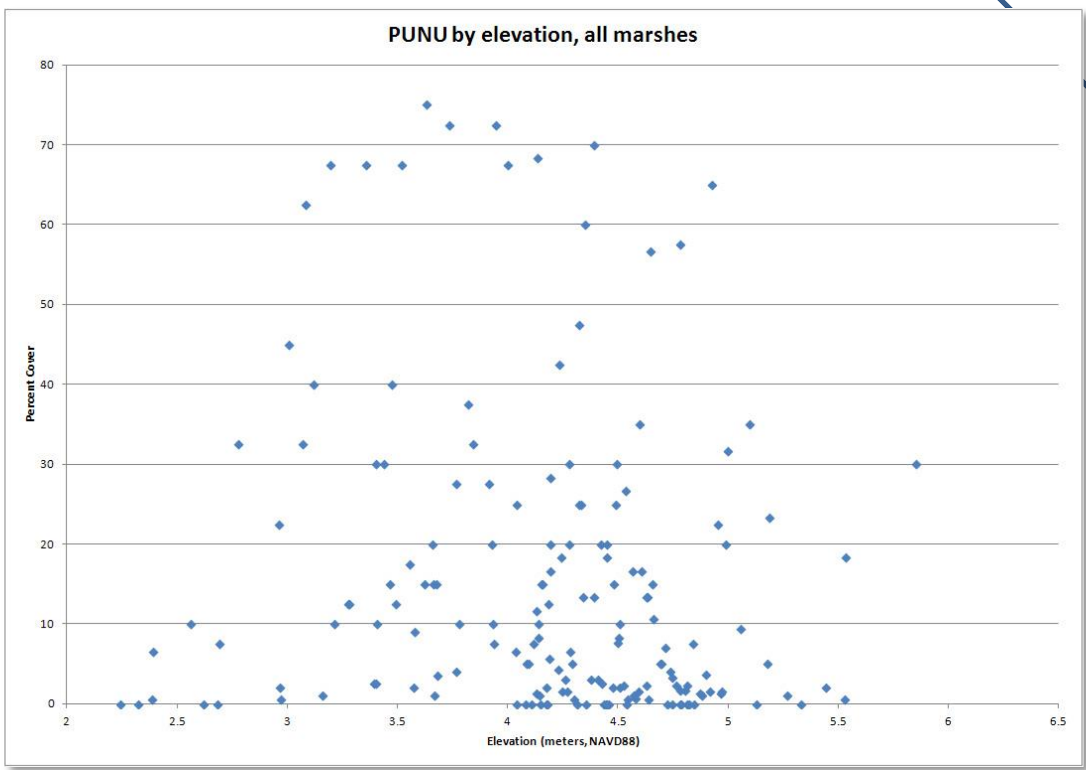


Figure 21. The range of elevations that *Puccinellia nutkaensis*, an emergent salt marsh grass species, occurred in Beluga Slough, China Poot, Fox River Flats, and Sadie Cove during 2011-2013 in Kachemak Bay, Alaska.

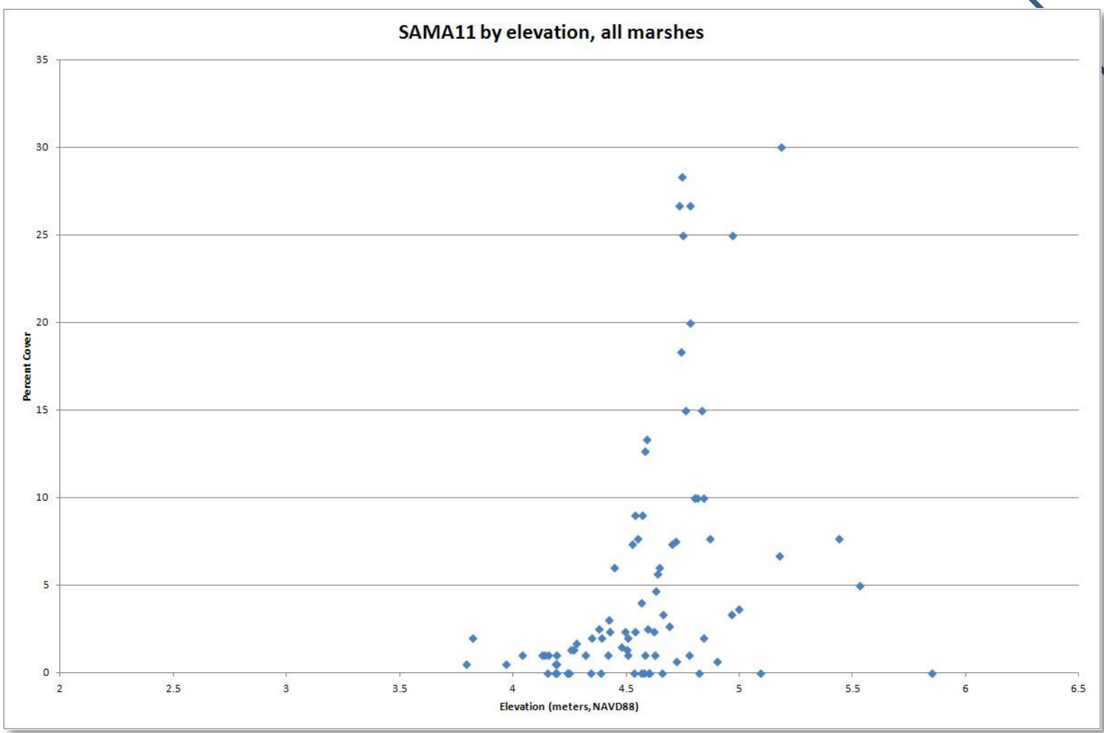


Figure 22. The range of elevations that *Salicornia maritima*, an emergent salt marsh plant species, occurred in Beluga Slough, China Poot, Fox River Flats, and Sadie Cove during 2011-2013 in Kachemak Bay, Alaska.

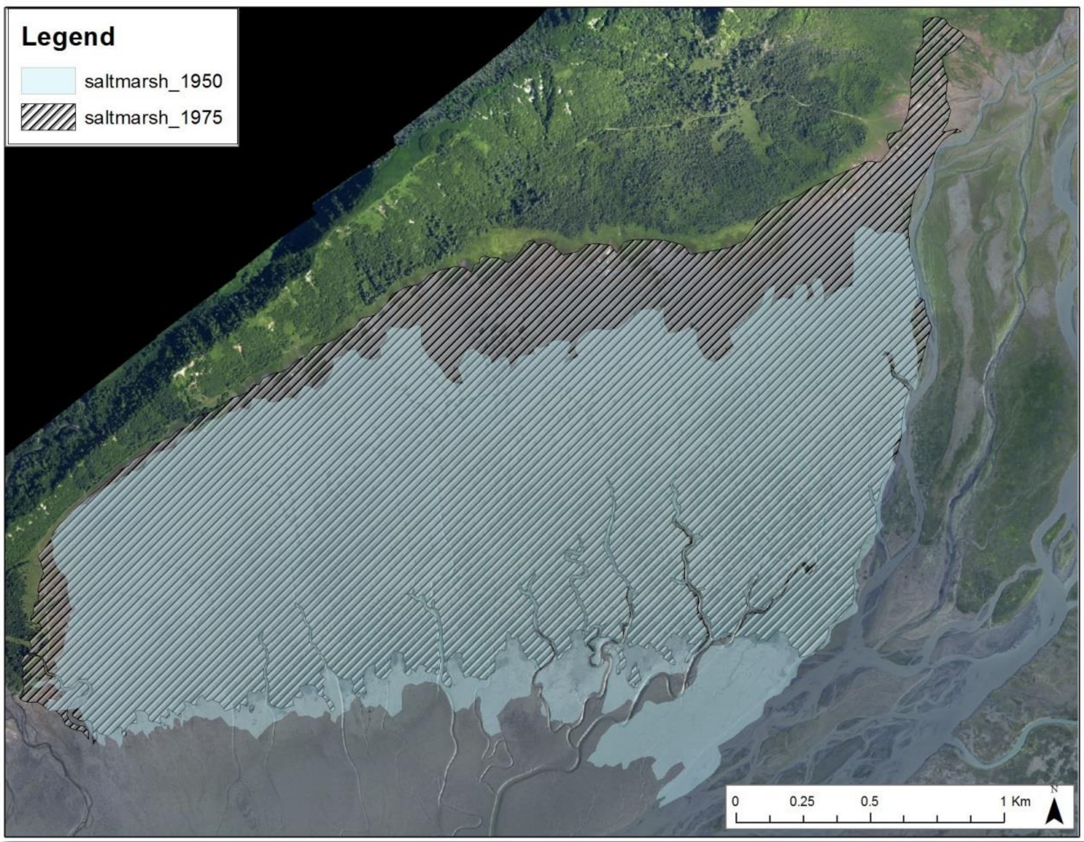


Figure 23. Changes in the area of salt marsh habitat between 1950 (prior to a major earthquake which caused subsidence) and 1975 in Fox River Flats, Kachemak Bay Alaska.

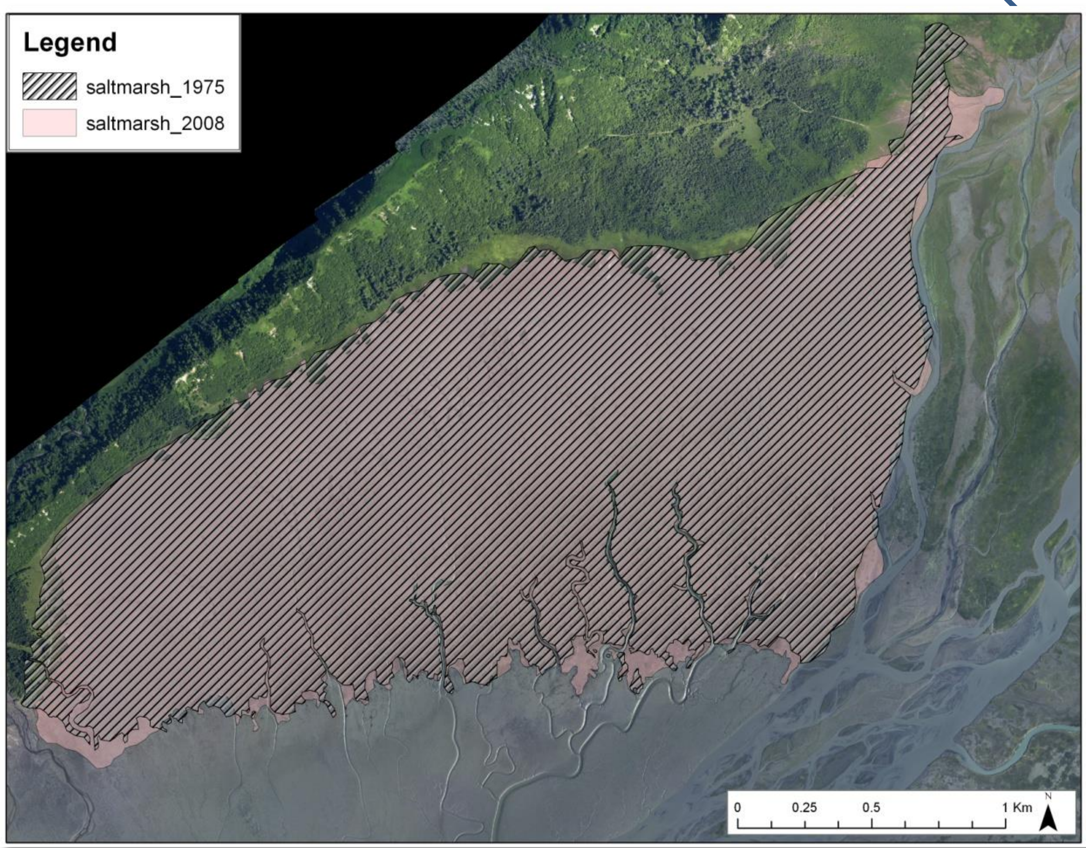


Figure 24. Changes in the area of salt marsh habitat between 1975 (11 years after a major earthquake caused subsidence) and 2008 in Fox River Flats, Kachemak Bay Alaska.

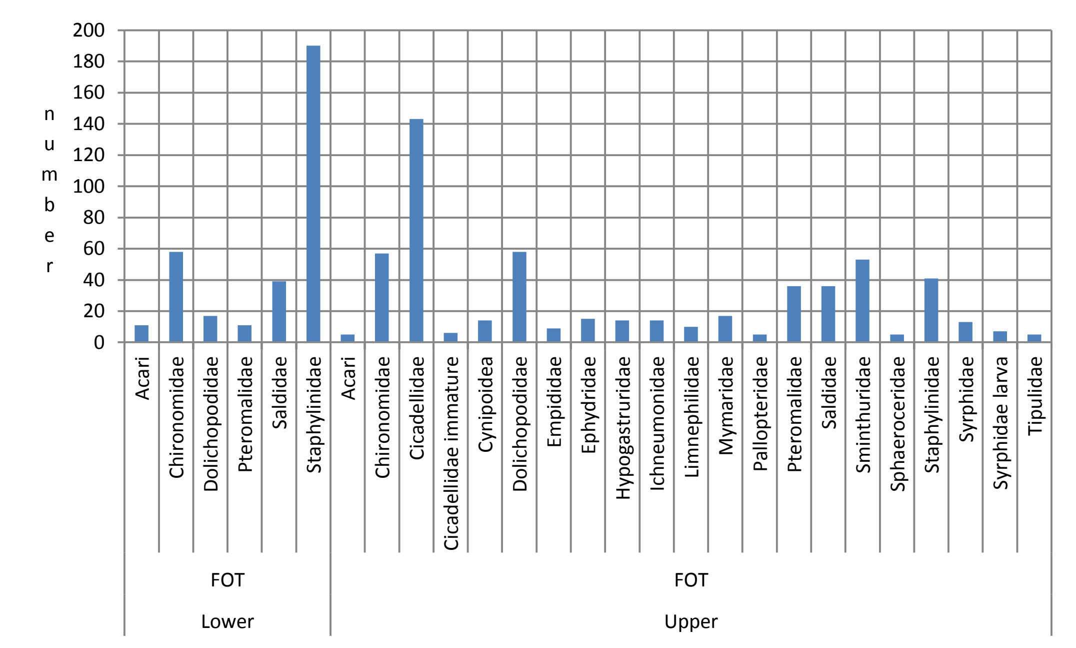


Figure 25. The number of insects by taxon collected in the lower and upper strata of Beluga Slough, Kachemak Bay, Alaska in 2011 by fall out traps.

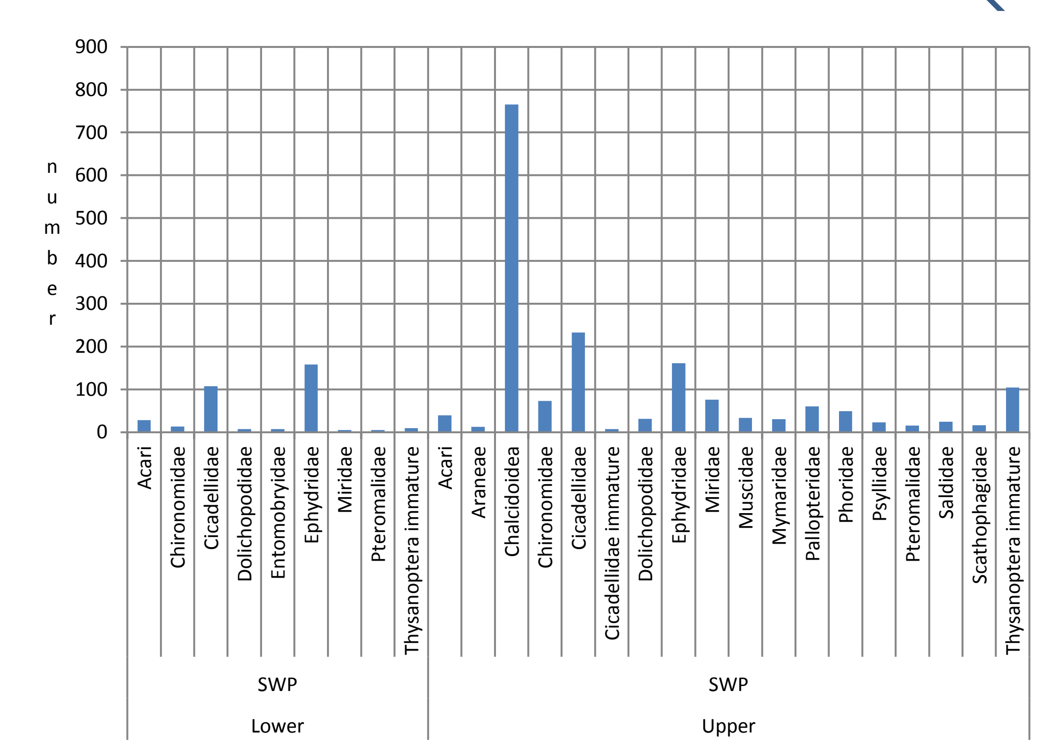


Figure 26. The number of insects by taxon collected in the lower and upper strata of Beluga Slough Kachemak Bay, Alaska in 2011 by bug sweeps.

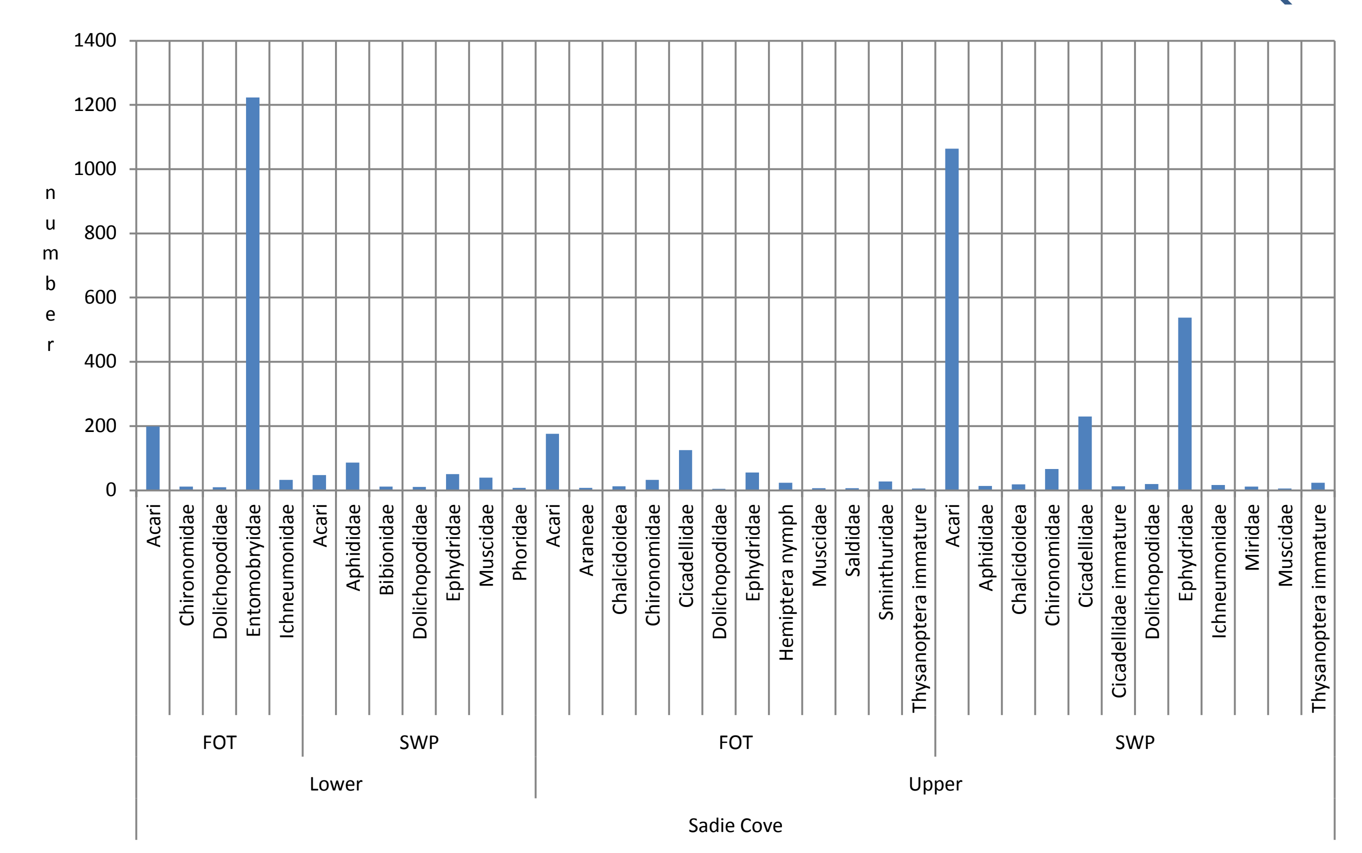


Figure 27. The number of insects by species collected in the lower and upper salt marsh habitats of Sadie Cove, Kachemak Bay Alaska in 2012 using insect fall out traps and sweep samples.

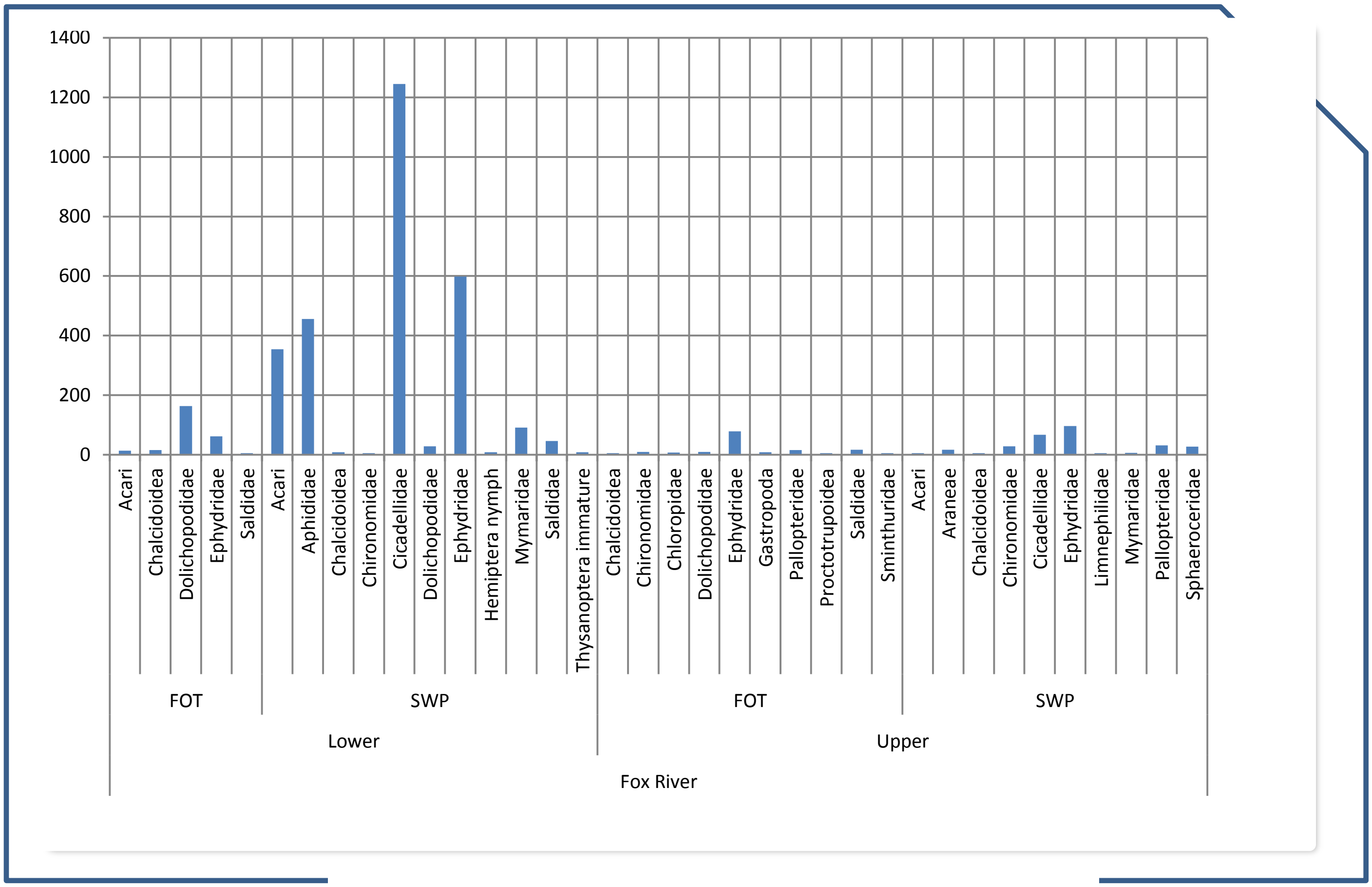


Figure 28. The number of insects by species collected in the lower and upper salt marsh habitats of Fox River Flats, Kachemak Bay Alaska in 2012 using insect fall out traps and sweep samples.

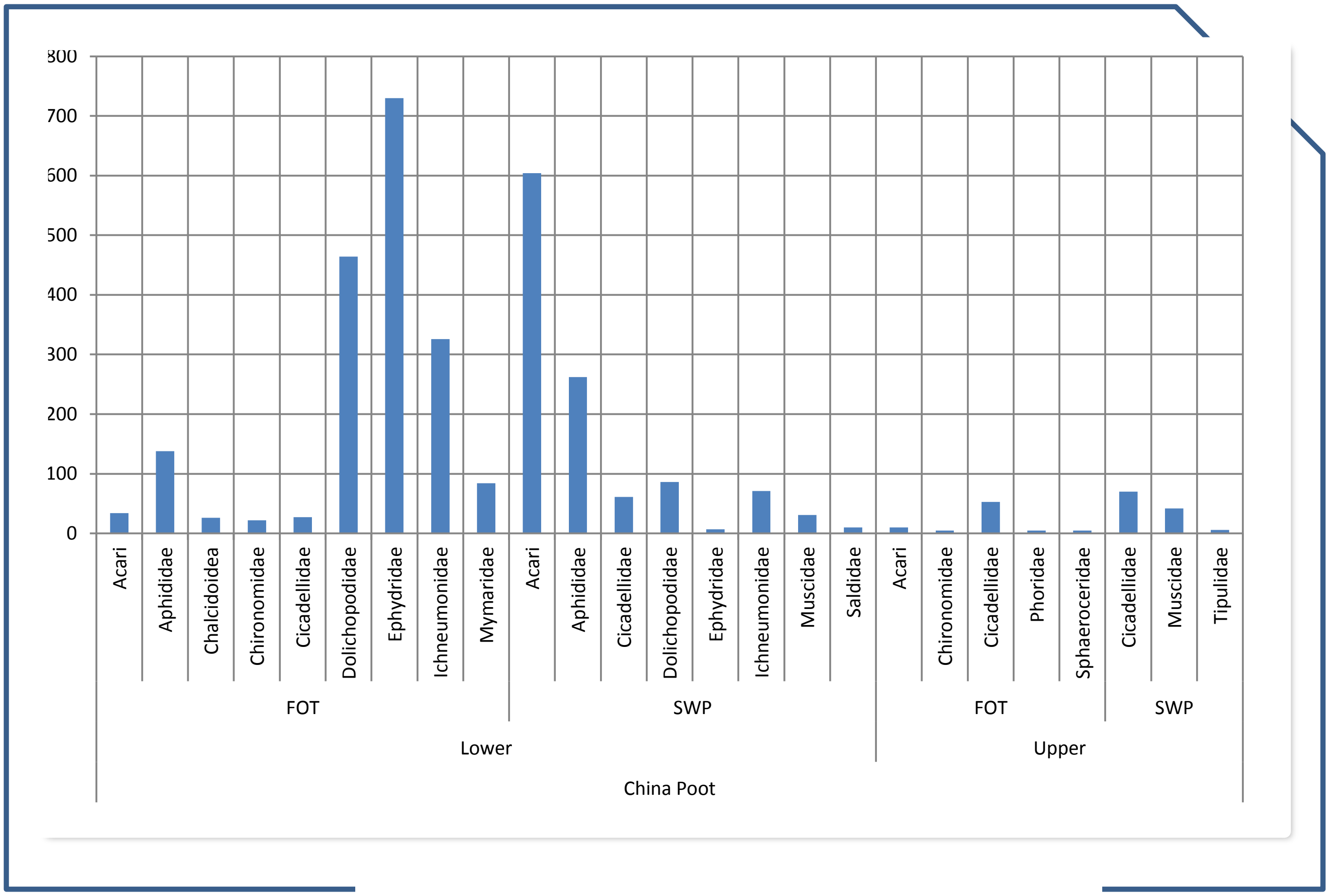


Figure29. The number of insects by species collected in the lower and upper salt marsh habitats of China Poot, Kachemak Bay Alaska in 2011 using insect fall out traps and sweep samples.

Figure 30. Fish sampling in the lower reach of the tidal gut in Fox River Flats, Kachemak Bay, Alaska. 2012.

Figure 31. Fish sampling in the upper reach of the tidal gut in Fox River Flats, Kachemak Bay, Alaska 2012. **Inset:** Juvenile coho salmon from the lower reach.

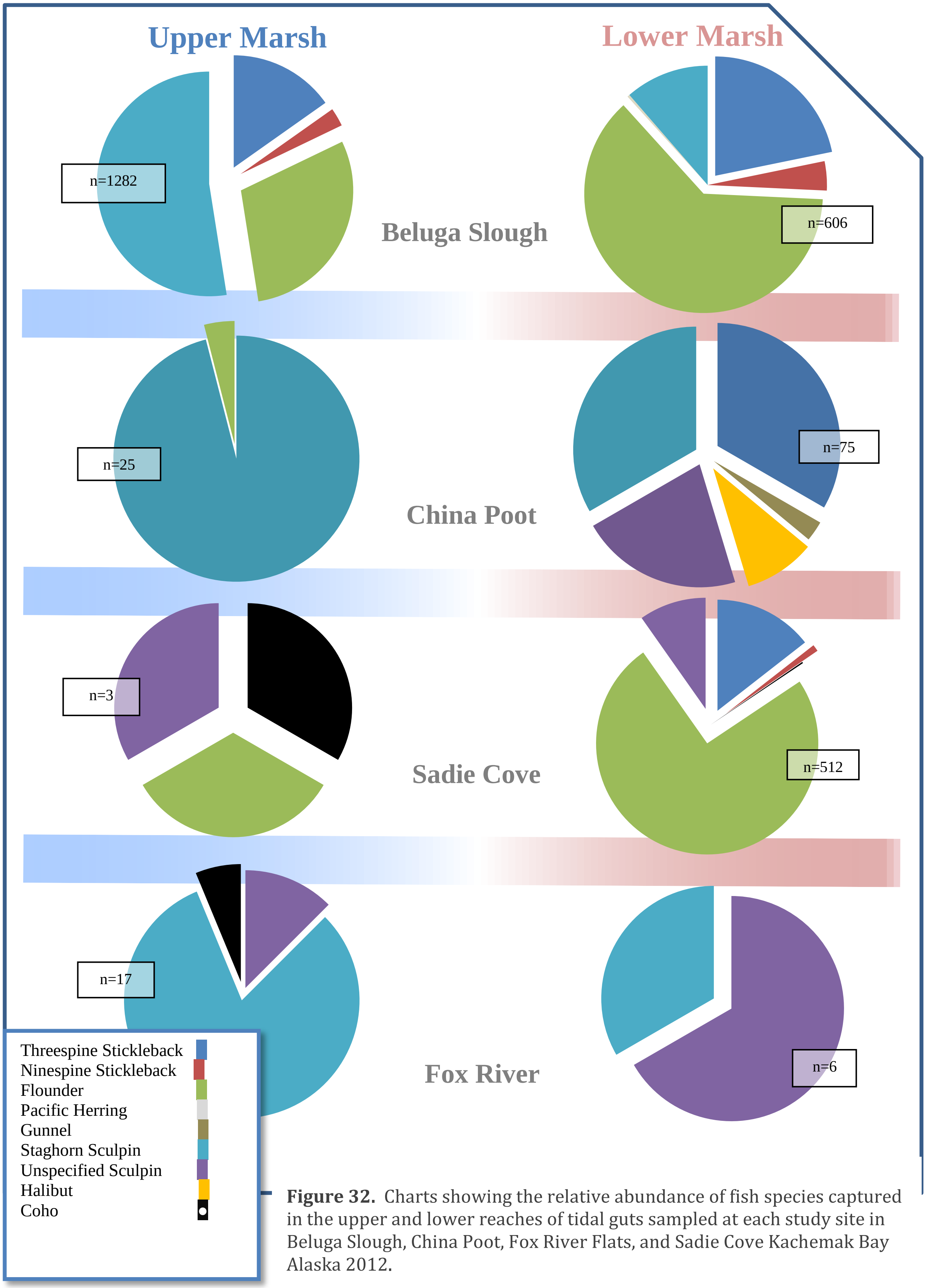


Figure 32. Charts showing the relative abundance of fish species captured in the upper and lower reaches of tidal guts sampled at each study site in Beluga Slough, China Poot, Fox River Flats, and Sadie Cove Kachemak Bay Alaska 2012.

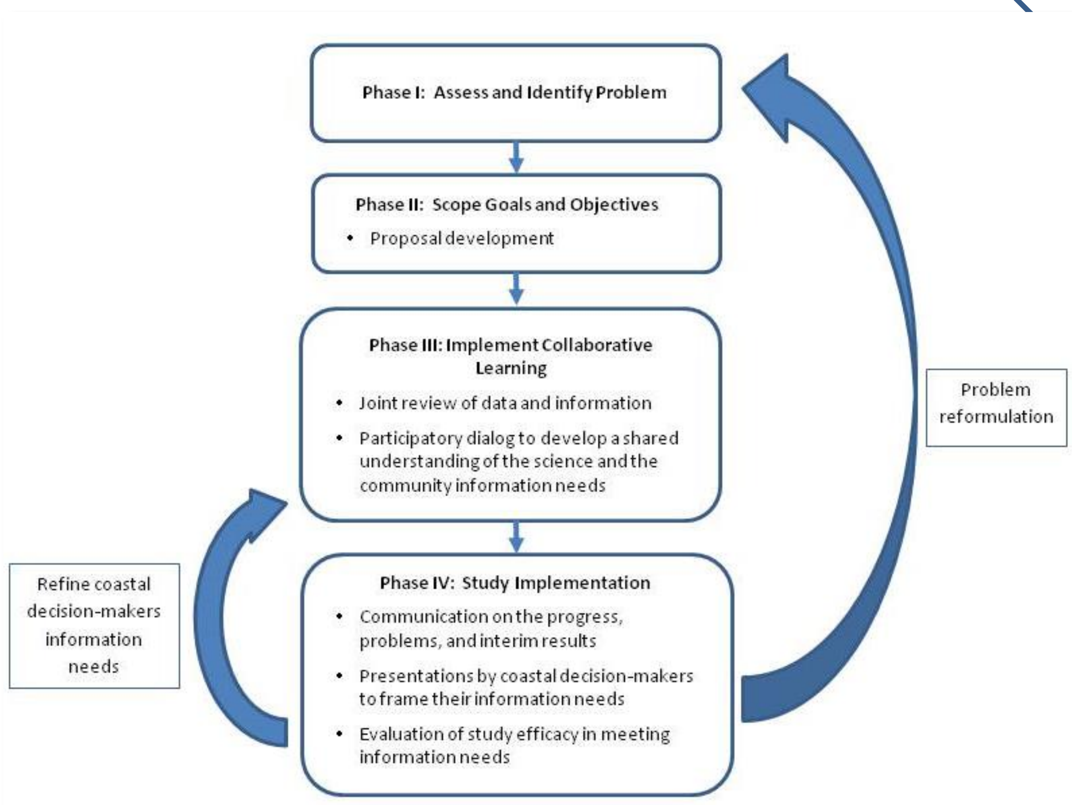


Figure 33. This is a participatory research diagram we illustrate the communication strategy used to connect science on relative sea level rise from the research project into coastal decision-making processes. We modeled this diagram after W. Allen *et al.* 2001 and the Collaborative Learning Guide by C. Feurt (2008).

Tables 1 – 6

Site	Area (km^2)	Watershed (km^2)	Type	Slope(%)[3]	Fresh Water Sources[4]
Beluga Slough	0.5	19.0	Beach barrier	0.52	surface water/ground water fed from Beluga Lake
Fox River Flats	98.6[1]	492.2	Pocket/delta	0.10	glacier melt water/ ground water/ precipitation/snow melt from Fox River
China Poot[2]	6.1	15.6[2]	Delta/beach barrier	0.29	Primarily glacial melt water fed until 1964 and intermittent glacier melt water/ precipitation/snow melt thereafter
Sadie Cove	0.6	23.5	Pocket	0.53	precipitation/snow melt (cut off from glacial melt-water for >60yrs and possibly much longer)

Table 1. During 2010-2013, we established and monitored four long-term monitoring sites in Beluga Slough, China Poot, Fox River Flats, and Sadie Cove salt marsh as part of our Kachemak Bay Research Reserve.

[1] The long-term vegetation monitoring is only 10.46 of the whole salt marsh. To understand the relationship between this and the size of the watershed, the area of the whole marsh is reported here (98.64 km2).
[2]China Poot receives overflow from the much larger Woznesenski River watershed (250.47 km2) during peak river discharge in late summer early fall.
[3]Slopes were calculated along the longest transect, from the highest vegetation plot to the lowest.
[4] There are no data sources for ground water in inputs or flow rates of rivers & streams

	Number of Taxa Represented at 12 Sampling Locations for Each Site			
Site	Insect Fall Out Trap: Upper Marsh (n=6/site)	Insect Fall Out Trap: Lower Marsh (n=6/site)	Sweep Sample Upper Marsh (n=6/site)	Sweep Sample Lower Marsh (n=6/site)
Beluga Slough (2011)	53	33	47	31
China Poot (2011)	33	34	15	15
Fox River Flats (2012)	28	18	29	20
Sadie Cove (2012)	33	21	27	23

Table 2. Insect diversity by sampling methods Insect Fall Out Traps and sweep samples for all sampling sites in Kachemak Bay, Alaska during fall 2011 and 2012.

		Beluga Slough		China Poot		Fox River Flats		Sadie Cove	
	Taxon	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**
Amphipoda	*Americorophium spinicorne*	12							
	Americorophium sp	1							
	Eogammarus sp.							22	
	Isaeidae								1
	Paramoera sp.				7				98
	unknown Amphipoda								2
Annelida	*Arenicolidae*				4				4
	Capitellidae		1						
	Eteone sp.		5						
	Oenonidae		18		32				1
	Oligochaete				1			14	155
	Phyllodocidae				1				
Archaeogastropoda	*Trochidae*								8
Barnacle	*Cirripedia Cirrus*								1
Bivalve	*Macoma balthica*	2			5		1		1
	Macoma sp.		2		14		4		
	Mya Arenaria				1			1	1
	Mytillidae				2				1
Diptera	*Ceratopogonidae*								
	Chironomidae					1	3		
	unknown						16		
	Diptera/hymenoptera				1		1		
	Dolichopodidae						7		
	Ephydridae		1						
	Muscidae				1				
Isopoda	*Gnorimosphaeroma sp.*				2				
	Idoteidae						1		
	Sphaeromatidae								1
Nematoda	*unknown Nematoda*	1							
Nemertea	*unknown Nemertean*				1				2

Table 3. Infaunal invertebrates found in soil core samples taken from surface sediments the Beluga Slough, China Poot, Fox River Flats, and Sadie Cove salt marshes during 2011 and 2012 in Kachemak Bay, Alaska.

Site	Date	Method	Species	Count	Avg Length (mm)	Range (mm)
Beluga Slough	8/12/2011	Seine	Threespine stickleback	33		
			Starry flounder	33		
			Staghorn sculpin	18		
	8/12/2011	Seine	Threespine stickleback	2,534		
			Ninespine stickleback	51		
			Starry flounder	88		
			Staghorn sculpin	41		
	8/12/2011	Fyke	Threespine stickleback	332		
			Ninespine stickleback	4		
			Starry flounder	55		
			Staghorn sculpin	72		
China Poot	8/19/2011	Seine	Threespine stickleback	258		
			Coho salmon	234	54	35-115
			Dolly varden	20	126	73-148
	8/19/2011	Fyke	Staghorn sculpin	2		

Table 4. Fish caught by species using seine (poll seine of 25m multiple reaches) and fyke (tidal gut habitat) nets in Beluga Slough and China Poot salt marsh habitats in Kachmak Bay during fall 2011.

Site	Date	Species	Number of Fish Captured	Avg Length (mm); n=10
Beluga Slough	8/8/2012	Threespine Stickleback	327	31
		Ninespine stickleback	58	42
		Starry Flounder	759	36
		Sand lance	2	42
		Staghorn sculpin	742	62
		Pacific herring	1	
China Poot	8/23/2012	Threespine	25	19
		Gunnel	2	83
		Halibut	7	35
		Sculpin sp.	16	37
		Staghorn sculpin	49	32
		Flounder	1	55
Fox River	8/24/2012	Threespine	1	170
		Sculpin sp.	6	98
		Staghorn sculpin	15	107
		Coho salmon	1	20
Sadie Cove	8/7/2012	Threespine	74	25
		Ninespine	5	23
		Coho salmon	2	40
		Flounder	383	23
		Sculpin sp.	51	27

Table 5. Count and average length for fish captured by species in a 100m of a tidal channel reach where sampled to depletion (upper and lower marsh sampling sites combined) in Kachemak Bay, Alaska during fall 2012.

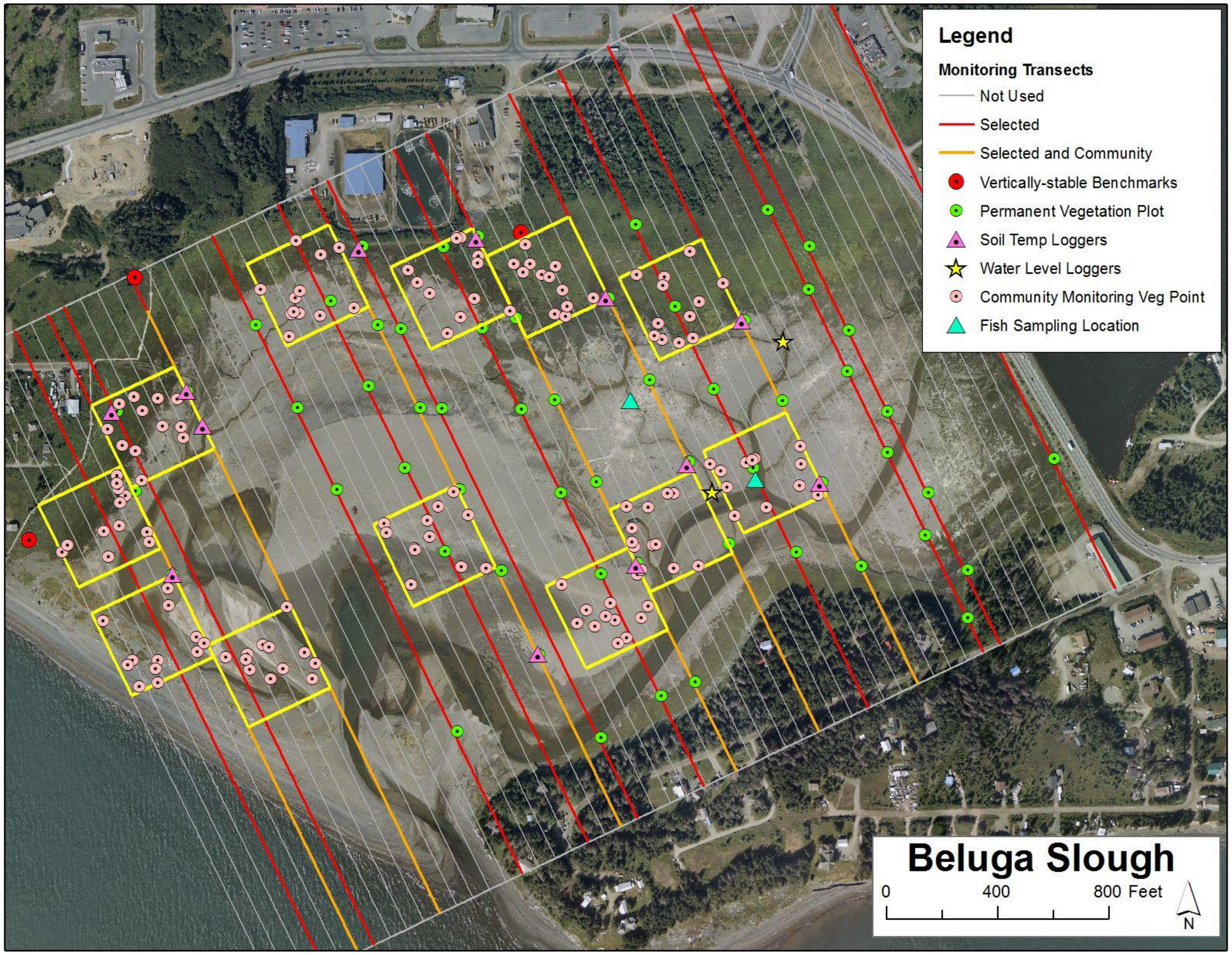
Core Intended Users (CIU)	Justification for listing this User in the Grant	Organization & Professional Responsibilities	How the User may apply this information	Supplementary Info Needed to Support Application of Project Results as Determined During the Course of the Study	Desired Outputs from the Study
City of Homer – Planning	Mayor requested information on coastal uplift & melting glaciers	Planning, zoning, and maintenance of city/port infrastructure	Predict potential problems and inform zoning and planning	Coastal erosion rates, sediment transport.	A geodatabase of uplift and sea-level rise projections so planning can use the informations in conjunction with other relevant data for projects.
City of Homer – Harbor	Water depth is critical to safe vessel traffic patterns	Maintenance and safety of the harbor users	Planning for harbor expansion and maintenance	Coastal erosion rates, sediment transport.	Important to compare with ACOE bench sites to understand how information is integrated (e.g similarities and difference). Indication of Spit sustainability into the future & whether continued infrastructure investment is practical. Projected amount of change for each year in projected timeframe. One page summary of study findings, distributable to Council and Port Commission.
Kenai Peninsula Borough	Land use changes including uplift and coastal erosion	Responsible for mapping natural hazard areas	Identify potential problems and inform planning and zoning	Coastal erosion rates, sediment transport.	Simple and concise messaging (“laymen terms”) of project outcome for use while talking to the public. Clear delineation of where this information applies and where it does not. Greatest audience is KPB general public.
Seldovia Village Tribe	Predicting changes to the local environment on tribal lands	Responsible for environmental monitoring of subsistence foods	Identify potential problems for subsistence harvest of bivalves/salmon	Life history and population trends of salmon & bivalves & how biology interacts w/ physical habitat	Understanding rates of coastal ‘rebound’ specifically in the context of how marine organisms will be affected. Information about river or channel entrance morphology and available bivalve habitat. Available information is final report and GIS layers.

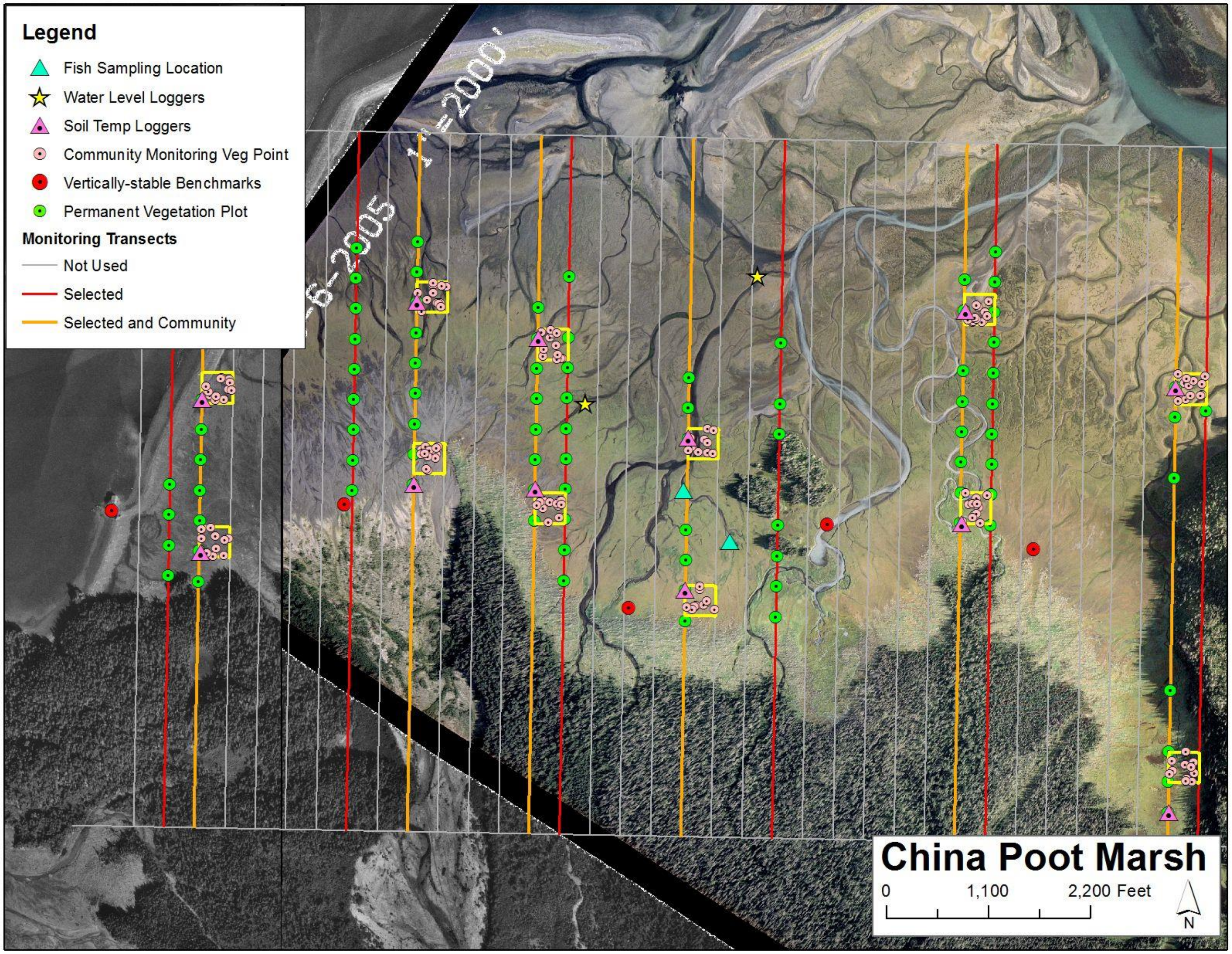
Table 6a. Integration matrix for coastal descion-makers on relative sea-level changes in Kachemak Bay, Alaska during 2011-2013.

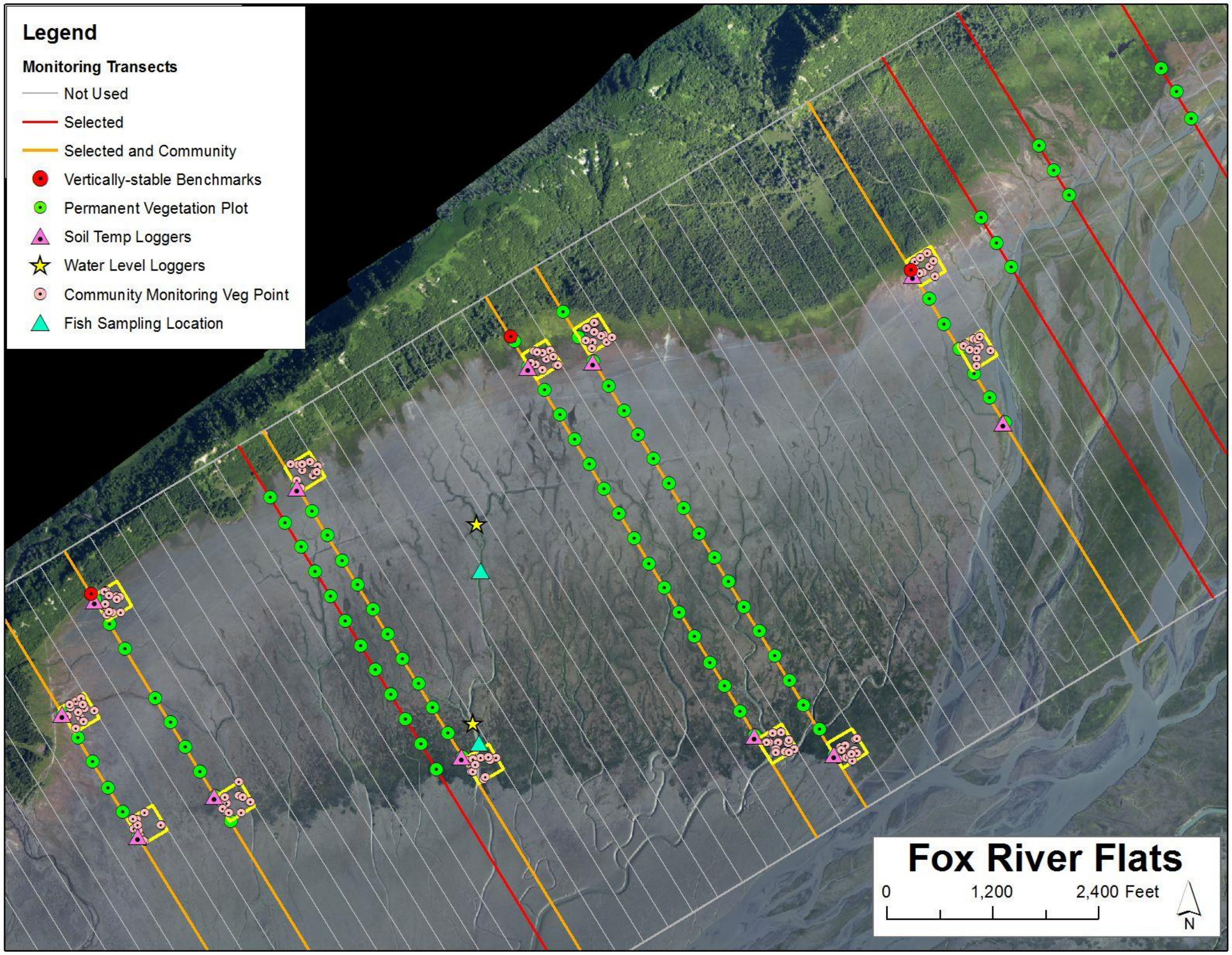
Core Intended Users (CIU)	Justification for listing this User in the Grant	Organization & Professional Responsibilities	How the User may apply this information	Supplementary Info Needed to Support Application of Project Results as Determined During the Course of the Study	Desired Outputs from Study (based on interviews)
Alaska Department of Natural Resources – Division of Mining, Land and Water	Primary manager of the state's land holdings	Ensure state title, prepare land use plans, leases & permits on state land	Accretion/reliction due to isostatic uplift	Must be paired with property ownership data.	Publically- available GIS layers on Parcel Viewer to assist in visually relaying information for shoreline development. Peer-reviewed publication of the results to promote confidence in permit related decisions.
NOAA/NOS/NCCOS-Kasitsna Bay Laboratory	Provides baseline information to KBL mission to understand climate change impacts on coastal ecosystems	Provide science products and tools to inform coastal management decisions	Support studies e.g. habitat impacts of glacial melt, habitat mapping, intertidal community biodiversity	Understanding of bathymetry, land/sea interface & elevation changes, physical circulation	Quantified rates of land-level change and SLR. Clear statement of known risk for projected timeframe. Clear delineation of where this information applies and where it does not. Projected change in salt marsh vegetation communities over time attributed to variations in land and sea level.
ADF&G Habitat Division	Primary manager of State designated critical habitat areas including Kachemak Bay/Fox River Flats, Homer Airport, Clam Gulch and Anchor River/Fritz Creek.	Conditions Special Area and Fish Habitat Permits involving habitat altering or potential habitat altering activities in anadromous streams and Critical Habitat Areas.	Gain understanding concerning how natural resource development projects can impact habitat and how to best condition permits to avoid or minimize potential problems.	Land/sea interface & elevation changes, coastal erosion rates, sediment transport?	Publically- available GIS layers on Parcel Viewer to assist in visually relaying information for shoreline development. Clear message of study outcome to provide scientific support and confidence in permitting-related decisions.

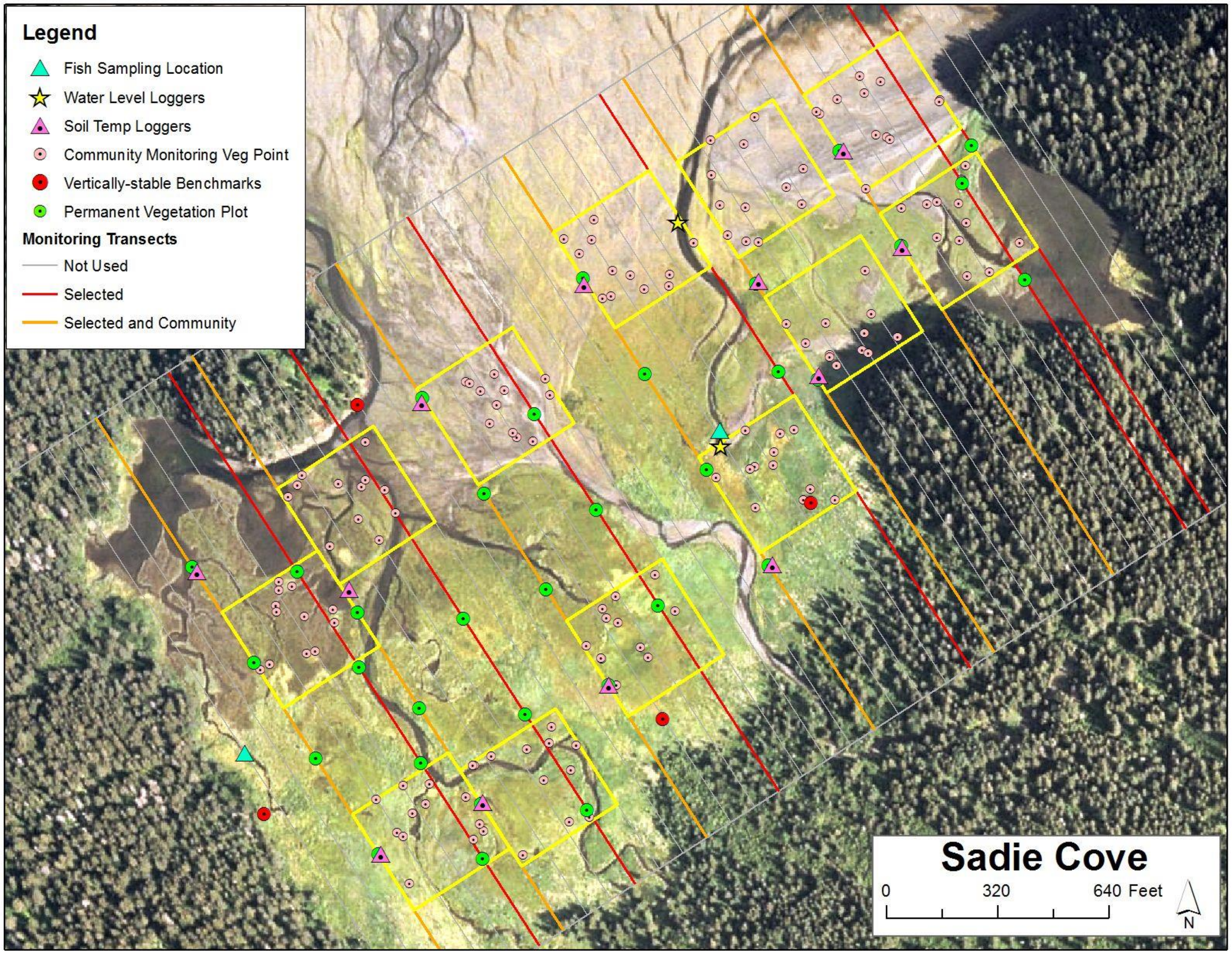
Table 6b. Integration matrix for coastal descion-makers on relative sea-level changes in Kachemak Bay, Alaska during 2011-2013.

Appendix A. Maps of Plant Community Monitoring in four Sentinel Sites in Kachemak Bay, Alaska.




Legend
Fish Sampling Location
Water Level Loggers
Soil Temp Loggers
Community Monitoring Veg Point
Vertically-stable Benchmarks
Permanent Vegetation Plot
Monitoring Transects
Not Used
Selected
Selected and Community
China Poot Marsh
0
1,100
2,200 Feet
N


Legend
Monitoring Transects
Not Used
Selected
Selected and Community
Vertically-stable Benchmarks
Permanent Vegetation Plot
Soil Temp Loggers
Water Level Loggers
Community Monitoring Veg Point
Fish Sampling Location
Fox River Flats
0
1,200
2,400 Feet
N


Legend
Fish Sampling Location
Water Level Loggers
Soil Temp Loggers
Community Monitoring Veg Point
Vertically-stable Benchmarks
Permanent Vegetation Plot
Monitoring Transects
Not Used
Selected
Selected and Community
Sadie Cove
0
320
640 Feet
N

Appendix B. Summary of data collected in the Citizen Science biological diversity sampling of Beluga Slough, China Poot, Fox River Flats, and Sadie Cove during 2011-2012 in Kachemak Bay, Alaska.

Appendix C. Project Communication Points for the study: Assessing Coastal Uplift and Habitat Changes in a Glacially Influenced Estuary System.

KACHEMAK BAY RESEARCH RESERVE

Salt Marsh Habitats: Citizen Science Monitoring 2011-12

In 2010, the Kachemak Bay Research Reserve was awarded a grant from the University of New Hampshire to study the relative sea-level rise in our Reserve. An element of the study included the development of a monitoring program for four salt marsh sites. In the vegetation community structure, salt marsh plants range from freshwater to salt-tolerant plants, providing a sensitive indicator of sea-level rise. When paired with models of land-level change, mapped vegetation communities provide valuable information on relative shifts in sea-level rise and land-level change over time.

Through this study, we also obtained baseline biological diversity information for each marsh, including insects, infaunal invertebrates, fish, birds, and mammals in the marshes. During 2011 and 2012, we enlisted 30 people to participate in citizen science trainings to help collect the data.

Common Name	***Beluga Slough***	***China Poot***	***Fox River***	***Sadie Cove***
Black Bear		☼		☼
Brown Bear			☼	
Cow			☼	
Coyote		☼		☼
Dog	☼			
Harbor Seal		☼		
Mink	☼			☼
Moose	☼		☼	
Muskrat	☼		☼	
Northern Red-backed Vole	☼			
River Otter		☼		☼
Sea Otter	☼			
Red Squirrel				☼
Wolf			☼	

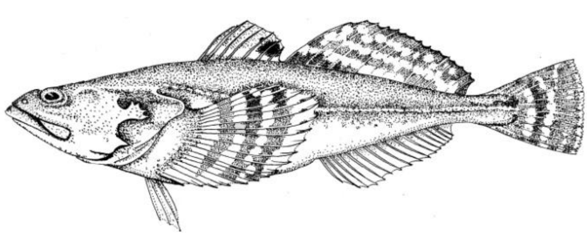
TABLE 1: MAMMAL SPECIES OR SIGN IDENTIFIED IN THE UPPER AND LOWER MARSHES DURING AUGUST 2011 AND 2012

Common Name	***Beluga Slough***	***China Poot***	***Fox River***	***Sadie Cove***
American Pipit		☼		
Bald Eagle	☼	☼	☼	☼
Belted Kingfisher	☼			
Common Loon		☼		
dabbling ducks	☼			
Dowitcher sp.	☼			
Fox Sparrow				☼
Glaucous Gull	☼			
Glaucous-winged Gull	☼	☼	☼	☼
Greater Yellowlegs	☼		☼	
Green-winged Teal	☼			
Pine Grosbeak				☼
Least Sandpiper	☼	☼	☼	
Mallard	☼			
Merlin	☼			☼
Mew Gull	☼			☼
Northern Harrier			☼	
Northern Pintail		☼		
Northwestern Crow	☼			☼
Orange-crowned Warbler			☼	
Peregrine Falcon	☼	☼		
Ring-necked Pheasant	☼			
Common Raven		☼	☼	
Sandhill Crane	☼		☼	
Sandpiper sp.	☼			
Savannah Sparrow	☼	☼		☼
Sharp-shinned Hawk				☼
Northern Shoveler	☼			
Spotted Sandpiper		☼		
Steller's Jay	☼			
Swainson's Thrush				☼
Wandering Tattler	☼			
White-fronted Goose			☼	
White-winged Crossbill				☼
Wilson's Snipe	☼			

TABLE 2: AVIAN SPECIES OR SIGN IDENTIFIED IN THE UPPER AND LOWER MARSHES DURING AUGUST 2011 AND 2012

During August 2011 and 2012 in the four salt marshes sampled, 69 plant species, 36 avian species, and 14 different mammal species were identified (visually or by sign of their existence such as scat, tracks, hair, etc.) [Tables 1-3].

Citizen scientists helped sample salt marsh vegetation at randomly placed 1x1 meter plots in the upper and lower marsh area. The methods were standardized to ongoing studies; at each plot, observers recorded the percent cover and frequency of occurrence for each plant species encountered. A relative *importance value* was then determined for each plant species and averaged across all plots. In Figures 1-8, the relative importance values are shown, as well as the vegetation maps associated with all four salt marshes (1996). The vegetation maps include fish species identified at each site in 2012.



This baseline data collected is important to characterize the current ecological conditions at each salt marsh site. Sites will continue to be monitored as an index of sea-level rise over time.

Using an integrated approach, citizen scientists gained a deeper understanding of the dynamic processes at work on coastal environments, such as the changes to tidewater plant and animal diversity associated with melting glaciers and rising sea water in and around Kachemak Bay. Further, the Reserve benefited from having many trained eyes making detailed assessments of the marsh biodiversity as it exists today. The Reserve has provided these citizen scientists with an opportunity to experience the salt marshes of Kachemak Bay in fine detail, examining their vegetative makeup, evaluating their differences, and understanding at a deep--even visceral--level the importance of these ecosystems to the overall health of the bay. They will see these marshes in a different light from now on and be better stewards because of it!

KACHEMAK BAY RESEARCH RESERVE

Salt Marsh Habitats: Citizen Science Monitoring 2011-12

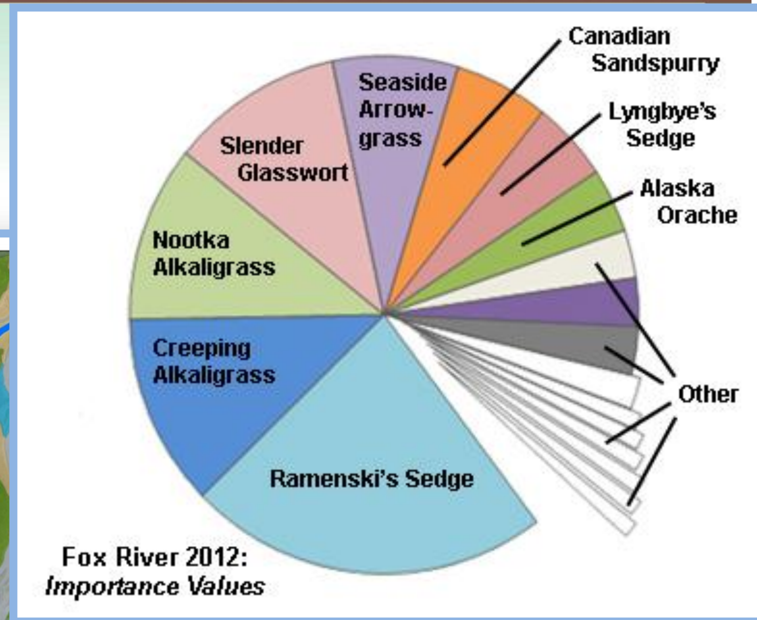


FIGURE 1: FOX RIVER SALT MARSH VEGETATION IMPORTANCE VALUES ARE CALCULATED FROM THE FREQUENCY AND PERCENT COVER FOR EACH SPECIES

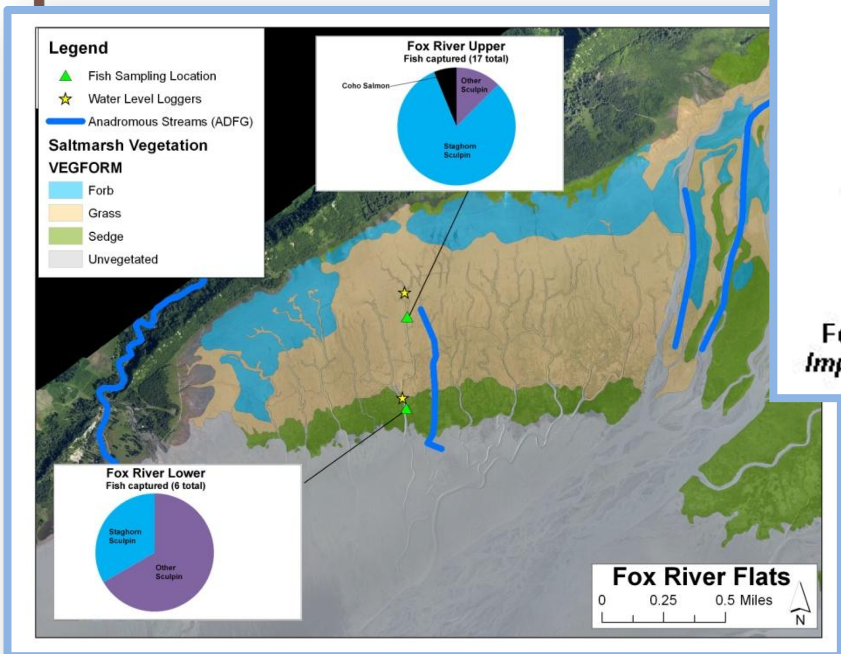
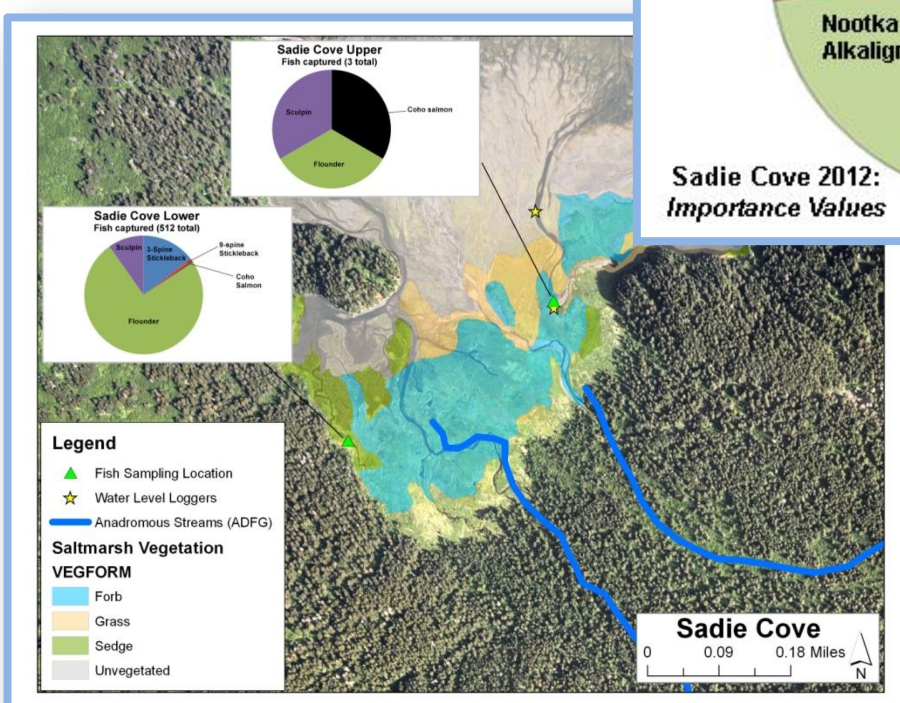


FIGURE 2: FOX RIVER EMERGENT VEGETATION COVER MAPAND KNOWN FISH SPECIES

FIGURE 4: SADIE COVE EMERGENT VEGETATION COVER MAPAND KNOWN FISH SPECIES



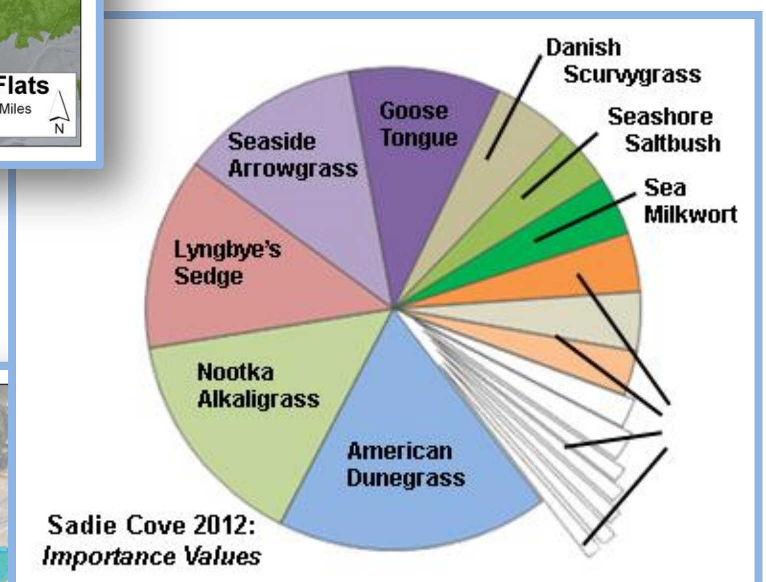


FIGURE3: SADIE COVE SALT MARSH VEGETATION IMPORTANCE VALUES ARE CALCULATED FROM THE FREQUENCY AND PERCENT COVER FOR EACH SPECIES

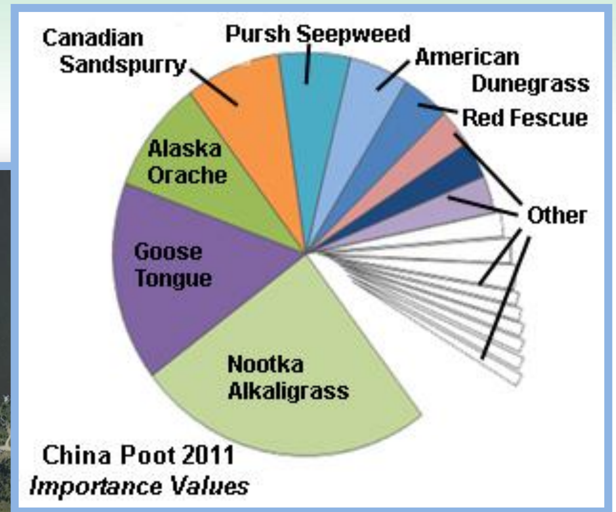


FIGURE 5: CHINA POOT SALT MARSH VEGETATION IMPORTANCE VALUES ARE CALCULATED FROM THE FREQUENCY AND PERCENT COVER FOR EACH SPECIES

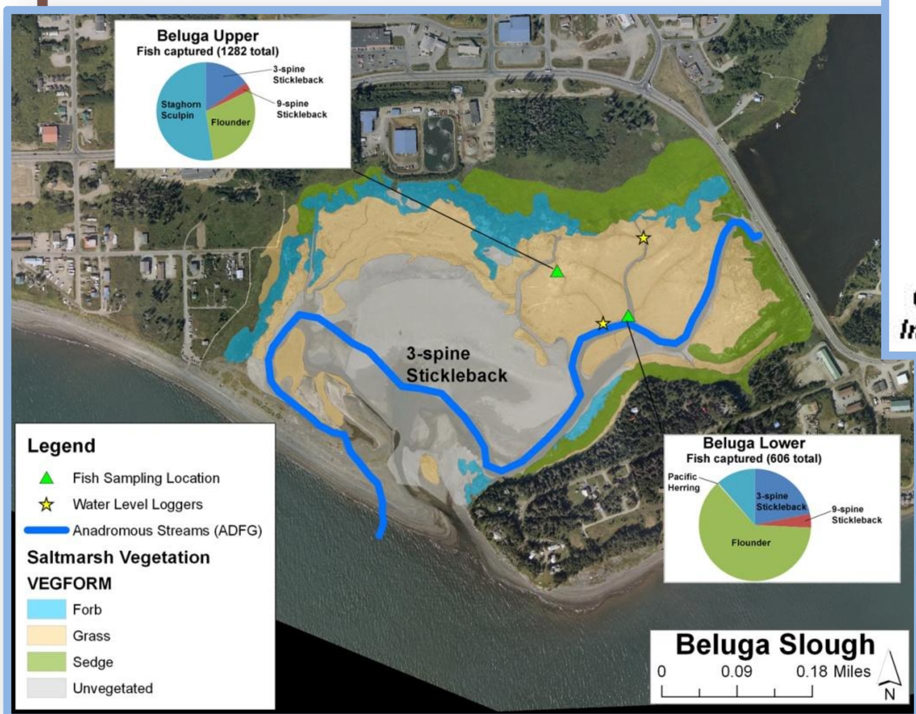


FIGURE 6: BELUGA SLOUGH EMERGENT VEGETATION COVER MAPAND KNOWN FISH SPECIES

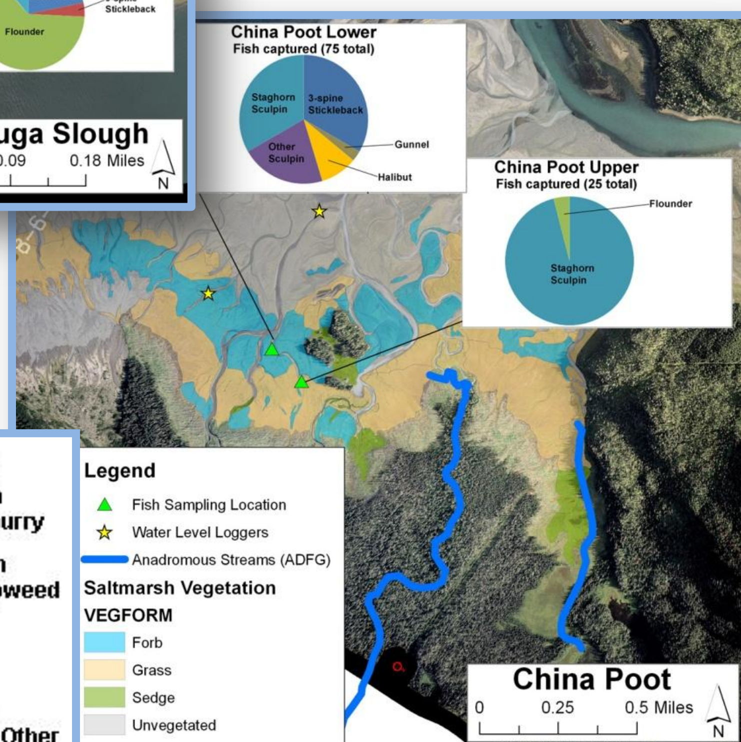


FIGURE 7: CHINA POOT EMERGENT VEGETATION COVER MAPAND KNOWN FISH SPECIES

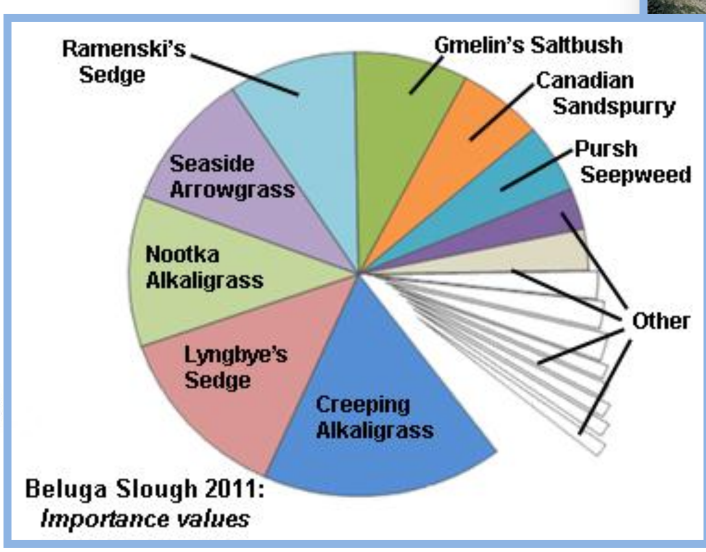


FIGURE 8: BELUGA SLOUGH SALT MARSH VEGETATION IMPORTANCE VALUES ARE CALCULATED FROM THE FREQUENCY AND PERCENT COVER FOR EACH SPECIES

TABLE 3: FREQUENCY OF OCCURANCE OF EMERGENT SALT MARSH VEGETATION IN BELUGA SLOUGH, CHINA POOT, SADIE COVE, AND FOX RIVER FLATES, KACHEMAK BAY, ALASKA DURING AUGUST 2011-2012

Common Name	Beluga Slough	China Poot	Fox River	Sadie Cove
Pineapple weed	1			
Oysterleaf	1			
Tall Jacob's-ladder	1			
Dwarf fireweed	1			
Circumpolar reedgrass	1			
Fourleaf mare's-tail	1			
Fowl bluegrass	1			
Bluejoint	2			
Western touch-me-not	2			
Common yarrow	3			
Beach pea	5	1		
Common dandelion	5	1		
Seaside ragwort	4	1		
Purple marshlocks	1	2		
Water horsetail	2	1		
Seaside sandplant	3			3
Scottish licorice-root	3	6		4
Gmelin's saltbush	60	14		17
Marsh willowherb	1	3	1	
Pacific silverweed	5	9	18	11
Nootka alkaligrass	59	91	53	76
Pursh seepweed	41	48	1	6
Ramenski's sedge	22	1	52	5
Red fescue	2	18	2	2
Seaside arrowgrass	41	16	44	32
Canadian sandspurry	51	55	41	28
Alaska orache	1	70	32	2
American dunegrass	11	12	2	35
Creeping alkaligrass	69	1	50	4
Goose tongue	22	72	20	35
Largeflower speargrass	2	4	1	1
Lyngbye's sedge	26	9	18	25
Saltmarsh starwort	17		11	26

Common Name	Beluga Slough	China Poot	Fox River	Sadie Cove
Annual bluegrass	6		11	
Bushy knotweed	1		4	
Slender grasswort	15		62	
Spike bentgrass	1		3	
Rough bentgrass	2		1	
Alkali buttercup			14	
Alsike clover			8	
Toad rush			6	
Marsh grass of Parnassus			2	
Chickweed, starwort			1	
Fragrant bedstraw			1	
Marsh felwort			1	
Yellow rattle		4	2	
Boreal starwort		1	2	
Field horsetail		1	2	
Marsh arrowgrass		1	5	
Canadian burnet		2		
Meadow barley		3		
Northern bedstraw		1		
Pacific hemlock parsley		1		
Tufted hairgrass		9		
Spotted water hemlock		2		
Sweetgrass		1		
Hornemann's willowherb		1		
Largeleaf avens		1		
Lutz spruce		1		
Mackenzie's water Hemlock		1		
Arctic dock		5		
Arctic starflower		5		
Arctic daisy		4		1
Scurvygrass		2		42
Sea milkwort		5		20
Seashore saltbush		15		31
Dwarf alkaligrass		20		9
Threepetal bedstraw		10		1
Seaside alkaligrass				1

MESSAGING FRAMEWORK:

ASSESSING COASTAL UPLIFT AND HABITAT CHANGES IN A GLACIALLY INFLUENCED ESTUARY SYSTEM

Prepared by: Kachemak Bay Research Reserve and the
University of Alaska Fairbanks Geophysical Institute with input
from the Homer community

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MESSAGING FRAMEWORK

BACKGROUND

Project title	**Assessing Coastal Uplift and Habitat Changes in a Glacially Influenced Estuary System Located in Kachemak Bay, Alaska**
Project description	A collaborative research project occurred from 2010-2013 to assess the rate of vertical changes in the coastal landscape encircling Kachemak Bay and to monitor the effects of uplift and sea-level rise on salt marsh communities.
Project approach	This study was a collaborative effort with intended users of the science; their perspectives informed the development of the problem, the implementation of the research, and ultimately, the practical application of study results to local coastal uplift and sea-level rise.
Project team	Leads: • Kachemak Bay National Estuarine Research Reserve (NERR) • University of Alaska Fairbanks, Geophysical Institute Intended Users: • NOAA – Kasitsna Bay Laboratory • Kenai Peninsula Borough • City of Homer • Seldovia Village Tribe • Alaska Department of Natural Resources – Division of Mining, Land, and Water • Kachemak Bay Research Reserve Community Council • U.S. Army Corp of Engineers
Project background	"…*Are we going to wash away, or are we going to have new acres of shoreline*?" That was the question that the mayor of Homer, Alaska, put to the Kachemak Bay NERR in 2009. Coastal Alaska is a diverse and dynamic landscape. In 1964, a powerful earthquake rocked south-central Alaska and the coast is still uplifting from that event today. In southeast and south-central Alaska, rapidly melting ice fields have reduced the weight on the earth's surface causing another form of uplift, isostatic rebound, in coastal communities. Melt water from these ice fields has contributed to regional sea level rise as it enters the near shore Alaska Coastal Current. In the balance of these conflicting forces are the communities that surround Kachemak Bay, such as Homer, that depend on local, nearshore fisheries for food and safe harbor infrastructure for transportation. To plan for a future in this uncertain landscape, local communities need to understand the implications that coastal uplift and sea level rise have for coastal erosion patterns, infrastructure construction and protection, planning, zoning, local food resources, and public safety.
Target audience	• Local, regional, and statewide coastal decision-makers (e.g. community leaders, coastal resource managers, planners) • Community members (e.g. general public) • K-16 students

SUMMARIZED MESSAGES

One-line study description	Investigating the Influences of Sea & Land-Level Changes on Coastal Habitats for Better-Informed Decision-Making
Summarized key messages	Understanding the physical processes of coastal uplift and sea-level change using up-to-date scientific information is important for local communities to plan for the future in an uncertain landscape.
	This study was a collaborative effort with intended users of the science; their perspectives informed the development of the problem, the implementation of the research, and ultimately, the practical application of study results to local coastal uplift and sea-level rise.
	The Kachemak Bay Research Reserve collaborated with the UAF Geophysical Institute to update projections of land-level change using high precision GPS instruments located at key sites within Kachemak Bay, and to evaluate sea-level rise through the year 2020.
	This study refined measurements of the movement and uplift of land following the 1964 earthquake and rapid ice-mass loss from ice fields in Kachemak Bay. Land uplift averaged approximately 8.6 mm/year (+/-0.5mm) or 0.34in/year. This rate, in most cases, currently outpaces that of global sea-level rise, which is averaged at 3.2 mm/year (.13 inch/year).
	Measured coastal uplift is fairly consistent across sites in Kachemak Bay, with the exception of the Homer Spit. The Spit is uplifting significantly less (at 5.6 mm/year or 0.22in/year) than other areas of similar substrate around Homer. However, acceleration of sea-level rise, increased sedimentation, storm surges, and unanticipated natural disasters could increase vulnerability of the Spit and its infrastructure.
	Within a salt marsh, vegetation is structured relative to different plant species tolerance to salt water. Plants that can withstand salt exposure dominate the shoreline, whereas less tolerant plants are located on higher ground. As sea level rises, plants extend their range in response to the changing saltwater exposure. Vegetation that was mapped during this study will continue to be monitored as an indicator of the relative shifts in sea and land levels over time.
	Communities surrounding Kachemak Bay depend on nearshore fisheries for food and safe harbor infrastructure for transportation. Through active engagement in this collaborative study, local decision-makers are uniquely poised to understand the implications that coastal uplift and sea-level rise have for infrastructure construction and protection, planning, zoning, local food resources, and public safety.

EXPANDED MESSAGES AND PROOF POINTS

Core message #1	Around Kachemak Bay, the rapidly receding glaciers are causing land to rise as the massive weight of ice is released (a geological effect referred to 'glacial isostatic rebound'). Across the globe, melted ice water from deglaciation returns to the ocean as global sea level rises. Understanding the physical processes of coastal uplift and sea-level rise and how they interact in Kachemak Bay is important for local communities to plan for the future in an uncertain landscape.
Proof points	• The Little Ice Age (1350 to 1770) was a period of cooling and glacial advance in Kachemak Bay. The enormous weight of the ice caused the land surface to depress and warp. At the end of the glacial period as glaciers are retreating, the release of weight is resulting in slow uplift or land rebound. • The rebound effect is similar to a rising vessel hull. Imagine a floating barge loaded with 200 tons of ice; as the ice melts and water runs overboard, the hull of the barge rises. • The changes in sea level from deglaciation are not the same everywhere in the oceans. Gravitational differences in the Earth's mass cause the rise in sea level to be higher at certain locations than others. • Monitoring sea-level rise and the uplift of land masses is important to understanding more about the processes associated with climate change.
Core message #2	Projections of land-level change (from isostatic rebound) and sea-level rise for Kachemak Bay were updated through the year 2020. These numeric models are based on the integration of land-surface and ice data collected at sites around Kachemak Bay from 2000 to 2013.
Proof points	• Land-level change was measured using repeated, high precision GPS instruments located at key sites within Kachemak Bay. These included repeated surveys of pre-existing GPS survey points, surveys of new benchmarks, and new Continuously Operating Reference Sites (CORS) that make daily position measurements. • Relative sea level, such as that measured by a tide gauge, is the difference between (absolute) sea level and land level. Sea-level rise were estimated from global sea-level rise models measured by satellite altimetry, and then cross-checked from measurements by a tide gauge located in Seldovia. • Projection models used are similar in structure to models for weather predictions, as they require the input of initial conditions for forecasting. • The models used for land-level changes provided changes contours based on static GPS and CORS site data to provide a higher-level of precision that existing predictions.

Core message #3	Land uplift in Kachemak Bay averaged approximately 8.6 mm/year (+/- 0.5mm) or 0.34in/year. This rate, in most cases, currently outpaces that of global sea-level rise, which is averaged at 3.2 mm/year (.13 inch/year). By the year 2020, the landscape surrounding Kachemak Bay is expected to rise by approximately 172.0 mm (6.6 in).
Proof points	• Existing models of vertical and horizontal land-level changes in the Kachemak Bay area were updated with data from this study. • In the analysis of vertical land movements, longer time series data (≥10years) suggest a fairly uniform uplift rate around Kachemak Bay independent of the surface substrate type. • Regional sea surface changes were estimated from the recent rate of global sea-level rise (published in the latest Intergovernmental Panel on Climate Change report, and corrected for the change in the sea surface shape caused by the local area ice loss.
Core message #4	Measured coastal uplift is fairly consistent across sites in Kachemak Bay, with the exception of the Homer Spit. The Spit is uplifting more slowly relative (at a rate of 5.6 mm/year or .22 inch/year) to the surrounding area and is currently outpacing global sea- level rise. However, unanticipated changes in the environment could increase the vulnerability of the Spit and its infrastructure. Instances such as sea-level rise acceleration, increased sedimentation, storm surges, and other unexpected natural disasters could jeopardize the current sustainability of the Spit.
Proof points	• The rate of uplift for the Homer Spit and other areas around Kachemak Bay were determined from vertical land movements measured by high-precision GPS from 2011-2013. • The Homer Spit is uplifting significantly less than other areas with similar substrate around Homer. • This is important because the Homer Spit will have a different trajectory relative to global sea level rise than the surrounding landscape, which could make it more vulnerable to inundation from storm events or sea level rise in the future.
Core message #5	Kachemak Bay is home to six communities that are dependent on boats for transportation, supplies, and economic livelihood through commercial fishing. In many of these communities there are no roads and the only access is by boat. Large boats can access only the deeper channels in the Bay, whereas other areas are only accessible by small craft at high tide. Rising land due to isostatic rebound will result in areas becoming increasingly unnavigable due to shallow water. Further, increased sedimentation and infilling by silt released from the many glaciers surrounding Kachemak Bay may further reduce navigation.
Proof points	• Navigation changes attributable to uplift are projected to be most

	pronounced in shallow areas of Kachemak Bay, which mainly occur at the head of the Bay. • Given the measured rate of uplift in Kachemak Bay, changes to navigable waters are anticipated to occur slowly over time. It is unlikely that the transition from navigable to unnavigable areas would occur over the course of a lifetime. • Currently unanticipated factors associated with land-level rise, such as coastal erosion or sediment transport, could accelerate the rate of change in the future.
Core message #6	The salt marsh communities in Kachemak Bay provide valuable habitat for certain marine organisms and wildlife. Shellfish, waterfowl, predatory mammals, and juvenile fish, including salmon, rely on these areas for food and shelter. As land levels change, these habitats and interactions between organisms there change also. Salt marshes areas left unexposed to tidal flooding can decrease habitat value by jeopardizing fish spawning, reducing waterfowl nesting areas, and inputting less detritus for invertebrate settlement.
Proof points	• This study demonstrated the importance of salt marsh habitat to a variety of fish, bird, insect, and mammal species, and provided baseline biological information that will be used to monitor habitat-level changes over time. • Currently unanticipated factors associated with land-level rise, such as coastal erosion or sediment transport, could accelerate the rate of change in the future.
Core message #7	Land-level changes in Kachemak Bay have ecological significance in the coastal zone because even small vertical changes in the land can shift large areas currently flooded by the tide to being exposed. The vegetation of shallow-water coastal areas has physiological adaptations specific for certain water-depth and salinity ranges. Changes to land level result in shifting mosaics of this coastal salt marsh vegetation. Plant communities were mapped in the focal salt marshes of this study to track differences in vegetation over time.
Proof points	• The plant community maps created for this project (are based on well-rectified high-resolution color imagery, and should allow for the detection of significant marsh migration using future mapping efforts. • Plant community surveys were conducted to calculate importance values (an index of plant frequency of occurrence and percent cover) for each plant species in each marsh. • In this study there were obvious small differences of plant species from year to year; however, there was no apparent directional increase or decrease in importance of any of these species. • It will be important to understand the short term variability of

	• plant species when examining data for longer term directional change in the future. • Key features to track will be upper limit of salt-tolerant vegetation communities, and high-marsh to low-marsh transitions.
Core message #8	The effect of sea-level rise and land-level change to shorelines may vary according to morphology, composition, and dominant processes of the coast. Within Kachemak Bay the impact of elevated storm surges are known to erode mobile substrates along coastal bluffs. Liberated sediment may ultimately be transited to downdrift shorelines, including the periphery of the Spit and harbor. The extent to which coastal uplift and sea-level rise drive sediment transport are currently unknown given the complexity of coastal processes.
Proof points	• This study provides background information on sea and land-level change that can inform future studies. • Further investigation is warranted to better understand sedimentation processes in Kachemak Bay and ultimately protect the integrity of the Spit and harbor infrastructure.
Core message #9	As new land emerges faster than the sea level is currently rising in Kachemak Bay so too does emerge the question of land ownership for tidally-bounded properties. Within Kachemak Bay there are three Critical Habitat Areas set aside to protect their natural features and habitat value for fish and wildlife. Land within the Critical Habitat Areas (CHA) is protected and managed by the State up to the mean high-tide line in some areas. As land rises beyond tidal inundation, the boundaries of these CHAs shrink and the emerging land may become available for private land ownership. With land rise of one-third inch per year, the ownership of hundreds of feet of land could be in question by the next century.
Proof points	• The Critical Habitat Areas within Kachemak Bay include the Kachemak Bay, Fox River Flats, and Homer Airport CHAs, and were established as early as 1972 protect and preserve habitat areas especially crucial to the perpetuation of fish and wildlife, and to restrict all other uses not compatible with that primary purpose. • In general, tide and submerged lands in Kachemak Bay are state owned. The City of Homer, Seldovia, U.S. Coast Guard, and the federal government have title to some tidelands within the Bay. Also, aviation corridors and land management transfers exist for airports and the University of Alaska. There are two private inholdings in the Fox River Flats and eleven privately owned tidelands parcels around the Bay. • In areas where the rising of land is seen, it will be necessary to define the exact limits and ownerships of properties. This issue is currently being addressed in areas of Southeast Alaska where rapid rates of coastal uplift is occurring.

Recommendations	This study provided a valuable and robust baseline of vertical land movements and relative sea-level rise for Kachemak Bay. Over time, this information will be valuable to help understand how these changes affect coastal habitat, infrastructure, and local food resources. Inherent in a study of this nature are uncertainties related to coastal processes. The following are recommendations to addresses these uncertainties and improve our understanding of the physical environment around Kachemak Bay: • Focused research to determine the extent to which coastal uplift and sea-level rise drive sediment transport along the Homer Spit; • Longer duration GPS monitoring of vertical uplift on the Homer Spit and at multiple locations to determine the trajectory across its entirety. Further, integration of information from this study with surveys by the U.S> Army Corps of Engineersto inform harbor dredging. • Continued updating of existing land-level change models and adding new monitoring sites at 10+ year intervals to reduce variability in vertical change projections