



Monitoring Coastal Salt Marshes in the Lake Clark and Katmai National Parklands of the Southwest Alaska Network

Natural Resource Technical Report NPS/SWAN/NRTR—2010/338



ON THE COVER

Point sampling for vegetation cover in a coastal meadow at Hallo Bay, Katmai National Park and Preserve, Alaska. Photograph by Torre Jorgenson

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Natural Resource Technical Report NPS/SWAN/NRTR—2010/338

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June 2010

U.S. Department of the Interior
National Park Service
Natural Resource Program Center
Fort Collins, Colorado

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Please cite this publication as:

Jorgenson, M. T., G. V. Frost, A. E. Miller, P. Spencer, M. Shephard, B. Mangipane, C. Moore, C. Lindsay. 2010. Monitoring coastal salt marshes in the Lake Clark and Katmai National Parklands of the Southwest Alaska Network. Natural Resource Technical Report NPS/SWAN/NRTR—2010/338. National Park Service, Fort Collins, Colorado.

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Acknowledgments

We would like to acknowledge the support of the Southwest Alaska Network. This monitoring project was initiated by Alan Bennett, Research Coordinator, and continued by Michael Shephard. Amy Miller, Ecologist, managed the project for NPS. Bill Thompson provided advice on sampling design. We thank Trish Loomis for helping manage the databases, Janet Kidd for technical review, and Pam Odom for report production.

Executive Summary

Monitoring of salt marshes in Lake Clark (LACL) and Katmai (KATM) National Parks and Preserves focuses on the major habitat characteristics that support nearshore and terrestrial indicators (e.g., brown bears, seabirds, intertidal marine invertebrates, and algae) in the Southwest Alaska Network (SWAN), and on the major drivers of change in these habitats. Drivers include tectonic uplift, erosional and depositional geomorphic processes, changing topography and surface hydrology, tidal fluctuations and storm surges, sedimentation rates, salinity, and vegetation succession. We used a nested sampling approach that incorporates extensive and intensive ground measurements and remote sensing techniques. The nested design includes: (1) field sampling at Silver Salmon, Chinitna Bay, and Hallo Bay; (2) establishment of four equi-distant transects oriented perpendicular to shoreline that capture topographic variation within each site; and (3) systematic allocation of vegetation monitoring plots every 100 m along the transects, with additional, targeted plots added in uncommon plant communities. The monitoring effort requires a team of six people to sample three sites over a four-week period every ten years. Dataloggers installed at each site are scheduled to be maintained every 1–3 years.

Topographic surveying revealed that surface elevations varied < 0.5 m across the active and inactive tidal flats, excluding the tidal channels, and 3–4 m across the barrier dunes. Lowest mean elevations relative to mean sea level (MSL) occurred on Barren Mudflats (-0.1 m) and Barren Beach (0.0 m). Mean elevations of plant communities ranged from 1.5 to 2.2 m on vegetated active tidal flats (saline) and from 2.0 to 3.4 m on inactive tidal flats (slightly brackish). Mean elevations of plant communities on beach ridges ranged from 3.2 to 3.5 m. Maximum observed elevation on beach ridges was 4.3 m relative to MSL. The topographic gradient forms the basis for large differences in soil water depths, soil salinity, and organic matter accumulation from the coast to the inland forests.

Tide and storm surge water levels recorded by submersible pressure transducers between 2007–2009 showed that higher-high water levels at Silver Salmon and Chinitna Bay typically reached ~ 2 m above MSL on a biweekly basis during summer months and reached ~ 2.5 m in mid-winter. Major storms with water levels greater than 2.5 m were recorded 4 times at Silver Salmon and Chinitna Bay over the measurement period.

Sediment monitoring stations were established at each plot by extracting and photographing small soil plugs to provide a baseline for future measurement of sediment accumulation relative to distinctive layers visible in the stratigraphy. Measurements of organic-horizon thickness in the soil plugs provided an indirect, inverse measure of sediment accumulation because heavy sedimentation prevents the accumulation of organic matter. Mean cumulative sediment thickness was lowest (0–2 cm) for *Lathyrus maritimus*-*Senecio pseudoarnica*, *Carex ramenskii*-*Stellaria humifusa*, and *Elymus mollis*-*Plantago maritima* plant communities on active tidal flats, and highest (20–30 cm) for *Calamagrostis canadensis*-*Equisetum fluviatile* and *Myrica gale*-*Salix fuscescens* on inactive tidal flats. Water depths and salinity (electrical conductivity; EC) measured during initial plot setup showed large differences among plant communities. Mean EC was lowest (< 100 $\mu\text{S}/\text{cm}$) on older beach ridges, which support mid- to late-successional communities, such as *Alnus sinuata*-*Dryopteris dilatata* and *Picea sitchensis*-*Angelica lucida*,

and highest (~15,000 to 18,000 $\mu\text{S}/\text{cm}$) in ponds on active tidal flats, which supported *Hippuris tetraphylla*-*Triglochin maritimum* and *Carex mackenziei*-*E. kamtschatica* communities.

Soil temperatures measured for two conditions, wet tidal flats and dry beach ridges, ranged from -4 to 10 °C, and surface (~5 cm depth) and deep (~20 cm depth) temperatures were similar. Soils remained near the freezing point during winter months, indicating that unfrozen water contents associated with saline conditions prevented the soils from totally freezing and temperatures from dropping substantially below freezing.

Vegetation cover measurements, obtained through point sampling at 100 points per plot, recorded a total of 127 taxa in 130 plots. The most abundant plant species in the coastal study sites included *Alnus sinuata*, *Achillea millefolium*, *Angelica lucida*, *Salix fuscescens*, *Myrica gale*, *Lathyrus maritimus*, *Potentilla egedii*, *Triglochin maritimum*, *Plantago maritima*, *Calamagrostis canadensis*, *Elymus arenarius mollis*, *Poa eminens*, *Carex lyngbyaei*, *Carex glareosa*, *Carex ramenskii*, and *Festuca rubra*. Multivariate analyses were used to classify the species cover data into 19 plant communities, of which 14 occurred on tidal flats and five on beach ridges. Mean percent cover of each species and growth form was calculated for each study site using the 78 systematic plots, and for each plant community across all sites using both the systematic and the targeted plots (130 plots, total). Overall, vegetative cover was dominated by forbs (57%) and sedges (34%) with minor amounts of deciduous shrubs (13%) and mosses (13%). Evergreen trees (1%), deciduous trees (0.1%), and lichens (0%) had negligible cover. When comparing mean vegetative cover across the three study sites, most values differed by <5%.

Landscape change was analyzed using a time-series of historical airphotos (1951 and 1957 B&W; 1978 and 1982 CIR) georectified to high-resolution satellite images (Ikonos 2000, 2004, 2005). Waterbody mapping revealed that the largest change occurred for nearshore water, where mean percent area across the three sites decreased 5.8% from the 1950s to the mid-2000s, due to sediment deposition along the shoreline and migration of the shoreline seaward. Smaller changes were observed for tidal guts, which decreased by 0.9%, and tidal rivers, which increased 0.6% in area. Overall erosion rates (negative indicates land gained) were similar at Hallo Bay (-2.3 m/yr) and Silver Salmon (-1.6 m/yr) for the entire 1951–1957 to 2000–2005 interval, compared to Chinitna Bay (-0.5 m/yr). Photo-interpretation of landscape change using a more comprehensive ecotype classification showed that roughly 20% of the area had changed. Mean percent area (average of three sites $\pm$ 1 SD) over the 1951–1957 to 2000–2005 time interval increased for Coastal Gravelly Saline Barrens ($2.1 \pm 1.3\%$), Coastal Sandy Dry Circumacidic Beach-pea Meadow ($1.8 \pm 2.8\%$), and Coastal Sandy Circumacidic Moist Sitka Spruce Woodland ($2.0 \pm 1.6\%$). Decreases in mean percent area were highest for Nearshore Water ($-3.2 \pm 3.0\%$), Coastal Sandy Moist Circumacidic Beachgrass-Umbel Meadow ($-1.5 \pm 1.6\%$), and Coastal Loamy Saline Wet Ramenski Sedge Meadow ($-1.2 \pm 1.0\%$). Geomorphic and ecological processes most responsible for the changes were shoreline deposition ($3.9 \pm 0.5\%$), early succession ($4.1 \pm 0.5\%$), late Succession ($3.4 \pm 2.1\%$), sedimentation ($2.4 \pm 2.1\%$), and channel deposition ($1.8 \pm 0.3\%$).

Introduction

Monitoring of salt marshes in the Lake Clark (LACL) and Katmai (KATM) National Parks focuses on the major habitat characteristics that are important to other nearshore and terrestrial indicators (e.g., brown bears, seabirds, intertidal marine invertebrates, and algae) in the Southwest Alaska Network (SWAN), and on the major drivers of ecological change. These drivers include tectonic uplift, changing erosional and depositional geomorphic process, changing topography and hydrology, tidal fluctuations and storm surges, sedimentation rates, salinity, and vegetation succession (Bird 2000). Tidal fluctuations and storm surges help control vegetation distribution by affecting water levels, sedimentation, and salinity. Sedimentation and erosion affect surface elevations, contribute nutrients, and can physically bury or disturb the surface. Salinity affects the osmotic potential of soil and is an important control over vegetation distribution (Vince and Snow 1984, Jorgenson 2000).

Dynamics of Coastal Ecosystems

The various geomorphic units associated with coastal regions, such as tidal flats, dunes, barrier spits, and tidal channels, are formed by differing erosional and depositional processes associated with waves, wind, and currents (Clifton et al. 1973, Harper and Morris 2005). Consequently, the units have varying topography, sediment textures, hydroperiods, currents, salinities, and vegetative cover. Coastal salt marshes are predominantly associated with active and inactive tidal flats (Jorgenson 2000). Within the tidal flats are varying surface microtopographies that include tidal channels, levees adjacent to the channels, and basins (pans) formed by impoundment of water behind the levees. Tidal channels through a marsh are important corridors for water, materials, and animals to move between vegetated tidal flats and the nearshore environment (Mitsch and Gosselink 2000). Water carrying suspended and dissolved material moves downstream during periods of low water levels and inland with tides and storms. Tidal channels also facilitate the drainage of the marsh during low tide, a process essential to the survival of many marsh plant species (Teal and Weinstein 2002). Animals such as fish and shellfish find refuge in creeks during low water levels and then enter tidal ponds to forage during times of high water levels (Laffaille et al. 2001). Levees are formed by deposition of sand by tidal water that overflows the channel banks and drops the coarser sediment load as the water loses velocity. The levees are better drained and are usually dominated by dunegrass (*Elymus arenarius mollis*). In contrast, basins are slight depressions where seawater can become trapped during high spring tides. Over the growing season, the basins can become increasingly saline as water is lost due to evapotranspiration. These high-salinity conditions limit seedling germination and plant growth. Without precipitation or additional tidal flooding, salt concentrations in basins can reach levels high enough to kill marsh plants and form a salt crust over the soil surface that limits future recolonization of the area (Adam 1990). Gravel beach ridges and sand dunes front many of the coastal marshes along the southwestern Alaska coast and protect the salt marshes from erosion during large storm events (Cusick and Bennett 2005). The beaches ridges are initially formed by wave action and then become covered by wind-blown sand. They rise high above the levels affected by tides and storms and are affected by wind-blown salts. Non-halophytic vegetation can colonize the older portions of dunes and can lead to the development of forest vegetation.

Topography (surface elevations), and bathymetry in the case of submerged land, are the most important factors affecting the composition and productivity of coastal ecosystems because they affect water levels and hydroperiod, surface-water flow, groundwater table, sedimentation rates,

carbon accumulation, salinity, and nutrients (Morris 2000, Jorgenson and Ely 2001, Hussein et al. 2004, van Proosdij et al. 2006). Changes in topography through erosion, subsidence, or sediment deposition, even of a few centimeters, can alter plant communities and plant productivity because each plant species is adapted to germinate and grow under a specific tidal regime, or hydroperiod, as it relates to water depth (Keddy and Reznicek 1982). Consequently, topographic variation increases the diversity of plant species and communities across a site.

Sediments accumulated from flood deposition and from organic matter derived from decaying vegetation are important to ecosystem processes because they raise the ground surface, add nutrients bound to the sediments, and maintain early successional plant species that establish on the disturbed mineral substrate (Nixon 1980, Odum 1980, Werner and Zedler 2002). The sediment supply may be altered by changes in upland runoff, reworking of marine-derived sediments, hydrologic patterns, and organic production occurring within the marsh (Cahoon and Turner 1989, Delaune et al. 1989). Sedimentation lowers flooding frequency by raising the surface relative to MSL, or may help counteract increasing flood frequency that can result from subsidence or increased sea level. Changes in upland runoff, and storm magnitude and frequency are the principal causes of increased sediment supply. In Cook Inlet, glacially fed rivers are important sources of sediment, and volcanic eruptions can deposit heavy blankets of volcanic ash.

Soil-water characteristics fundamental to the function of coastal ecosystems include ground or surface water depth, soil temperature, salinity, and pH. Duration of flooding and degree of soil saturation affects soil moisture and aeration, type and amount of soluble materials, osmotic potential, redox potential, and pH of the soil solution (Paul and Clark 1989). Marsh sediments are mostly anaerobic, which can result in high levels of H₂S and low pH, both of which can inhibit plant growth (Pomeroy and Wiegert 1981). Exchange between sediments and floodwater occurs through sedimentation, diffusion, bioturbation, and seepage (Wiegert and Freeman 1990). Salinity exerts strong control on the distribution and abundance of estuarine vegetation because species differ in their osmoregulatory abilities and salinity tolerances (Kuramoto and Brest 1979, Adams et al. 1992, Jorgenson 2000). Soil-water pH provides a fundamental control on ion mobility, nutrient availability, and microbial reactions (Paul and Clark 1989).

Soil temperature is a primary determinant of the rate of biological processes. Thus, productivity and growth of phytoplankton (Goldman and Carpenter 1974) and submerged aquatic vegetation (Marsh et al. 1986), microbial metabolism (Adams 1990), sediment oxygen demand (Portnoy 1991), nutrient remineralization (Nowicki and Nixon 1985), and faunal recruitment (Day et al. 1989) are all strongly influenced by temperature. In addition, primary production and decomposition at temperate latitudes are largely a function of seasonal temperature differences (Day et al. 1989). For example, eelgrass (*Zostera marina*) becomes more susceptible to the negative impacts of algal epiphytes at high water temperatures (Neckles et al. 1993).

Nutrient pools and fluxes, which provide a fundamental control over the productivity and composition of salt marsh biota, were not included in the monitoring program because of high temporal and spatial variability, and the high cost of sampling and laboratory analysis. Water quality parameters and nutrient concentrations are common components of coastal monitoring in areas with substantial human populations (Kopp and Neckles 2004), and are being monitored in nearshore marine waters of the SWAN under a separate protocol.

Vegetation is a fundamental component of salt marshes because it provides the primary food source for herbivorous mammals, birds, and invertebrates, and provides plant litter for microbial and invertebrate consumers. A salt marsh is physically dependent on its plants because plant roots and stems anchor the substratum, reduce water velocities and affect sedimentation rates, and enable the gradual build up of sediment and organic matter (Ruddy et al. 1998). The distribution and abundance of coastal plant species in turn are affected by the extremely dynamic nature of coastal habitats resulting from wide daily and seasonal fluctuations in surface water and root-zone salinity, temperature, and dissolved oxygen. The gradient in physical and chemical conditions, particularly salinity gradients and duration of inundation, result in zonation of vegetation associated with the ecological tolerances of individual species (Vince and Snow 1984).

Monitoring Objectives

The objectives of salt marsh monitoring in the SWAN were identified during initial protocol development (Jorgenson 2007). The protocol relied in part on the extensive literature available on coastal monitoring (e.g., Melzian 2003, Thayer et al. 2003), as well as numerous existing federal and state coastal monitoring programs that have already developed standard operating procedures (Roman et al. 2001, McCobb and Weiskel 2003, Kopp and Neckles 2004, Steyer et al. 1995). Numerous studies of Alaskan coastal marshes also were reviewed to assist the protocol development effort, including studies of coastal ecosystems along the North Gulf Coast (Ruby 1977), and Cook Inlet (ADCE 1978; Ritchie et al. 1981; Vince and Snow 1984; Snow and Vince 1984; Racine and Brouillette 1995; Talbot et al. 1995; Tande 1996; DeVelice et al. 1999; Jorgenson et al. 2003, 2004). Of particular relevance to the SWAN monitoring program were the mapping and classification of coastal marshes at LACL (Tande 1996) and upper Cook Inlet (Vince and Snow 1984, Jorgenson et al. 2003), which provided the foundation for a classification system used for characterizing photo-trend plots and for mapping geomorphic units within each site. The shore-zone mapping by Harper and Morris (2005) also was useful in characterizing shorelines within the various coastal landscape units (subsections) for stratification in the sampling program. In developing the monitoring program we targeted biophysical variables (highlighted in gray in Figure 1) with low temporal variability that can be sampled over long intervals (10 years), and variables with high temporal variability that can be monitored reliably with dataloggers at short time intervals over long unattended periods.

Two monitoring sites (Silver Salmon; Chinitna Bay) were established in LACL in 2007 to document baseline conditions and to evaluate and refine the monitoring protocols. A third site (Hallo Bay) was established in KATM in 2008. The resulting three sites are intended to be monitored over a two-year period every ten years. This annual report provides a summary of the data that were collected during the first 2-year monitoring period and provides descriptive summaries of the biophysical components of the salt marsh ecosystems.

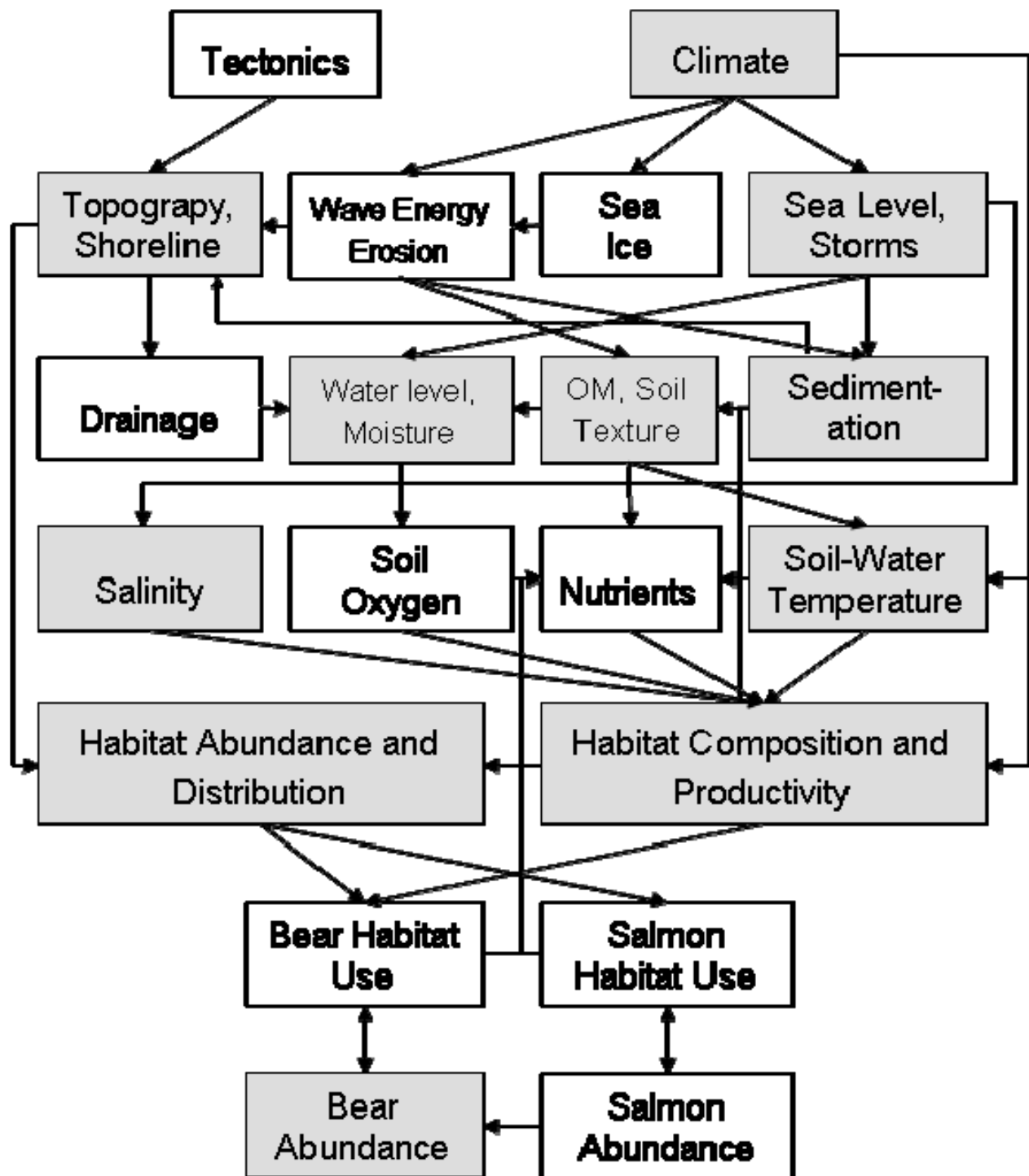


Figure 1. Conceptual model of linkages among abiotic and biotic components of coastal ecosystems of southwest Alaska. Shaded variables are being monitored through this (salt marsh) or other protocols (climate; bear abundance).

Specific objectives of the long-term coastal monitoring program are to:

- 1) Detect change in salt-marsh topography through ground-based measurements across a topographic gradient from lower to upper marsh to assess whether upper, mid-, and lower marsh zones are accreting or eroding;
- 2) Monitor tidal fluctuations, storm surges, and water levels in tidal channels with submersible water-level recorders;
- 3) Document sedimentation rates, pore-water salinity, and pH across the topographic gradient through ground-based measurements;
- 4) Detect change in the cover and/or frequency of vegetation across the gradient through ground-based measurements;
- 5) Determine changes in the abundance and distribution of plant community types across the gradient, using point-intercept sampling along transects, and through photographs taken at permanent photo points on the ground;
- 6) Detect decadal changes in the areal extent of surface water in tidal guts and ponds and of major ecotypes through remote sensing; and
- 7) Sample in a logistically practical, safe, and cost-effective manner.

Methods

Sampling Design

The sampling design consisted of a nested approach, using extensive and intensive ground measurements and remote sensing techniques. The nested sampling design included: (1) stratification of coastal landscapes along the KATM and LACL coast using ecological subsections modified from Shephard (2000) and Spencer (2002) (Figure 2); (2) establishment of equally distributed monitoring transects oriented perpendicular to the coastline to encompass elevation and salinity gradients; and (3) systematic allocation of vegetation monitoring plots every 100 m along the transects. In addition, subjectively placed plots were established in uncommon vegetation communities along the transects to increase the sample size for communities inadequately sampled by the systematic plots. The systematically distributed plots are useful for analyzing overall species abundance, whereas the subjectively located plots are useful when analyzing species abundance by community. Coastal subsections dominated by salt marshes included the Chinitna Bay (CHBA) tidal flats and Silver Salmon Creek (SISA) meadows in LACL, and Hallo Bay (HABA) in KATM (Figures 3 and 4). All three sites are characterized by a complex of coastal ecosystems, including salt marshes, beach ridges and dunes, freshwater marshes associated with tectonic uplift, and sandy deltas.

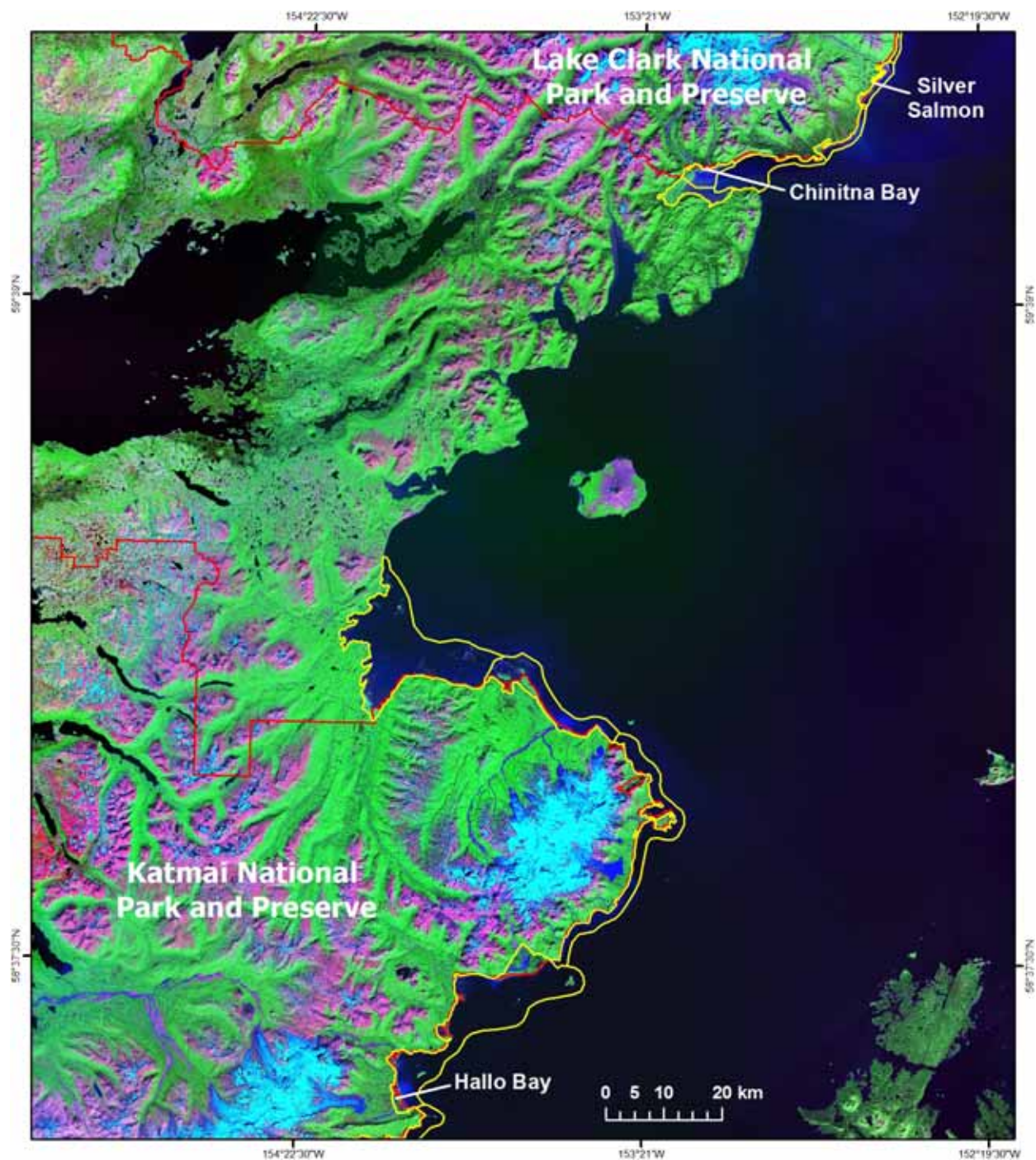


Figure 2. Locations of salt marsh study sites at Silver Salmon (SISA), Chinitna Bay (CHBA), and Hallo Bay (HABA) in relation to coastal subsections (yellow) in Lake Clark and Katmai National Parks and Preserves.

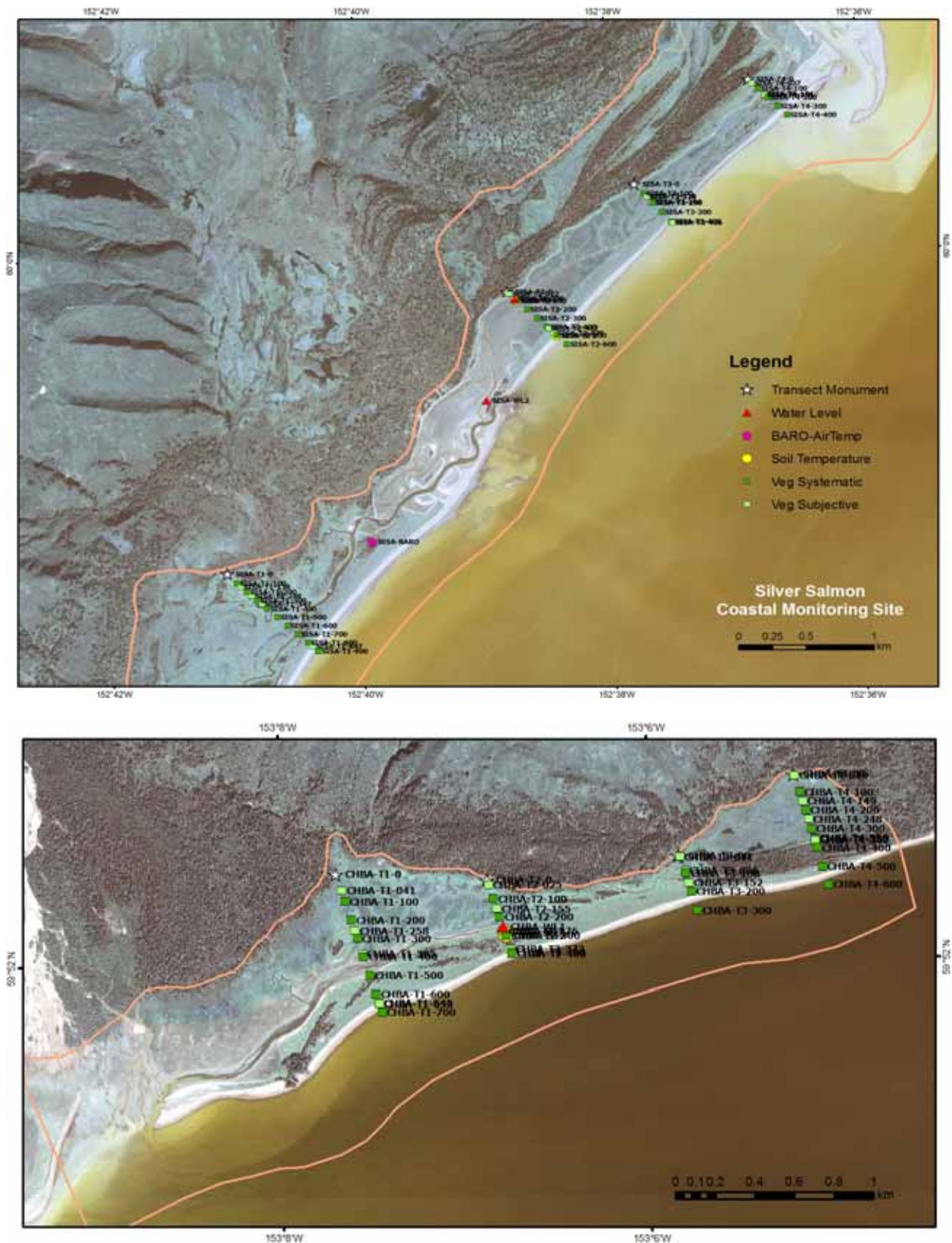


Figure 3. Silver Salmon (SISA) and Chinitna Bay (CHBA) coastal monitoring sites with monitoring plots (green squares) situated along transects oriented across the coastal gradient, perpendicular to the coast.

Field Sampling

The monitoring networks at SISA, CHBA, and HABA were set up by 5–6 people during 6–11 July 2007, 12–19 July 2007, and 18–26 July 2008, respectively. At each site, four transects were established at roughly equal intervals perpendicular to the coastline. Transects started in the upper marsh, at the marsh-upland boundary, with the zero endpoint marked by a stamped monument cap with magnet. Transects ended at the shoreline near the low tide line. Transect length varied from ~300 to ~1400 m, and transects were spaced roughly 1 km apart, depending on the total area of the site. Permanent plots were established every 100 m along each transect and marked by small wooden stakes (2" × 2" × 18"). At each plot, data were collected on ground and surface water levels and chemistry, sedimentation, and vegetation (Figure 5). Ground- and water-surface elevations were surveyed along each transect and at each plot using an autolevel and rod (Figure 6). The elevations were referenced to benchmark rods driven into the ground at the starting (0 m) end of each transect. Photographs were obtained prior to vegetation sampling in the plot. Photographs included: (1) one photo from each end of the plot with the stake visible at the bottom of the photo; (2) a vertical photo of the ground taken at the stake along the transect; and (3) a photo of the soil plug (Figure 7). Salinity, sedimentation, and vegetation sampling were co-located and geo-referenced along each toposequence.

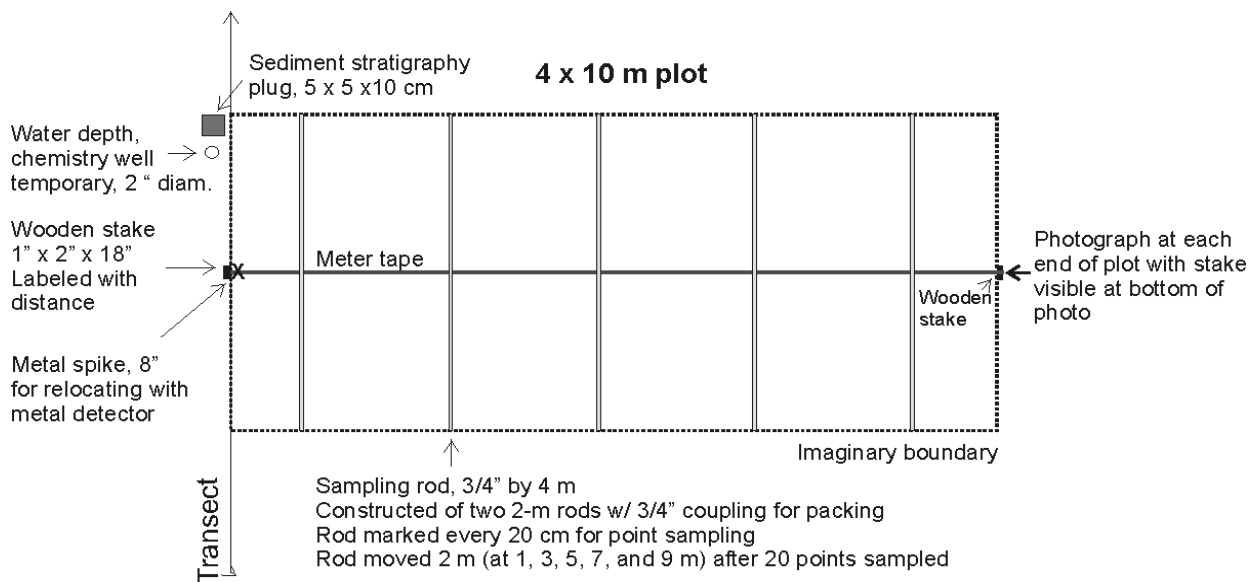


Figure 5. Layout of intensive permanent plot for taking photos, monitoring vegetation (species cover), and sampling sediment stratigraphy and water chemistry.

Water depth, temperature, salinity, and pH were measured at permanent plots in shallow temporary wells created by inserting a 3.8 cm diam. soil probe at each plot and using portable salinity and pH meters, similar to methods described by McCobb and Weiskel (2003). Baseline soil stratigraphy for measuring future sedimentation was established by extracting a soil plug, trimming it with a knife, placing ruler for scale, and photographing the soil (e.g., Figure 7). Sediment accumulation will be measured in future years by comparing photographs among years and measuring accumulation above a distinctive marker horizon. Surface manipulation such as painting the surface, or use of sand marker layer, was not feasible because of bear disturbance. While using distinctive natural layers is less precise than an artificial marker such as spray paint,

the approach is more secure and the precision (1–3 mm) is sufficient for repeating over 10-year intervals.



Figure 6. Scenes of topographic surveying along transect (left) and vegetation sampling at permanent plots (right).



Figure 7. Examples of photographic documentation obtained at each plot, including photographs of the center of the plot (left), a vertical view of the ground (center), and of a soil plug (right).

Vegetative cover in the plot was sampled using the point-sampling technique (Elzinga et al. 2001). Cover of vascular and nonvascular plants was determined by sampling at 100 points systematically distributed across the plot (Figure 5). This method required sampling 20 points spaced 20-cm apart along a 4-m-long rod, which was placed perpendicular to the plot direction. The rod was moved in 2-m increments (1, 3, 5, 7, and 9 m from 0 m end stake on the meter tape) across the plot after sampling of each rod-length was completed. Cover at each point was sampled with a vertically oriented laser pointer mounted on an aluminum rod (Figure 6). Plants intercepted at each layer by the laser pointer were recorded and the rod was moved 20 cm to the next point. In addition to species cover, we recorded bare soil, litter alone (when live plants were not present), and water (either above or below plants). Because multiple layers were recorded at each point, plant cover often exceeded 100% per plot.

Water levels and soil temperatures were measured using dataloggers. Water levels were measured in nearshore tidal guts at two locations at SISA and one location each at both CHBA and HABA using submersible pressure transducers (In Situ TROLL and Aqual TROLL, In Situ, Inc., Ft. Collins, CO). Water level recorders were installed in shallow, protected, permanently flooded locations; thus, we only sampled intermediate water levels and high tides and not the entire tidal range. We assigned provisional elevations above MSL to SISA-WL1 (-0.05 m), SISA-WL2 (-0.25 m), CHBA-WL1 (0.10 m), and HABA-WL1 (0.05 m) based on provisional elevations calculated for the transect surveys. Two pressure transducers (barologgers, In Situ Baro Troll, In Situ, Inc., Ft. Collins, CO) were suspended in trees at 1.5 m height at SISA and at HABA to record barometric pressure for use in correcting water depths. Soil temperatures were measured at 5 cm and 20 cm depths in two plant communities (wet meadow on tidal flats and dry meadow on beach ridge) in each of the three sites with small two-channel dataloggers (HoboPro V2, Onset Computer Corp, Bourne, MA).

The sampling produced seven sets of field data. Transect elevations, environmental plot characteristics, and vegetation cover data were recorded as separate data files on Pocket PCs (IPAQ 4705, HP). Plot locations were collected on a mapping grade GPS (Trimble GoeXT, Trimble Navigation Ltd., Sunnyvale, CA) and differentially corrected using the Kenai CORS base station. Digital photographs were taken at each plot and later labeled in the office. Water level and temperature were recorded by dataloggers. Five digital files (elevation, plot environmental characteristics, vegetation, location, soil temperatures) are maintained in a single MS Access database. The water-level data was processed using AQUARIUS time-series software (Aquatic Informatics, Inc., Vancouver, B.C.) and are maintained within a separate proprietary database. The plot photographs are linked to the Access database in a plot data viewing form. Voucher specimens were submitted to the University of Alaska Fairbanks Herbarium (ALA) for taxonomic determination.

Photo-interpretation of Landscape Change

The detection of landscape change has four components: (1) georectification of a time-series of images, (2) mapping of coastal waterbodies, (3) deriving maps of the main shoreline from the map of nearshore water, and (4) point sampling of ecosystem types. Mapping or point sampling was done for each period for each site. Data for each parameter was summarized by site, which is considered to be the sample unit, and by year. Mean characteristics of the three sites were calculated for each period. Images from similar years (e.g., 1951 and 1957) were combined into periods (e.g., 1951–1957) and time between periods is termed an interval (e.g. 1951–1957 to 1978–1982). The mapping and point sampling was done by photo-interpretation of pattern, texture, and color of image characteristics and used field plots as ground reference information.

Georectification of aerial photographs or satellite images was done in a multistage process. First, the recent Ikonos imagery was used as the base map for controlling the historical airphotos. The orthorectified Ikonos imagery was clipped to each site to allow better local rectification of the imagery. The clipped images were georectified to ground control points obtained from differentially corrected GPS coordinates for monitoring plots in distinctive locations. The historical photography from 1951–1957 and 1978–1982 (Table 1) were orthorectified to the original orthorectified Ikonos base image and DEM with a second-order polynomial transformation using Imagine software (ERDAS, Inc., Atlanta, GA). We used distinctive features on the various sets of imagery to provide broad spatial control for the airphotos. The airphotos

were then clipped to the site and reprojected to the clipped Ikonos imagery with a second order polynomial transformation using ArcMap software (ESRI, Redmond, CA). The images were georeferenced to North American Datum of 1983 (NAD83) and Albers Alaska Equal Area Conic projection.

Table 1. Characteristics of images used for detecting landscape change.

Original Image ID	Final File ID	Date and Type	Resolution (m)	Rectification Error (RMS, m)
3570010001	ChinitnaBay_Ikonos_2004_AlbAK83_clip_rect-gndcpts.img	2004-08-14 Ikonos	1	2
7680060007	silverSalmon_2005-08-14_Ikonos-AlbAK83_clip_rect-gndcpts.img	2005-08-14 Ikonos	1	2
	HalloBay_2000-5-27_IKONOS-AlbAK83_clip_rectify_gcp.img	2005-5-27 Ikonos	4	4
AR5780026677547	Silver Salmon 1978_CIR_clipped-rerectified2.img	1978-08-26 CIR	1.0	2
AR5780026677710	ChinitnaBay_1978_CIR_7710_cam_rms002_aoi_poly2_rms2pt15.img	1978-08-26 CIR	1.0	2
AR5820031080071	HalloBay_1982-08-03_AlbAK83_clip_rms1.img	1982-08-03 CIR	1.9	1
ARBM02020050506	Silver-Salmon_1957_clip-rerect_rms003.img	1957-08-02 B&W	1.1	3
ARBM02220425594	ChinitnaBay_1957_poly3_001_aoi_poly1_rms2pt52.img	1957/06/06 B&W	1.0	3
ARCNAE000040128	HalloBay_1951-06-11_AlbAK83_clip_rms1.img	1951/06/11 B&W	0.9	1

Waterbodies were mapped for each period within each of the three sites using a geomorphic classification that included both terrestrial and aquatic units (Table 2). Only distinct waterbodies were delineated, and thus wet meadows or shallow marshes with indistinct water margins were not included. The nearshore water also was mapped at each site, extending to an arbitrary boundary at 300–400 m from the shoreline. Each mapped polygon was coded with site, year, period, and geounit. Change in waterbody extent was evaluated by summing areas by waterbody type, site, and period. Because the sites have different sizes, the areas were converted to percent area of site. To assess changes, a mean percent area and 95% confidence interval (CI) were calculated for each waterbody type across the three sites for each period.

The shoreline was derived from the waterbody units described above. The shoreline for nearshore water was defined as the wetting line on the slope of the beach or on the tidal flat. The wetting line was evident as a distinct change in color and tone on the imagery between dry, light colored sand not affected by normal tides and wet, dark colored sand that was saturated by the most recent tidal cycle. While this definition is imprecise and map accuracy is limited to several meters, it is sufficient for measuring change of 10s of meters over decades. The boundary is more satisfactory than the water's edge, because of the high tidal fluctuation and the sensitivity to the date and time of image acquisition. The wetting line is also more useful than the vegetated boundary, which is problematic because it can be considerably higher and further inland than the higher-high tide line and can be subject to disturbances by storms. The shoreline for display in separate shoreline maps (e.g., Figure 17) was derived from the waterbody layer, as follows:

First, the nearshore water polygon from the waterbody layer (polygon features) was copied to the shoreline layer (polyline features). Second, the offshore segments of the polygons were trimmed off to preserve only the shoreline segments of the original nearshore water polygon. Note that during mapping of the nearshore polygons, the nearshore water was extended directly across the mouths of river and tidal channels.

Table 2. Classification and description of geomorphic units for salt marshes along Cook Inlet, AK.

Geomorphic Unit	Description
Barrier Islands and Spits (Mi)	Undifferentiated gravelly or sandy barrier islands, spits connected to the mainland, and bay barriers. They typically are linear features parallel to the coast, although spits may have more variable orientations.
Active Sandy Beach (Mba)	Wave eroded and deposited sandy material on sloping beaches fronting open water. Surface varies from barren to vegetated by early successional plants
Coastal Overwash Fans (Mo)	Gravelly to sand sediments deposited in fan-shaped to linear lobes formed by breaching of beaches and dunes during large storm events. The material typically grades from coarse to fine perpendicular to the shoreline.
Coastal Active Dune (Mda)	Very fine to fine sand deposited in wind-blown dunes parallel to the coast and downwind from sandy beach deposits. Active dunes have <3 cm of organic matter within the top 30 cm, indicating frequent deposition.
Coastal Inactive Dune (Mdi)	Very fine to fine sand deposited in wind-blown dunes parallel to the coast and downwind from sandy beach deposits. Inactive dunes have >3 cm of organic matter within the top 30 cm, indicating infrequent deposition.
Active Tidal Flat (Mta)	Areas of nearly flat, barren mud or fine sand that are periodically inundated by tidal waters. Tidal flats occur on seaward margins of deltaic estuaries, lagoons, leeward portions of bays and inlets, and at mouths of rivers. Tidal flats may vary widely in salinity depending on tidal flooding and influx of fresh water. Active flats have <3 cm of organics within the top 30 cm, indicating frequent deposition.
Inactive Tidal Flat (Mti)	Similar to active tidal flats, but flooded only during large storms. The sediments are only slightly brackish and the surface usually is well vegetated. The silty sediments have >3 cm of organics within the top 30 cm.
Abandoned Tidal Flat (Mtb)	Similar to active tidal flats, but rarely flooded by storms. The flats often have been uplifted by tectonic events. The sediments are non-saline and the surface usually is well vegetated. The silty sediments have >10 cm of organic matter formed by non-halophytic vegetation within the top 30 cm.
Tidal Lagoons (Wetl)	Shallow estuarine water protected from open water by barrier islands and spits. Water is slightly brackish to brackish depending on the input of freshwater.
Tidal Ponds (Wetp)	Coastal ponds that are flooded periodically with saltwater during high tides or storm surges. Salinity levels often are increased by subsequent evaporation of impounded saline water. The substrate frequently is silt with some clay and fine sand, and occasionally contains peat.
Tidal River (Wetr)	Permanently flooded river channels that are affected by daily tidal fluctuations and have correspondingly variable salinity. The channels generally experience peak flooding during spring breakup and lowest water levels during mid-summer. During winter, deeper channels can have elevated salinity levels.
Tidal Active Chan. (Wetca)	Regularly flooded, dendritic, small channels (guts) on tidal flats. Typically they have muddy sediments and lack vegetation.
Tidal Inactive Channel (Wetci)	Irregularly flooded, dendritic, small channels (guts) on tidal flats affected only by storm events. Typically they have muddy sediments, are fresh to slightly brackish, and are vegetated by nonhalophytic vegetation that are slightly salt tolerant. Permanently flooded waterbodies within inactive channels are mapped as Tidal Ponds.
Nearshore Water (Wmn)	Marine water near the shoreline. Winds, tides, river discharge, and sea ice create dynamic changes in physical and chemical characteristics. Bottom sediments vary from wave cut bedrock, to gravel, to mud. During winter the water is covered with ice floes.
Shallow, isolated lakes (Wlsi)	Shallow isolated lakes and ponds are freshwater bodies that are not affected by tides or storm surges. These may occur on abandoned tidal flats and beaver impounded drainages at the margins to the tidal flats.

Shoreline erosion rates were determined by calculating differences in areas of nearshore water for each time interval for each site. The difference in area was then divided by the length of shoreline to obtain a mean erosion width for each time interval. The mean width was divided by the time interval to calculate a mean erosion rate for the interval. Because shoreline widths change over each interval, we used the offshore boundary of the site parallel to the shoreline as a fixed, smoothed, shoreline for comparisons among intervals.

To assess landscape change, we developed a mapping classification of ecosystem types (ecotypes) that incorporated physiographic, geomorphic, chemistry, and vegetation characteristics. It was necessary to use this more comprehensive classification because the plant community classification developed from the vegetation data was insufficient to cover the full range of geomorphic and vegetative characteristics of the site. For example, portions of each site were covered by gravelly floodplains and nearshore water not included in the field sampling. In addition, the ecotype classification was more useful for differentiating geomorphic and ecological processes associated with landscape change than the vegetation data alone. The ecotype classification was developed by cross-tabulating data for physiography, geomorphic unit, soil texture, site chemistry, and plant community type from the plot database and identifying and selecting the most frequent combinations. Most ecotypes were associated with a unique plant community. Ecotypes that were not represented in the plot database (e.g. Riverine Gravelly Alkaline Barrens) were assigned through photointerpretation of physiographic unit, assignment of a dominant vegetation structure, and our experience in other coastal regions.

Table 3. Classification of geomorphic and ecological processes associated with landscape change of coastal ecosystems.

Change Type	Description
None	No change in ecotype.
Shoreline Erosion	Change from land to nearshore water.
Shoreline Erosion-Deposition	Change from land to nearshore water, and back to nearshore water.
Shoreline Deposition	Change from nearshore water to land.
Channel Erosion	Change from land to tidal river or tidal gut.
Channel Erosion and Deposition	Change from land to tidal river or tidal gut back to land.
Channel Deposition	Change from tidal river or tidal gut to land.
Sedimentation	Change from vegetated ecotype to barren land or earlier successional ecotype.
Beaver Dam	Change from land to water caused by a beaver dam.
Paludification	Change from water or marsh ecotypes to wet meadow ecotypes.
Sedimentation and Succession	Change from vegetated ecotype to barren land, and back to vegetated ecotype.
Shoreline Deposition and Succession	Change from water to barren land and then to vegetated land.
Early Succession	Change from barren land to an early successional ecotype with meadow or shrub vegetation.
Late Succession	Change from an early successional ecotype (meadow and shrub) to forested ecotype.
Tidal Fluctuation	Change from nearshore water to tidal flat in offshore areas, or vice-versa due to normal tidal fluctuation. While this change is distinctive on imagery, it was ignored and the barren tidal flat was assigned to nearshore water because it is not a persistent change.

To quantify change in the distribution and abundance of ecotypes, we used point sampling to determine the relative cover of the ecotypes on a time-series of images. The sampling used a 200-m grid with a random start established with a GIS, for a total of 634 grid points across the three sites. At each grid point, the ecotype was determined through photo-interpretation using the classes listed in Table 7.

Where change was evident among periods, the change was attributed to a specific geomorphic or ecological process defined in Table 3. The monitoring plots served as reference plots for helping control the accuracy of the photo-interpretation. The photo-interpretation was done on-screen using ArcGIS software, and the ecotype at each point for each of the three periods was entered into an attribute table. Attributes for each point include site, ecotype55, ecotype80, ecotype05, change55-80, change80-05, change55-05, and notes.

Data Analysis

The sampling was designed to allow a generalized linear model with repeated measures to be used for testing differences among multiple years for single variables. However, at this early stage of collection of baseline data, we simply calculated descriptive statistics for most parameters using a plant community classification we developed from the vegetation data. Descriptive statistics (n, mean, SD) were used to characterize central tendencies for elevation, cumulative organic thickness, salinity, and soil water depth by plant community. For tidal water level and salinity, and for soil and air temperatures, the time-series data were simply plotted to visually identify seasonal trends. For the landscape change analysis, we aggregated the data by site and period, and then used the mean and 95% CI to evaluate differences among the three time periods and sites.

Vegetation classification involved several steps following the general procedures described in McCune and Grace (2002). First, the data were organized in a matrix by 121 species by 130 plots. Second, communities were classified using the TWINSpan routine in PC-ORD software to sort data by plot and species and to hierarchically cluster the plots. Communities were differentiated at the 75% information remaining level. Third, the data were analyzed by nonmetric multidimensional scaling (NMS) to identify structural relationships in the data set. The NMS analysis was run in the "autopilot" mode that finds the optimal solution for number of runs, best solution for each dimensionality, and testing for significance. We used the Sorensen distance measure. Fourth, the sample plots were plotted according to the distance measures for the first two axes and labeled according to the TWINSpan cluster they were identified with. The clusters for each TWINSpan-class are plotted on the NMS axes and reviewed to identify outliers for each cluster. For each outlier, the species-cover tables were reviewed to identify the reason for the outlier and a decision was made whether to keep the outlier, eliminate the outlier, or reclassify it. Once the plant communities were established, each plot was assigned a community name that was based on its dominant species and a diagnostic species that differentiated the community from other similar communities.

Results and Discussion

Topography

Topographic surveying was completed along four transects each at SISA, CHBA, and HABA (Figures 7–9). The surveying revealed that surface elevations varied < 0.5 m across the inactive tidal flats, excluding the tidal channels, and 3–4 m across the barrier dunes. Plot locations on the transects are shown in Figures 3 and 4.

When comparing elevations by plant community across all transects, large differences were found among communities (Figure 10). Lowest mean elevations occurred on Barren Mudflats (-0.1 m) and Barren Beach (0.0 m). Mean elevations of plant communities ranged from 1.5 to 2.2 m above MSL on vegetated active tidal flats (saline) and from 2.0 to 3.4 m above MSL on inactive tidal flats (slightly brackish). In contrast, mean elevations of plant communities on beach ridges ranged from 3.2 to 3.5 m. Maximum observed elevation on ridges was 4.3 m above MSL. Note that the elevations were based on intermediate quality DGPS measurements (~ 1 m vertical accuracy) used to calculate benchmark elevations and hopefully will be improved with future acquisition of high accuracy DGPS data.

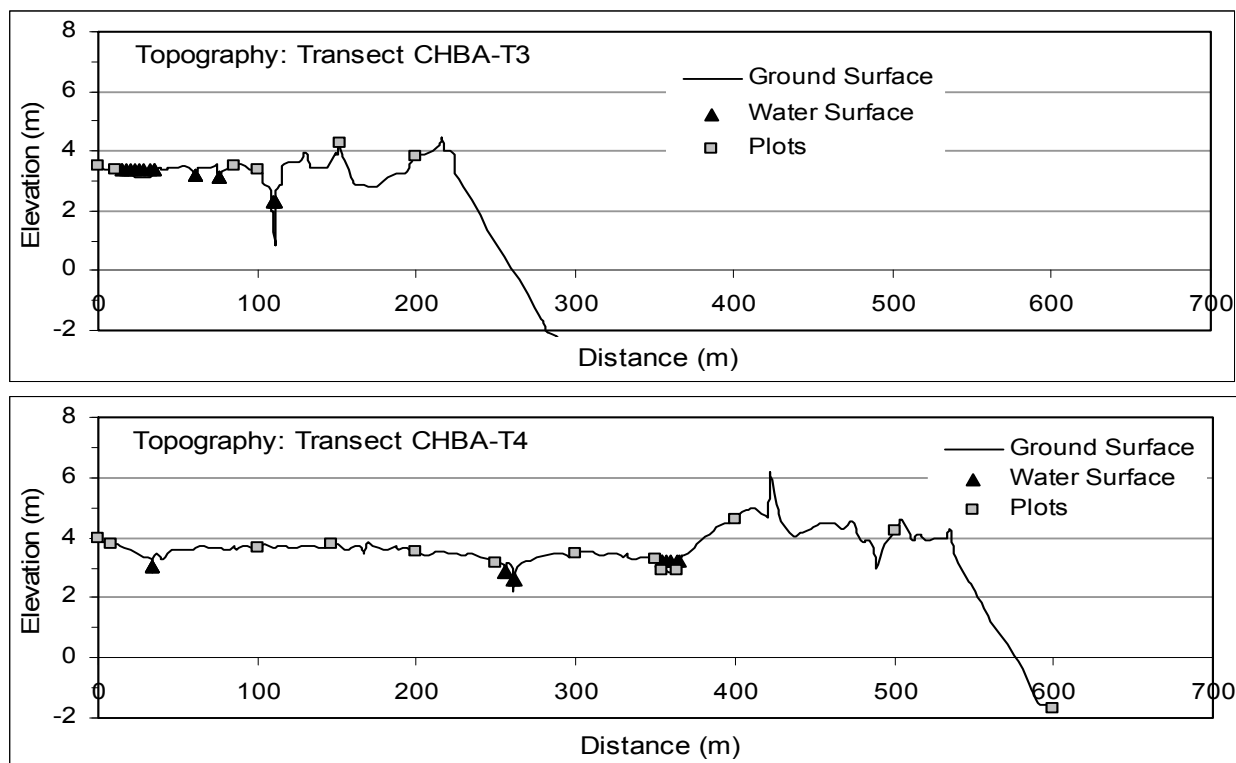


Figure 7. Topographic profiles for two of four transects sampled at Chinitna Bay (CHBA).

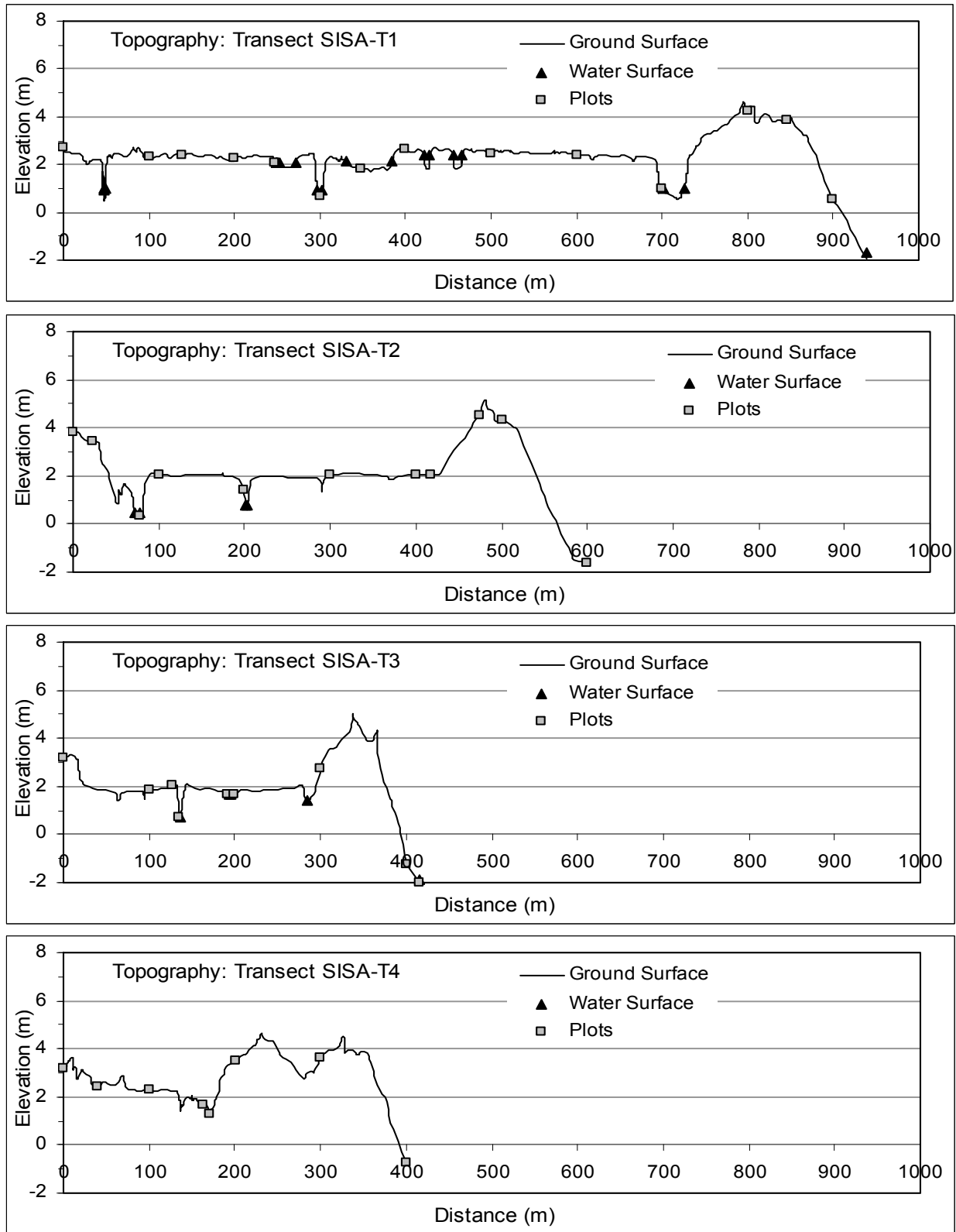


Figure 8. Topographic profiles for four transects at Silver Salmon (SISA).

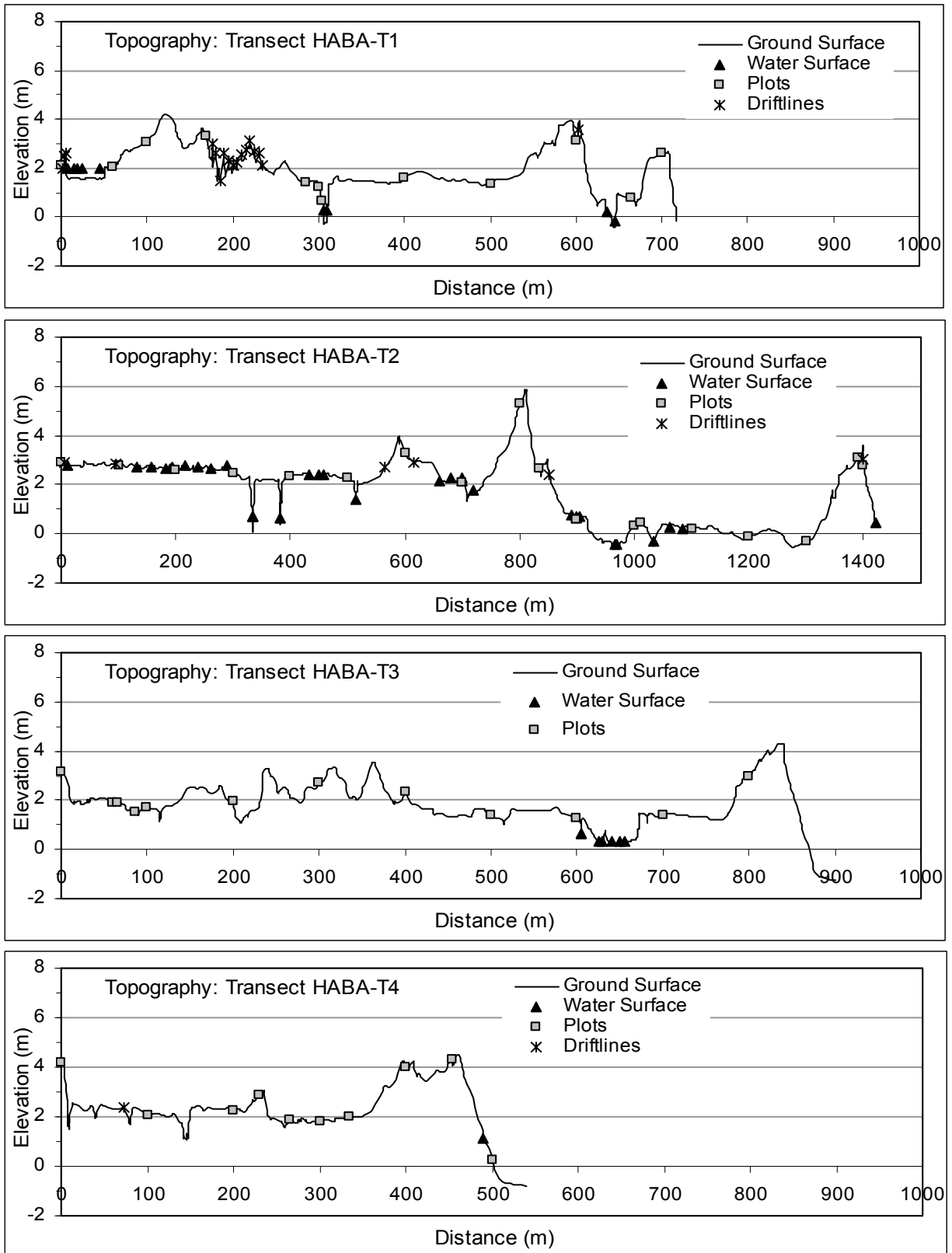


Figure 9. Topographic profiles for four transects at Hallo Bay (HABA).

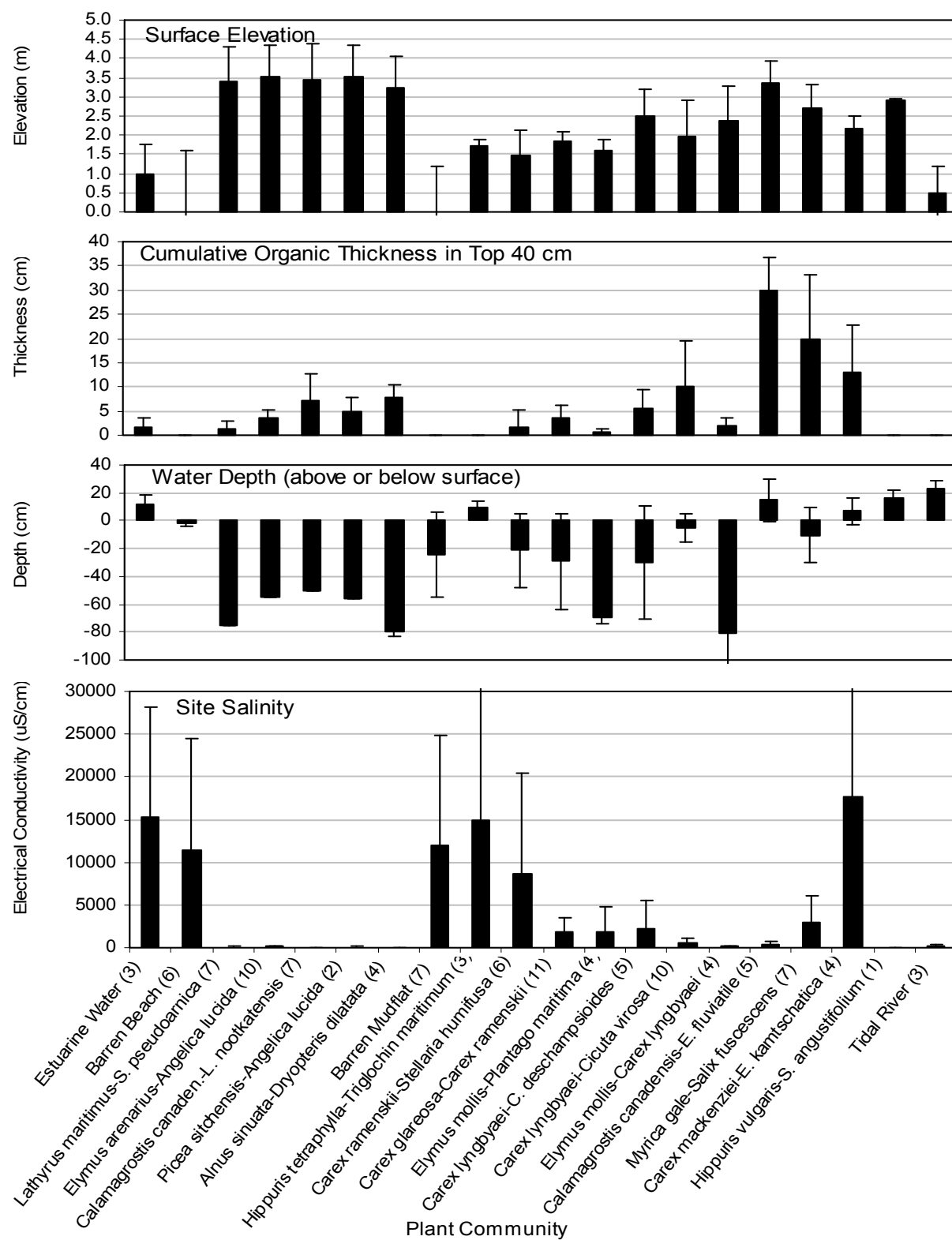


Figure 10. Mean ($\pm$ SD) surface elevations, cumulative organic thickness in top 40 cm, water depths, and salinity (electrical conductivity) by plant community. Samples sizes in parentheses after communities.

Tides and Storm Surges

Water levels were monitored using submersible pressure transducers at two locations at SISA and one location at CHBA starting in October 2007, and at one location at HABA since July 2008 (Figure 11). In addition, one datalogger each have been recording barometric pressure and air temperature at both SISA and HABA for use in correcting pressures when converting pressures to water levels. Water levels and temperatures at SISA and CHBA are presented in Figures 12 and 13.



Figure 11. Views of water level and barometric pressure recorders at the Silver Salmon (SISA), Chinitna Bay (CHBA), and Hallo Bay (HABA) coastal sites.

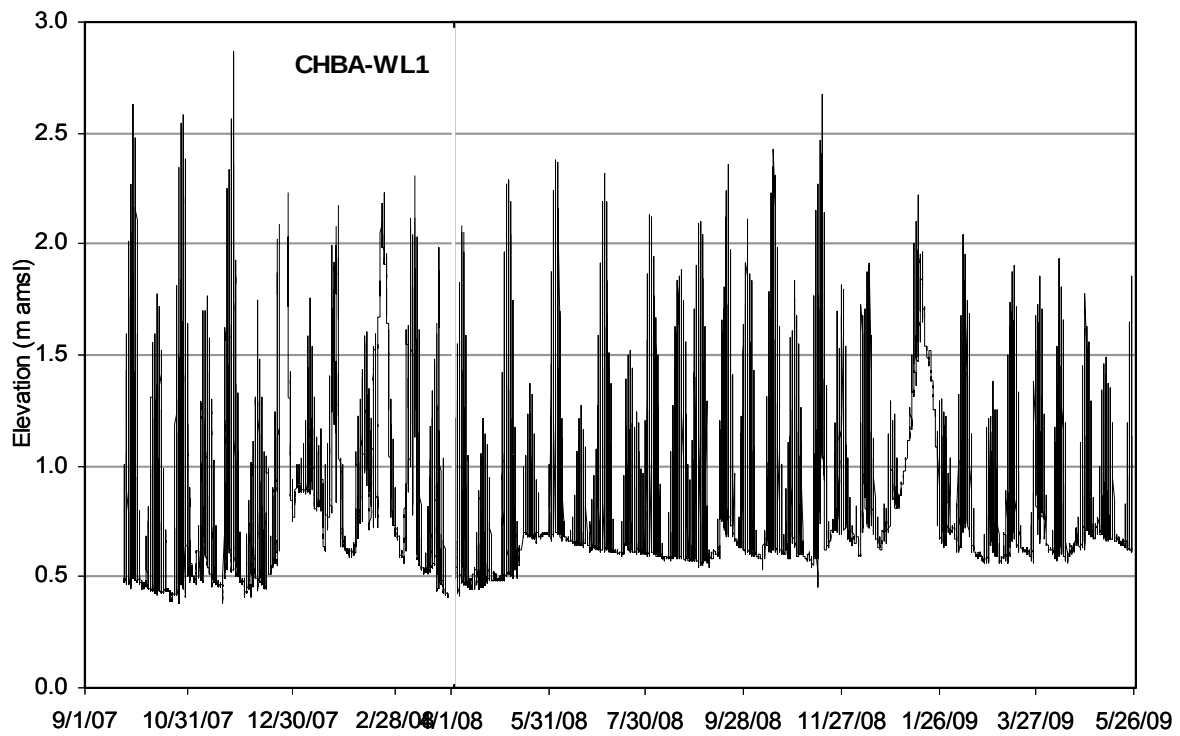
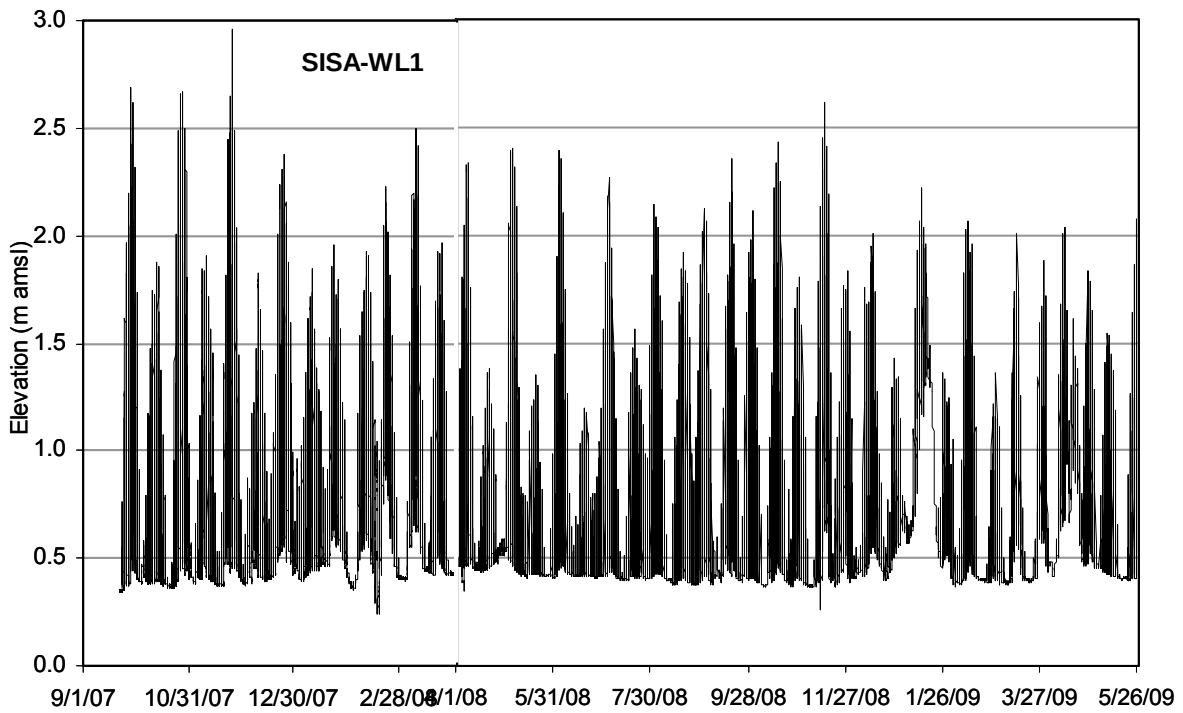


Figure 12. Water levels at Silver Salmon (SISA) and Chinitna Bay (CHBA) September 2007 to May 2009.

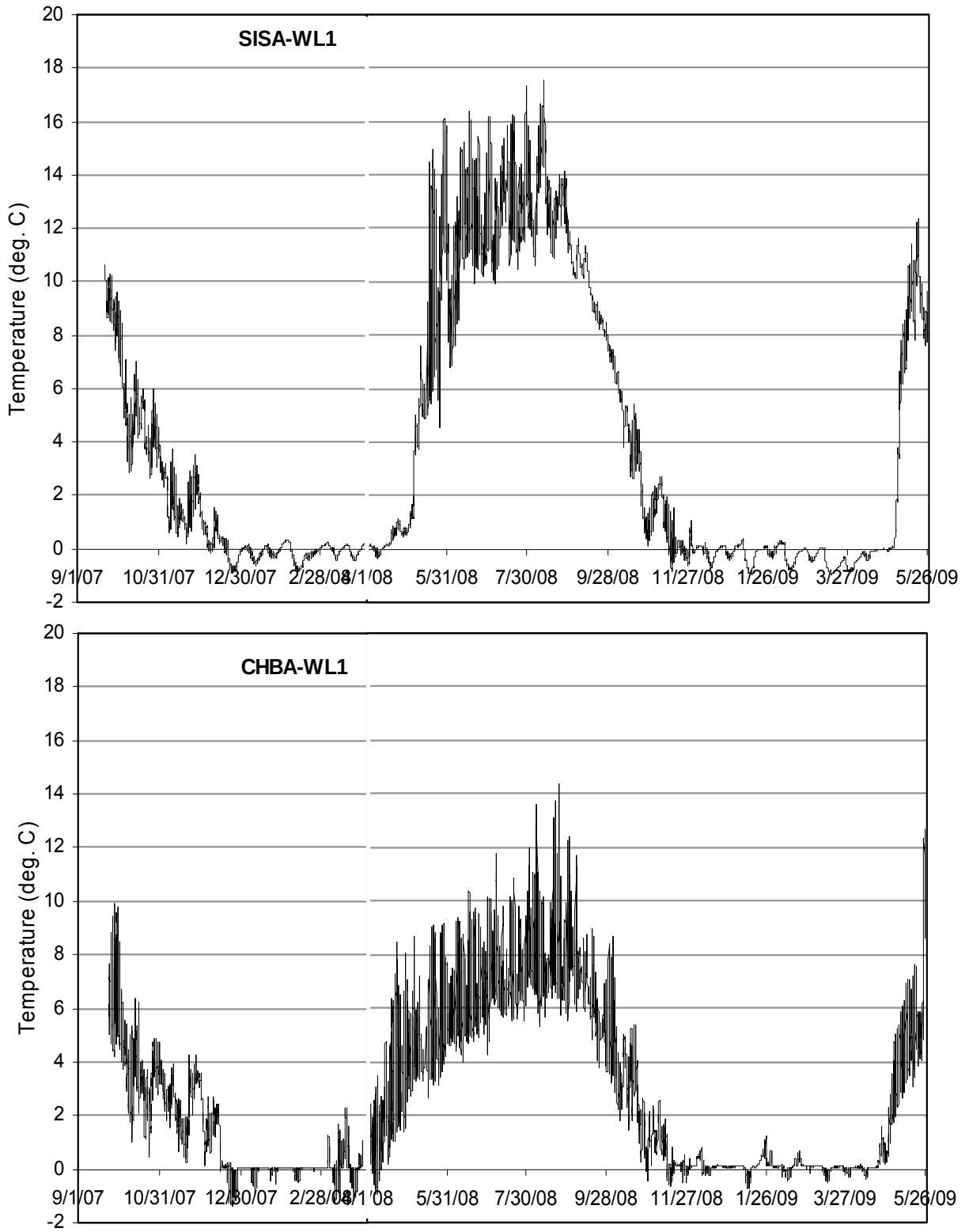


Figure 13. Water temperatures at Silver Salmon (SISA) and Chinitna Bay (CHBA).

Higher-high water levels at SISA and CHBA typically reached ~2 m above MSL on a biweekly basis during summer months and reached ~2.5 m in mid-winter. Major storms with water levels above 2.5 m were recorded four times at SISA and CHBA over the observation period, with a maximum observed height of 2.9 m. Note that the dataloggers were not able to record the full range of tide levels because the instruments were established in shallow, protected areas.

Based on mean ground surface elevations of ~1.5–1.8 m above MSL for the lowest plant communities (*Carex ramenskii-Stellaria humifusa*, *Elymus mollis-Plantago maritima*) on active tidal flats (Figure 13), the results indicate that the lowest plant communities on the active tidal flats were flooded nearly every month. Based on mean elevations of 2.7–3.4 m for the highest plant communities (*Calamagrostis canadensis-Equisetum fluviatile* and *Myrica gale-Salix fuscescens*) on inactive tidal flats, the maximum recorded storm height of 2.9 m indicates a portion of the slightly brackish plant communities were flooded once over the nearly 2-yr period. However, the elevations of the benchmarks and tidal gauges were not sufficiently accurate to allow strong conclusions regarding flooding effects across plant communities with small differences in elevations.

Water temperatures in the tidal guts reached maximum temperatures of 17.5 and 14.3 °C at CHBA and SISA, respectively. During mid-summer, temperatures typically fluctuated 5–7 °C daily. During winter months, temperatures were maintained near 0 °C at both sites for 3–5 months. Temperatures indicate that the channels become ice free between mid-March and mid-April.

Sedimentation and Salinity

Soil plugs were photographed at each plot to establish baseline conditions for monitoring sediment accumulation (Figure 14). At some plots in Hallo Bay, tephra from the eruption of Novarupta on June 6, 1912, left a distinctive stratigraphic marker that can be used for measuring sediment accumulation rates. For example, at one site in Hallo Bay, 14 cm of sediment has accumulated over a 96-yr period, roughly equivalent to a sedimentation rate of 1.5 mm/yr.

Measurements of organic-horizon thickness in the soils at the plots provide an indirect, inverse measure of sedimentation accumulation because heavy sedimentation prevents the accumulation of organic matter. Mean cumulative thickness of organic horizons in the top 40 cm ranged from 0 cm to 29.8 cm across all plots (Figure 10). When comparing cumulative organic thickness among plant communities, cumulative thickness was lowest (0–2 cm) for *Lathyrus maritimus-Senecio pseudoarnica*, *Carex ramenskii-Stellaria humifusa*, and *Elymus mollis-Plantago maritima* on active tidal flats, and highest (20–30 cm) for *Calamagrostis canadensis-Equisetum fluviatile* and *Myrica gale-Salix fuscescens* on inactive tidal flats.

Water depths and salinity (as measured by electrical conductivity, EC) were collected during initial plot setup (Figure 10). When comparing differences among plant communities, mean EC ranged from 41 to 17,657 µS/cm across all classes. Mean EC was lowest (<100 µS/cm) on older beach ridges, which support mid- to late-successional communities such as *Alnus sinuata-Dryopteris dilatata* and *Picea sitchensis-Angelica lucida*, and highest (~15,000 to 18,000 µS/cm) in ponds on active tidal flats, which support *Hippuris tetraphylla-Triglochin maritimum* and *Carex mackenziei-E. kamtschatica* communities. While monitoring dynamic parameters, such as

EC, every 10 years isn't sufficient to detect small changes, the data are useful for comparing environmental conditions among plant communities within each monitoring period.



Figure 14. Photographs of soil plugs extracted for documenting current sediment layers and stratigraphy for use in future measurement of sediment accumulation.

Soil Temperature

Soil temperatures were monitored at two plots within the three study sites to assess changes in temperatures within a wet salt marsh and a dry sand dune ecosystem. At each plot, soil temperatures were measured near the surface (~5 cm depth) and at a deeper (~20 cm) horizon, while air temperatures were obtained from the barometric pressure dataloggers situated at ~150 cm above ground. Data from a one-year period for each of two sites at SISA and CHBA are presented in Figure 15.

At SISA, air temperatures ranged from -17 to 10 °C from September through May. Across both wet and dry sites, soil temperatures ranged from -4 to 10 °C, and were comparable at both depths. Soils remained near the freezing point during winter months, indicating that unfrozen water contents associated with saline conditions prevented the soils from totally freezing and temperatures from dropping substantially below freezing. When comparing differences between wet and dry sites, soil temperatures were remarkably similar among sites, although the wet meadow site at SISA thawed nearly two weeks earlier in April, presumably due to tidal flooding. Upon collection of a longer time-series of temperature data, more rigorous analyses can be made of differences in mean annual temperatures, freezing- and thawing-degree days, and length for freezing season between plant communities and among years.

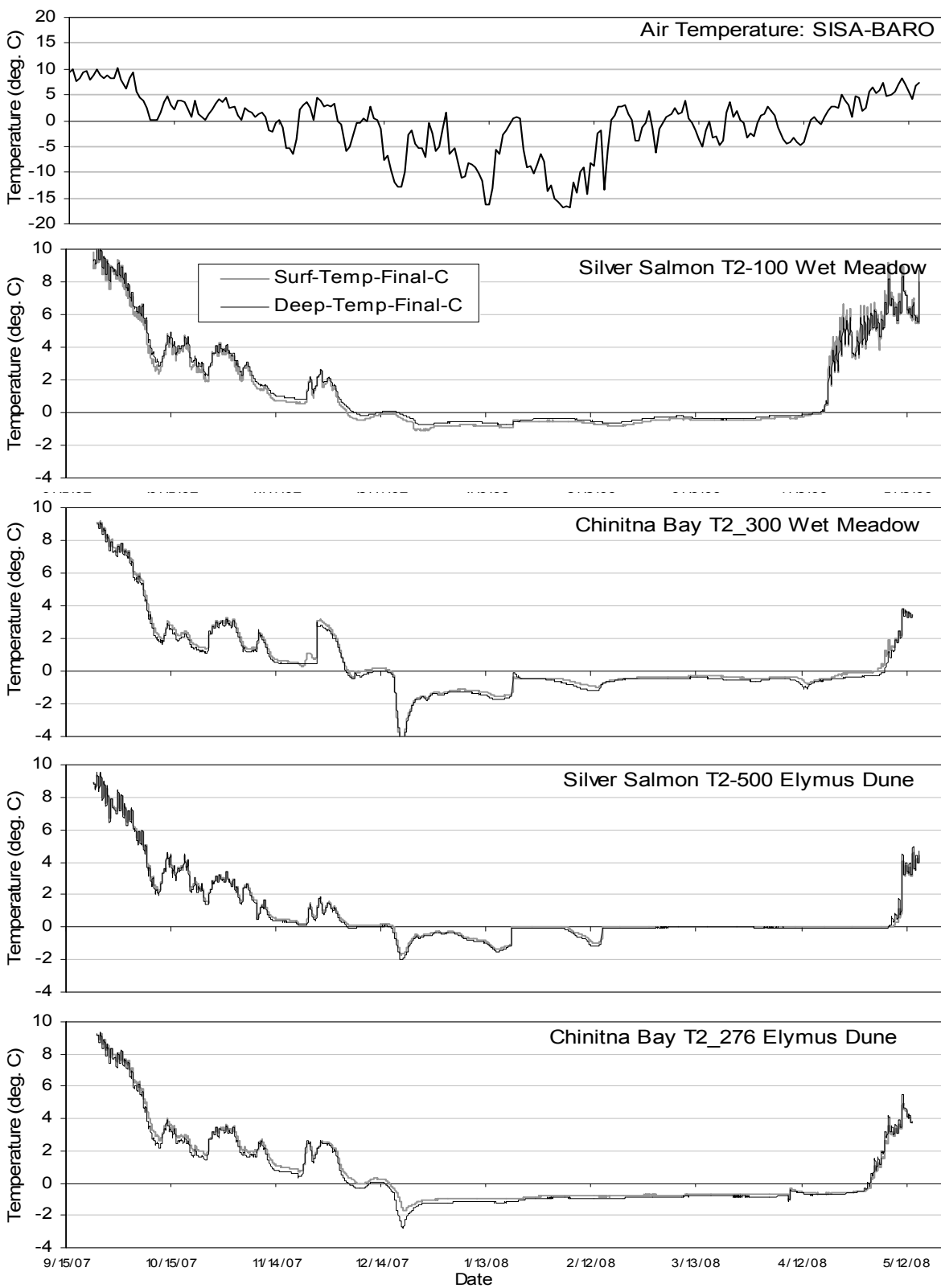


Figure 15. Air and soil temperatures at 5 cm and 20 cm for two soil types at Silver Salmon (SISA) and Chinitna Bay (CHBA).

Vegetation

Vegetation cover data collected at 130 plots across the three study sites were used to classify 19 plant communities, based on cluster analysis and NMS ordination (Figure 16). These were broadly grouped into 14 communities on tidal flats and five communities on beach ridges. A total of 127 taxa were observed in the plots.

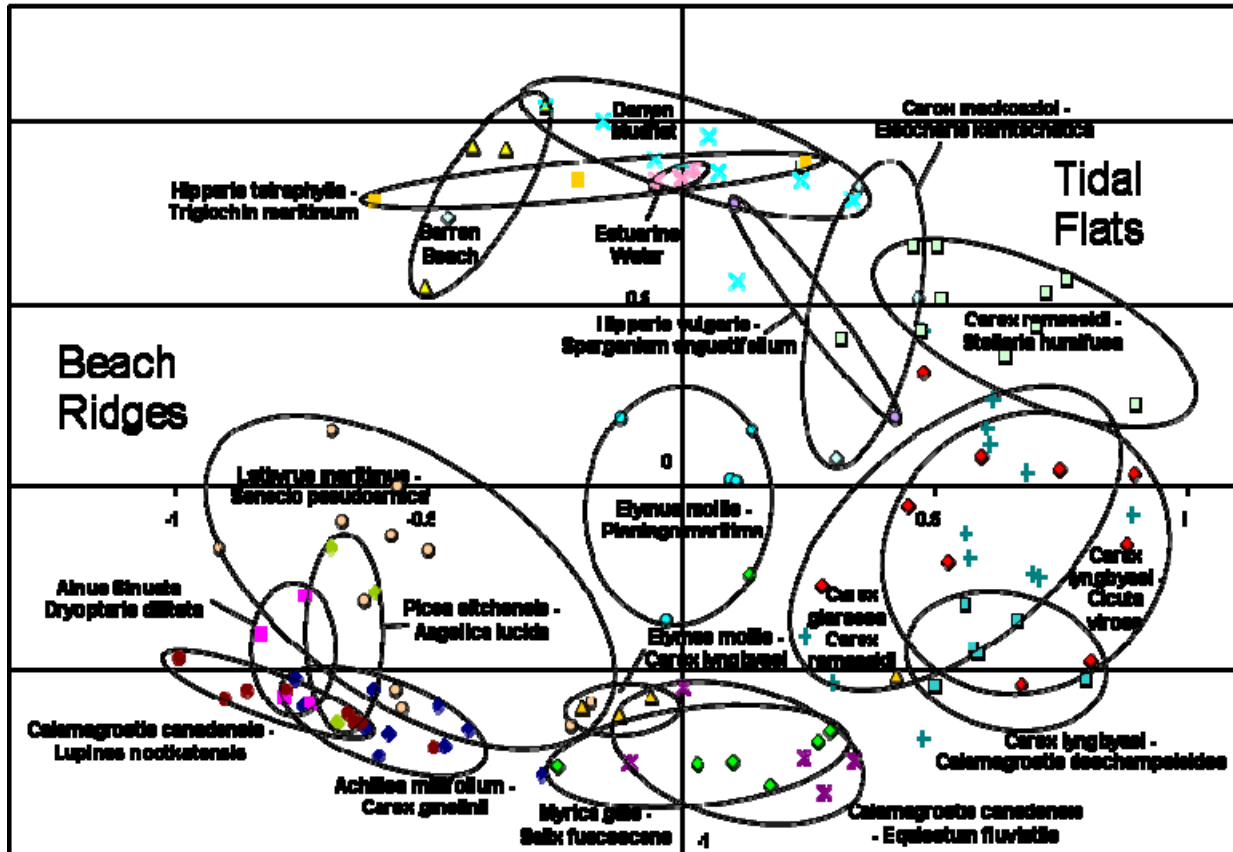


Figure 16. Ordination of species composition based on nonmetric multidimensional scaling. Ellipses highlight the central tendencies (some outliers excluded) grouping of plots by plant community.

The mean cover of each plant species was analyzed by site and by plant community. When comparing differences among sites using only systematically located plots, 37 taxa were sampled at all three sites and 47 taxa were sampled at only one site (Table 4). When comparing differences among sites for all plots, species counts totaled 58, 93, and 102 for SISA, CHBA, and HABA, respectively. The lower total count at SISA was due to the inclusion of fewer inland, nonsaline plant communities than for the other two sites. Overall, vegetative cover was dominated by forbs (57%) and sedges (34%) with minor amounts of deciduous shrubs (13%) and mosses (13%). Evergreen trees (1%), deciduous trees (0.1%), and lichens (0%) had negligible cover. The most abundant plant species at the coastal sites included *Lathyrus maritimus*, *Potentilla egedii*, *Triglochin maritimum*, *Plantago maritima*, *Calamagrostis canadensis*, *Elymus arenarius mollis*, *Poa eminens*, *Carex lyngbyaei*, *Carex glareosa*, *Carex ramenskii*, *Festuca rubra*, *Alnus sinuata*, *Achillea millefolium*, *Angelica lucida*, *Salix fuscescens*, and *Myrica gale*. For most species, mean cover varied by <5% among sites.

The mean cover of each plant species by plant community, which included the targeted plots in uncommon plant communities, showed large differences among plant communities (Tables 5 and 6). Species composition and cover was broadly differentiated by plant communities on wet tidal flats and dry beach ridges, with many species occurring only on one or the other surficial deposit. Dominant species on the brackish to saline active tidal flats included *Plantago maritima*, *Triglochin maritimum*, *Carex ramenskii*, *Potentilla egedii*, *Poa eminens*, *Carex glareosa*, *Calamagrostis deschampsoides*, *Festuca rubra*, and *Elymus arenarius mollis*. Dominant species on slightly brackish to fresh inactive tidal flats included *Carex lyngbyaei*, *Calamagrostis canadensis*, *Myrica gale*, *Salix fuscescens*, and *Carex pluriflora*. Dominant plants on early successional communities on gravelly beach ridges included *Senecio pseudoarnica*, *Carex gmelinii*, *Lathyrus maritimus maritimus*, *Elymus arenarius mollis*, *Festuca rubra*, *Achillea millefolium*, and *Angelica lucida*. Later successional vegetation on beach ridges included *Calamagrostis canadensis*, *Alnus sinuata*, *Dryopteris dilatata americana*, *Epilobium angustifolium*, *Picea sitchensis*, *Lupinus nootkatensis*, and *Rhytidadelphus* spp. Repetitive 'hits,' or intercepts, of a species within a plot provide an index of biomass, as cover estimates are highly correlated with biomass. Highest values for total live cover for herbaceous or low shrub communities occurred in *Myrica gale*-*Salix fuscescens* (251%), *Elymus mollis*-*Carex lyngbyae* (244%), and *Carex lyngbyaei*-*C. deschampsoides* (214%). In contrast, barren to partially vegetated areas had little total live cover.

Plant communities on the active tidal flats are of particular importance for the salt marsh monitoring. The *Carex ramenskii*-*Stellaria humifusa* community, in particular, provides critical foraging, mating and rearing habitat for brown bears. Brown bears graze on *Carex ramenskii*, a wet meadow dominant, and also dig for clams and feed on spawning salmon in these environments. The cropping of the sedge maintains short-stature grazing lawns across much of the flats behind the protective dunes.

An ecological land classification (ELC) was developed to relate the distribution of plant communities to geomorphology, soil texture, drainage, and soil chemistry (Table 7). The classification includes 25 ecotypes, including three barren classes and four nonvegetated waterbodies. In addition, two of the ecotypes do not have a plant community type derived from our plot sampling, but were recognized by the dominant plant species (e.g. *Picea sitchensis*, *Salix barclayi*). Plant communities and their co-varying landscape characteristics were assigned an ecotype name useful to a broader audience not familiar with plant taxonomy. This broader classification, which includes ecosystem types that were not vegetated and/or that were not sampled in the field, is more amenable to comprehensive mapping across the entire sites. The ELC, which was based on independently measured and classified attributes, illustrates the strong relationship between vegetation and geomorphic processes. The wet, muddy tidal flats were differentiated from the dry, gravelly beach ridges based on differing depositional processes related to wave energy and flooding regime. With each of those broad geomorphic environments, active (<3 cm of organics in the top 30 cm), inactive (>3 cm of interbedded organics in the top 30 cm), and abandoned (>10 cm of pure organics at surface) depositional regimes were differentiated to reflect differing flooding frequency and sedimentation rate. Within these finer-level geomorphic distinctions, there are gradients in soil texture, drainage, and salinity that help determine the occurrence of specific plant communities. The relationships are useful for predicting the response of vegetation to changing geomorphic processes and for mapping change over time.

Table 4. Mean plant cover (%) and 90% CI for three coastal sites in SWAN, based on 78 systematically distributed plots.

Species or Cover	CHBA (20)		HABA (35)		SISA (23)		Overall (n=78)		
	Mean	CI	Mean	CI	Mean	CI	Mean	CI	Freq. %
<i>Picea sitchensis</i>	3.1	3.3	0.2	0.3	1.1	1.3	1.2	0.9	11.5
Evergreen Tree Total	3.1	3.3	0.2	0.3	1.1	1.3	1.2	0.9	11.5
<i>Betula papyrifera</i> var. <i>kenaica</i>	0.1	0.2	0.3	0.4	0.0		0.1	0.2	3.8
Deciduous Tree Total	0.1	0.2	0.3	0.4	0.0		0.1	0.2	3.8
<i>Alnus sinuata</i>	4.0	6.6	1.9	3.1	0.0		1.9	2.2	2.6
<i>Betula nana</i>	0.4	0.4	0.6	0.9	0.0		0.3	0.4	3.8
<i>Myrica gale</i>	7.6	9.2	7.3	5.5	0.0		5.2	3.4	10.3
<i>Oplopanax horridus</i>	1.2	1.9	0.0		0.0		0.3	0.5	1.3
<i>Ribes laxiflorum</i>	0.7	1.1	0.0		0.0		0.2	0.3	1.3
<i>Ribes triste</i>	0.4	0.6	0.0		0.0		0.1	0.1	1.3
<i>Salix barclayi</i>	0.0	0.0	0.0		0.0		0.0	0.0	1.3
<i>Salix fuscescens</i>	9.5	8.9	5.6	5.4	0.0		4.9	3.4	10.3
<i>Salix planifolia pulchra</i>	0.2	0.2	0.0		0.0		0.0	0.1	2.6
<i>Salix</i> sp.	0.3	0.4	0.0		0.0		0.1	0.1	1.3
<i>Sambucus racemosa</i>	0.0	0.0	0.0		0.0		0.0	0.0	1.3
<i>Viburnum edule</i>	0.4	0.7	0.0		0.0		0.1	0.2	1.3
Deciduous Shrubs Total	24.3	18.6	15.3	10.9	0.0		13.1	6.9	15.4
<i>Empetrum nigrum</i>	0.0		0.0	0.0	0.0		0.0	0.0	1.3
<i>Vaccinium vitis-idaea</i>	0.0		0.1	0.2	0.0		0.1	0.1	1.3
Evergreen Shrubs Total	0.0		0.1	0.2	0.0		0.1	0.1	1.3
<i>Achillea millefolium</i>	10.8	7.8	6.6	3.4	14.5	10.0	10.0	3.9	33.3
<i>Angelica lucida</i>	3.2	2.2	2.1	1.7	11.1	8.6	5.0	2.8	32.1
<i>Atriplex gmelini</i>	0.0		0.1	0.1	0.0		0.0	0.0	1.3
<i>Cardamine</i> sp.	0.0		0.0		0.0	0.0	0.0	0.0	1.3
<i>Chenopodium glaucum</i>	0.0		0.0	0.0	0.0		0.0	0.0	2.6
<i>Chrysanthemum arcticum</i>	0.8	0.6	1.7	1.7	1.4	1.6	1.4	0.9	19.2
<i>Cicuta virosa</i>	0.0	0.0	0.7	0.9	0.0		0.3	0.4	6.4
<i>Conioselinum chinense</i>	0.5	0.5	1.5	1.5	0.8	1.0	1.0	0.7	14.1
<i>Cornus suecica</i>	0.0		0.3	0.5	0.0		0.1	0.2	1.3
<i>Cystopteris fragilis</i>	0.1	0.1	0.0		0.0		0.0	0.0	1.3
<i>Drosera rotundifolia</i>	0.0		0.0	0.0	0.0		0.0	0.0	1.3
<i>Dryopteris dilatata americana</i>	3.7	6.0	0.0	0.0	0.0		0.9	1.5	2.6
<i>Epilobium angustifolium</i>	0.0	0.0	3.6	2.8	0.1	0.2	1.7	1.3	12.8
<i>Epilobium palustre</i>	0.4	0.6	0.5	0.6	0.0	0.0	0.4	0.3	12.8
<i>Equisetum fluviatile</i>	1.3	2.1	0.0		0.0		0.3	0.5	2.6
<i>Fritillaria camschatcensis</i>	0.0	0.0	0.7	0.5	0.6	0.6	0.5	0.3	14.1
<i>Galium trifidum trifidum</i>	0.3	0.4	0.4	0.3	0.2	0.2	0.3	0.2	14.1
<i>Geranium erianthum</i>	0.6	1.0	1.6	1.3	0.0		0.9	0.6	6.4
<i>Gymnocarpium dryopteris</i>	1.3	2.1	0.0		0.0		0.3	0.5	1.3
<i>Hippuris tetraphylla</i>	2.5	4.0	0.0	0.0	0.0		0.6	1.0	2.6
<i>Honckenya peploides</i>	0.0	0.0	0.0	0.0	0.0		0.0	0.0	3.8
<i>Iris setosa</i>	0.0		0.9	0.8	0.2	0.4	0.5	0.4	7.7
<i>Lathyrus maritimus maritimus</i>	15.2	12.1	6.8	6.1	6.0	5.7	8.7	4.4	34.6
<i>Lathyrus palustris</i>	0.0		0.6	0.7	0.0		0.3	0.3	6.4
<i>Ligusticum scoticum</i>	1.4	1.1	2.3	2.1	1.0	0.9	1.7	1.0	29.5
<i>Lupinus nootkatensis</i>	0.0		1.7	1.4	1.1	1.2	1.1	0.7	11.5

Table 4 (cont.).

Species or Cover	CHBA (20)		HABA (35)		SISA (23)		Overall (n=78)		
	Mean	CI	Mean	CI	Mean	CI	Mean	CI	Freq. %
<i>Mertensia maritima</i>	0.0		0.0	0.0	0.0		0.0	0.0	1.3
<i>Moehringia lateriflora</i>	4.1	3.5	0.3	0.3	0.0		1.2	0.9	12.8
<i>Myriophyllum</i> sp.	2.5	4.1	0.0		0.0		0.6	1.1	1.3
<i>Plantago maritima</i>	1.6	1.9	3.4	2.2	6.8	5.1	3.9	1.9	21.8
<i>Polemonium acutiflorum</i>	0.0	0.0	0.0		0.0		0.0	0.0	1.3
<i>Polygonum viviparum</i>	0.0		0.0	0.0	0.0		0.0	0.0	5.1
<i>Potamogeton filiformis</i>	0.0		0.1	0.1	0.0		0.0	0.0	1.3
<i>Potentilla egedii</i>	6.3	4.8	4.5	3.5	4.6	3.9	5.0	2.3	32.1
<i>Potentilla palustris</i>	2.0	2.5	1.0	1.2	0.0		1.0	0.8	12.8
<i>Rhinanthus minor borealis</i>	0.1	0.1	0.3	0.3	2.6	2.8	0.9	0.8	12.8
<i>Rubus arcticus</i>	0.0	0.0	1.1	1.2	0.0		0.5	0.5	10.3
<i>Rumex fenestratus</i>	0.1	0.2	0.0		0.0	0.0	0.0	0.0	2.6
<i>Saussurea nuda</i>	0.0		0.0		0.1	0.1	0.0	0.0	2.6
<i>Senecio pseudoarnica</i>	0.0		0.0	0.0	0.2	0.4	0.1	0.1	5.1
<i>Solidago multiradiata</i> var. <i>multiradiata</i>	0.0		0.1	0.2	0.0		0.1	0.1	1.3
<i>Stellaria borealis</i>	0.0		0.1	0.1	0.0		0.0	0.1	1.3
<i>Stellaria crassifolia</i>	0.1	0.1	0.7	0.8	3.4	4.1	1.4	1.3	15.4
<i>Stellaria crispa</i>	0.0		0.0	0.0	0.0		0.0	0.0	1.3
<i>Stellaria humifusa</i>	0.0		1.0	1.4	2.1	1.7	1.1	0.8	12.8
<i>Stellaria</i> sp.	0.0		0.3	0.2	0.0		0.1	0.1	6.4
<i>Streptopus amplexifolius</i>	0.0	0.0	0.0		0.0		0.0	0.0	1.3
<i>Thelypteris phegopteris</i>	0.8	1.2	0.0	0.0	0.0		0.2	0.3	2.6
<i>Trientalis europaea</i>	2.0	1.3	1.1	0.9	0.9	0.7	1.3	0.6	28.2
<i>Triglochin maritimum</i>	2.3	1.7	2.5	2.1	5.7	3.4	3.4	1.5	32.1
<i>Triglochin palustris</i>	1.5	1.6	0.0	0.0	0.1	0.1	0.4	0.4	10.3
<i>Viola</i> sp.	0.0		0.1	0.1	0.0		0.0	0.0	1.3
Forbs Total	64.8	21.7	48.9	14.6	63.5	23.6	57.3	11.0	85.9
<i>Agrostis alaskana</i>	0.0		0.0	0.0	0.0		0.0	0.0	1.3
<i>Calamagrostis canadensis</i>	6.4	4.6	13.5	6.4	5.1	4.9	9.2	3.5	33.3
<i>Calamagrostis</i> <i>deschampsoides</i>	1.3	1.6	1.0	1.0	7.0	5.5	2.8	1.8	19.2
<i>Deschampsia beringensis</i>	0.0		0.1	0.1	0.0		0.1	0.1	7.7
<i>Elymus arenarius mollis</i>	17.7	13.5	13.4	8.8	8.8	6.8	13.2	5.6	41.0
<i>Festuca rubra</i>	10.3	6.5	3.8	2.8	7.4	4.3	6.5	2.4	47.4
<i>Hierochloa odorata</i>	0.0		0.0		0.6	0.9	0.2	0.3	1.3
<i>Hordeum brachyantherum</i>	3.4	5.5	0.0		1.0	1.1	1.1	1.4	3.8
<i>Poa arctica</i>	1.8	2.2	0.0	0.0	0.0		0.5	0.6	5.1
<i>Poa eminens</i>	3.3	3.8	1.2	1.2	2.9	2.0	2.3	1.3	26.9
<i>Poa pratensis</i>	0.0		0.1	0.1	0.0		0.0	0.1	1.3
<i>Poa</i> sp.	0.0	0.0	0.0		1.0	1.0	0.3	0.3	6.4
<i>Puccinellia grandis</i>	0.2	0.3	0.0		0.0		0.1	0.1	1.3
<i>Puccinellia nutkaensis</i>	0.0		2.7	3.1	0.0		1.2	1.4	6.4
<i>Puccinellia phryganodes</i>	0.2	0.2	4.2	4.0	0.0		1.9	1.8	11.5
Grasses Total	44.4	20.5	40.1	12.1	33.7	13.5	39.3	8.5	82.1

Table 4 (cont.).

Species or Cover	CHBA (20)		HABA (35)		SISA (23)		Overall (n=78)		
	Mean	CI	Mean	CI	Mean	CI	Mean	CI	Freq. %
Carex aquatilis aquatilis	0.0		0.0		0.3	0.3	0.1	0.1	3.8
Carex canescens	0.0	0.0	0.8	1.3	0.0		0.3	0.6	3.8
Carex glareosa	6.5	6.5	0.7	1.0	7.3	9.2	4.1	3.2	16.7
Carex gmelinii	6.3	5.4	0.7	0.8	1.9	2.2	2.5	1.6	21.8
Carex lyngbyaei	3.5	3.5	17.0	12.4	17.0	16.0	13.6	7.3	29.5
Carex mackenziei	0.5	0.7	1.5	1.6	0.2	0.3	0.8	0.8	7.7
Carex macrochaeta	0.0		1.2	1.2	0.0		0.6	0.6	5.1
Carex pluriflora	6.4	6.0	0.8	0.8	0.7	0.9	2.2	1.6	12.8
Carex ramenskii	12.2	12.0	8.8	5.8	8.8	6.7	9.7	4.4	21.8
Eleocharis kamtschatica	0.0		1.1	1.5	0.0		0.5	0.7	3.8
Eleocharis palustris	0.2	0.2	0.0		0.0		0.0	0.1	1.3
Juncus arcticus	0.0		0.0	0.0	0.0		0.0	0.0	2.6
Sedges Total	35.3	15.5	32.7	13.0	36.1	17.5	34.4	8.6	74.4
Cladonia sp.	0.0		0.0	0.0	0.1	0.1	0.0	0.0	3.8
Lichens Total	0.0		0.0	0.0	0.1	0.1	0.0	0.0	3.8
Litter alone	7.7	3.1	12.6	4.1	8.3	3.6	10.1	2.3	70.5
Litter Total	7.7	3.1	12.6	4.1	8.3	3.6	10.1	2.3	70.5
Aulacomnium palustre	0.0		0.1	0.2	0.0		0.1	0.1	2.6
Campyllum stellatum	0.0		0.0	0.0	0.0		0.0	0.0	1.3
Dicranum sp.	0.0		0.1	0.1	0.0		0.1	0.1	3.8
Ditrichum flexicaule	0.0		0.0	0.0	0.0		0.0	0.0	1.3
Drepanocladus revolvens	0.0		0.4	0.7	0.0		0.2	0.3	1.3
Hylocomium splendens	0.0	0.0	0.3	0.3	0.0		0.2	0.2	6.4
Pleurozium schreberi	1.3	2.1	1.6	1.6	0.0	0.1	1.1	0.9	10.3
Pohlia sp.	0.0		0.0		0.1	0.1	0.0	0.0	1.3
Polytrichum sp.	0.0		0.0	0.0	0.0	0.1	0.0	0.0	2.6
Ptilium crista-castrensis	0.0	0.0	0.1	0.2	0.0		0.1	0.1	3.8
Rhytidiadelphus sp.	0.0		7.1	3.7	0.0		3.2	1.8	15.4
Rhytidiadelphus triquetrus	0.0		0.4	0.4	0.0		0.2	0.2	6.4
Sanionia uncinata	0.0		1.1	0.8	5.4	4.4	2.1	1.4	15.4
Sphagnum sp.	0.6	0.8	0.7	1.2	0.0	0.1	0.5	0.6	5.1
Sphagnum squarrosum	0.4	0.5	0.5	0.6	0.3	0.4	0.4	0.3	6.4
Unknown liverwort	0.0		0.0	0.0	0.0		0.0	0.0	1.3
Unknown moss	14.3	7.4	0.1	0.1	3.7	4.1	4.8	2.5	26.9
Mosses Total	16.6	8.9	12.8	5.7	9.7	6.0	12.8	3.8	48.7
Unknown algae	3.6	5.9	0.1	0.2	0.0		1.0	1.5	5.1
Algae Total	3.6	5.9	0.1	0.2	0.0		1.0	1.5	5.1
Bare Soil	20.8	15.0	18.7	11.2	19.6	13.0	19.5	7.3	41.0
Water	0.2	0.3	13.2	8.0	4.6	7.1	7.3	4.3	16.7
Bare Ground Total	21.0	14.9	31.9	13.1	24.1	14.1	26.8	8.1	48.7
Grand Total	220.8	31.4	195.0	19.1	176.7	27.2	196.2	14.4	100.0

Table 5. Mean cover (%; includes multiple layers) of plant species on coastal flats within SWAN. Species with a frequency of >70% within class are in boldface type, dominant and differential species for identifying community are underlined, and trace species (cover ≤1%) are indicated by zeros.

Species or Cover	Barren Mudflat	Carex ramenskii-Stellaria humifusa	Carex glareosa-Carex ramenskii	Elymus mollis-Plantago maritima	Elymus mollis-Carex lyngbyaei	Carex lyngbyaei-C. deschampsiioides	Carex mackenziei-Eleocharis kamtschatica	Carex lyngbyaei-Cicuta virosa	Myrica gale-Salix fuscescens	C. canadensis-Equis. fluviatile	Hippuris tetra. Triglochin marit.	Hippuris vulgaris-Sparg. angustifol.	Estuarine Water	River	Overall
Bare Soil	6	11	4	4		0	1	2	0	0	6				9
Honckenya peploides	3														0
Puccinellia pumila	3														0
Puccinellia nutkaensis	9	3		0											1
Puccinellia phryganodes	1	6	1	3									0		3
Plantago maritima	1	18	6	16				0							5
Triglochin maritimum	2	18	13	5	1	3	1	0			2				5
Carex ramenskii	0	79	27	6		5	9	0			2				15
Potentilla egedii	2	13	18	15	17	9	1	1	0						7
Stellaria humifusa	1	9	2	0				0							1
Triglochin palustris		1	3	1		3	0	0							1
Deschampsia beringensis	0		1	1		1	0	1	0						0
Poa eminens		2	15	1	6	8	0	0	0						4
Carex glareosa			53	1	2	6		0	1						9
Calamagrostis deschampsiioides		1	12		0	16	4	5	1	0					4
Chrysanthemum arcticum	0		5	7	2	3	1	0							2
Festuca rubra	0		15	7	10	8			1	2					4
Lathyrus maritimus	0		1	7	8				0						1
Elymus arenarius mollis	0	1	1	70	75	4									8
Ligusticum scoticum			0	4	4	1	0		1						1
Hordeum brachyantherum					22										1
Achillea millefolium					19	0		0	2	0					1
Conioselinum chinense					5	0			4						1
Angelica lucida			0		4				0						0
Stellaria crassifolia			0	2	4	1				1					0
Hierochloa odorata					3					2					0
Trientalis europaea					2	1		0	1	0					0
Carex mackenziei						4	23	1			0				1
Eleocharis kamtschatica							10	0							0
Carex lyngbyaei	0		3	0	39	89	10	128	20	15		8			28
Cicuta virosa						1		6		0		0			1
Galium trifidum			0		0	2		2	0	0					0
Calamagrostis canadensis					21	0	0	8	44	26					7
Myrica gale						10	1	0	72	1		10			7
Salix fuscescens						15		0	45	19					6
Potentilla palustris						0	1	1	10	9					1
Unknown moss			2		1	19	0	9	4	29					5
Carex pluriflora			2		0	4	2	0	13	18					3
Epilobium palustre			0			0	0	2	1	2					0
Lathyrus palustris						0		2	1						0
Picea sitchensis									3	9					1
Sphagnum sp.								0	5	2					1
Sphagnum squarrosum							3	1	2	11					1
Equisetum fluviatile									4	21					1
Carex canescens									4	7					1
Salix planifolia pulchra									0	14					1
Unknown algae	0	0					6	0			28				1
Hippuris tetrphylla							0	0			32		1		1
Myriophyllum sp.											17	1			1
Potamogeton pectinatus											11				0
Potamogeton sp.												10			0
Sparganium angustifolium												44			1
Hippuris vulgaris												45			1
Litter alone	1	6	19	26	10	23	11	21	11	16		2			12
Water	9	5				2	58	4	0		32	37	100	100	15
Total Live Cover	4	149	180	147	244	214	77	166	251	199	91	117	1	0	147
Sample Size	9	10	13	5	4	7	4	10	7	4	3	2	6	1	85

Table 6. Mean cover (%; includes multiple layers) of plant species on coastal beach ridges within SWAN. Species with a frequency of >70% within class are in boldface type, dominant and differential species for identifying community are underlined, and trace species (cover ≤1%) are indicated by zeros.

SpeciesName	Alnus sinuata- Dryopteris dilatata	Calamagrostis- canadensis- Lupinus nootkatensis	Picea sitchensis- Angelica lucida	Achillea millefolium- Carex gmelini	Lathyrus maritimus- Senecio pseudoarn.	Barren Beach	Overall
Alnus sinuata	75						6.7
Dryopteris dilatata americana	44						3.9
Athyrium filix-femina cyclosorum	11						1.0
Viburnum edule	7						0.6
Gymnocarpium dryopteris	6						0.6
Oplopanax horridus	6						0.5
Thelypteris phegopteris	4	0					0.4
Ribes laxiflorum	3						0.3
Ribes triste	2						0.2
Ptilium crista-castrensis	1	1		0			0.2
Salix barclayi	7	6					1.6
Rubus arcticus	3	5	0				1.2
Carex macrochaeta	0	5					1.0
Salix planifolia pulchra		5					0.8
Myrica gale		3					0.5
Betula papyrifera var. kenaica	0	1					0.2
Rhytidiadelphus triquetrus	0	2		0			0.3
Hylocomium splendens	0	2		0			0.3
Iris setosa	0	4	1				0.8
Geranium erianthum	0	7	3				1.5
Conioselinum chinense	1	2	3	5			1.7
Fritillaria camschatcensis	1	2	3	1			1.0
Epilobium angustifolium	24	19	2		1	0	5.8
Calamagrostis canadensis	35	34	4	0	3		10.2
Rhytidiadelphus sp.	6	25			1		5.2
Lupinus nootkatensis	1	16	4	4			4.2
Pleurozium schreberi	1	8		7			3.1
Sanionia uncinata	1	5	14	7			3.7
Trientalis europaea	3	3	5	4	4		2.8
Picea sitchensis	2	1	20	0			2.0
Unknown moss	3	9	15	16	4		7.8
Angelica lucida	5	5	17	28	8		10.7
Achillea millefolium	10	31	25	59	9		23.6
Festuca rubra	1	6	6	17	25		10.8
Elymus arenarius mollis	2	8	7	39	70	1	26.5
Lathyrus maritimus maritimus	2	9	24	21	91	1	28.9
Carex gmelinii		1	1	17	3		4.8
Moehringia lateriflora	0	3	4	3	4		2.6
Calamagrostis deschampsoides			5				0.4
Carex pluriflora			3				0.3
Poa arctica	0	0	1	3	0		0.8
Stellaria crassifolia		0		8			1.8
Rhinanthus minor borealis				6	1		1.6
Hordeum brachyantherum				4	0		0.9
Ligusticum scoticum	0	2		3	8		2.7
Galium trifidum trifidum	0	0		1	1		0.3
Carex mackenziei					4		0.8
Carex macrocephala					8		1.7
Senecio pseudoarnica					6	0	1.3
Poa eminens					5		1.2
Chrysanthemum arcticum					2		0.4
Honckenya peploides					1	4	1.1
Bare Soil			2	1	3	95	19.9
Litter alone	5	12	13	7	8	3	7.6
Total Live Cover	265	230	163	256	259	6	194
Sample Size	4	8	4	10	10	9	45

Table 7. Ecological land classification for coastal ecosystems within three monitoring sites in Lake Clark and Katmai National Park and Preserves.

Geomorphic Unit	Soil Texture	Drainage	Soil Chem.	Plant Community	Ecotype
Active Coastal Beach, Active Coastal Dune	Gravel, Sand	Excessive-Well	Saline-Brackish	Barren Beach	Coastal Gravelly Saline Barrens
	Sand, Gravel	Excessive-Slightly Ex	Circum-acidic	<i>Lathyrus maritimus-Senecio pseudoarnica</i>	Coastal Sandy Dry Circumacidic Beach-pea Meadow
Inactive Coastal Beach, Inactive Coastal Dune,	Sand	Slightly Excessive-Well	Circum-acidic	<i>Picea sitchensis-Angelica lucida</i>	Coastal Sandy Circumacidic Moist Sitka Spruce Woodland
				<i>Elymus arenarius-Angelica lucida</i>	Coastal Sandy Moist Circumacidic Beachgrass-Umbel Meadow
	Sand	Well	Circum-acidic	ND	Upland Sandy Moist Willow Tall Shrub
	Sand, Gravel	Slightly Excessive-Well	Circum-acidic	<i>Alnus sinuata-Dryopteris dilatata</i>	Upland Sandy Moist Circumacidic Alder Shrub
				<i>Calamagr. canadensis-Lupinus nootkatensis</i>	Upland Sandy Circumacidic Moist Bluejoint-Lupine Meadow
				ND	Upland Sandy Circumacidic Moist Sitka Spruce Woodland
Active Tidal Flats	Loam-Sand	Slightly Poor-Very Poor	Saline-Brackish	<i>Barren Mudflat</i>	Coastal Loamy Flat Barrens
				<i>Barren Tidal Channels</i>	Coastal Loamy Channel Barren
	Loam	Mod. Well-Very Poor	Saline-Brackish	<i>Carex ramenskii-Stellaria humifusa</i>	Coastal Loamy Saline Wet Ramenski Sedge Meadow
			Brackish	<i>Carex glareosa-Carex ramenskii</i>	Coastal Loamy Brackish Wet Sedge-Grass Meadow
		Mod. Well-Somewhat Pr.	Brackish	<i>Elymus mollis-Plantago maritima</i>	Coastal Loamy Brackish Wet Elymus-Forb Meadow
			Slightly Brackish	<i>Elymus mollis-Carex lyngbyaei</i>	Coastal Loamy Slightly Brackish Wet Elymus-Sedge Meadow
Inactive Tidal Flats	Loam	Poor-Very Poor	Brackish	<i>Carex lyngbyaei-Calam. Deschampsioides</i>	Coastal Loamy Brackish Wet Lyngbye Sedge Meadow
	Loam-Organic-rich	Very Poor	Slightly Brackish	<i>Carex lyngbyaei-Cicuta virosa</i>	C. Organic-rich Slightly Brackish Wet Lyngbye Sedge-Herb Meadow
			Brackish	<i>Carex mackenziei-Eleocharis kamtschatica</i>	Coastal Loamy Brackish Wet Mackenzie Sedge Meadow
Abandoned Tidal Flats, Inactive Tidal Flats	Loam-Org-rich	Slightly Poor-Very Poor	Circum-acidic	<i>Myrica gale-Salix fuscenscens</i>	Lowland Organic-rich Circumacidic Wet Sweetgale Low Shrub
	Organic-rich	Very Poor	Circum-acidic	<i>Calamagrostis canadensis-Equisetum fluviatile</i>	Lowland Organic-rich Circumacidic Wet Bluejoint Meadow
Isolated Shallow Estuarine Lake	Water	Very Poor-Flooded	Saline-Brackish	<i>Hippuris tetrphylla-Triglochin maritimum</i>	Coastal Saline Maretail Marsh
		Flooded	Brackish	Estuarine Water	Coastal Brackish Ponds
			Circum-acidic	<i>Hippuris vulgaris-Sparganium angustifolium</i>	Lacustrine Circumacidic Maretail Marsh
Tidal River	Water	Flooded	Circum-acidic	Tidal River	Tidal River
Nearshore Water	Water	Flooded	Saline	Estuarine Water	Coastal Tidal Channels
			Saline	Nearshore Water	Nearshore Water

Landscape Change

The analysis of historical airphotos (1951 and 1957 B&W, 1978 and 1982 CIR) georectified to high-resolution satellite images (2000, 2004 and 2005 Ikonos) shows substantial changes in waterbodies, shorelines, ecosystem types (ecotypes), and geomorphic and ecological processes across the three study sites. The abundance of six types of waterbodies varied considerably among sites, especially for nearshore water because of the amount of land relative to nearshore water within the site boundaries (Figure 17, Table 1). For example, mean percent area for nearshore water within the fixed boundaries of the study sites varied from 15 to 43% across the sites, whereas, tidal ponds and tidal guts only ranged from 0.3 to 1.3% and 1.2 to 1.7%, respectively (Figure 18). Over time, the largest change occurred in nearshore water, where mean percent area in 2000–2005 decreased 5.8% from 1951–1957, due to sediment deposition along the shoreline and migration of the shoreline seaward. Tectonic uplift from the 1964 earthquake may have contributed more exposed land. Tidal guts decreased by 0.9%, whereas tidal rivers increased 0.6% in area.

Shoreline changes were calculated from changes in nearshore water derived from the waterbody mapping. When comparing land lost or gained among the three sites, HABA (114 ha over entire period) and SISA (81 ha) gained land through shoreline deposition during both time intervals, whereas, CHBA both gained and lost land over the two intervals, but ended up losing 24 ha overall (Figure 19). The average erosion rates (negative indicates land gained) for each site were similar at HABA (-2.3 m/yr) and SISA (-1.6 m/yr) for the entire 1951–1957 to 2000–2005 interval, compared to CHBA (-0.5 m/yr). Lower rates at CHBA may have been due to high sediment input from West and Middle Glacier Creeks. When erosion rates were averaged across sites for each interval, there was little difference between the 1951–1957 to 1978–1982 interval (1.6 ± 0.9 m/yr, 95% CI, $n=3$) and the 1978–1982 to 2000–2005 interval (1.7 ± 2.0 m/yr).

Ecotypes, which combine plant communities with co-varying geomorphic characteristics in a broadly applicable ecological land classification (Table 7), showed substantial changes in abundance over the two time intervals across the three sites, based on photo-interpretation of change at 634 grid points (Table 8, Figure 20). Increases in mean percent area (average of three sites) for the 1951–1957 to 2000–2005 interval were highest for Coastal Gravelly Saline Barrens (2.1 ± 1.3 , 95% CI, $n=3$), Coastal Sandy Dry Circumacidic Beach-pea Meadow (1.8 ± 2.8), and Coastal Sandy Circumacidic Moist Sitka Spruce Woodland (2.0 ± 1.6). The increases were associated with deposition of new sediments on the gravel beach ridges and successional development of vegetation. Decreases in mean percent area were highest for Nearshore Water (-3.2 ± 3.0), Coastal Sandy Moist Circumacidic Beachgrass-Umbel Meadow (-1.5 ± 1.6), and Coastal Loamy Saline Wet Ramenski Sedge Meadow (-1.2 ± 1.0). Due to the variability in change among areas, the 95% CI can be used to help assess whether the changes were consistent among sites and can be reliably detected (where CI interval does not overlap 0). Only four ecotypes showed consistent changes: Coastal Gravelly Saline Barrens increased and Nearshore Water decreased due to shoreline accretion. Coastal Sandy Circumacidic Moist Sitka Spruce Woodland increased due to forest expansion on dunes, and Coastal Loamy Saline Wet Ramenski Sedge Meadow decreased due to channel migration and sedimentation. For ecotypes that had <1% change, the 95% CI always included 0, indicating that small changes could not be reliably detected.

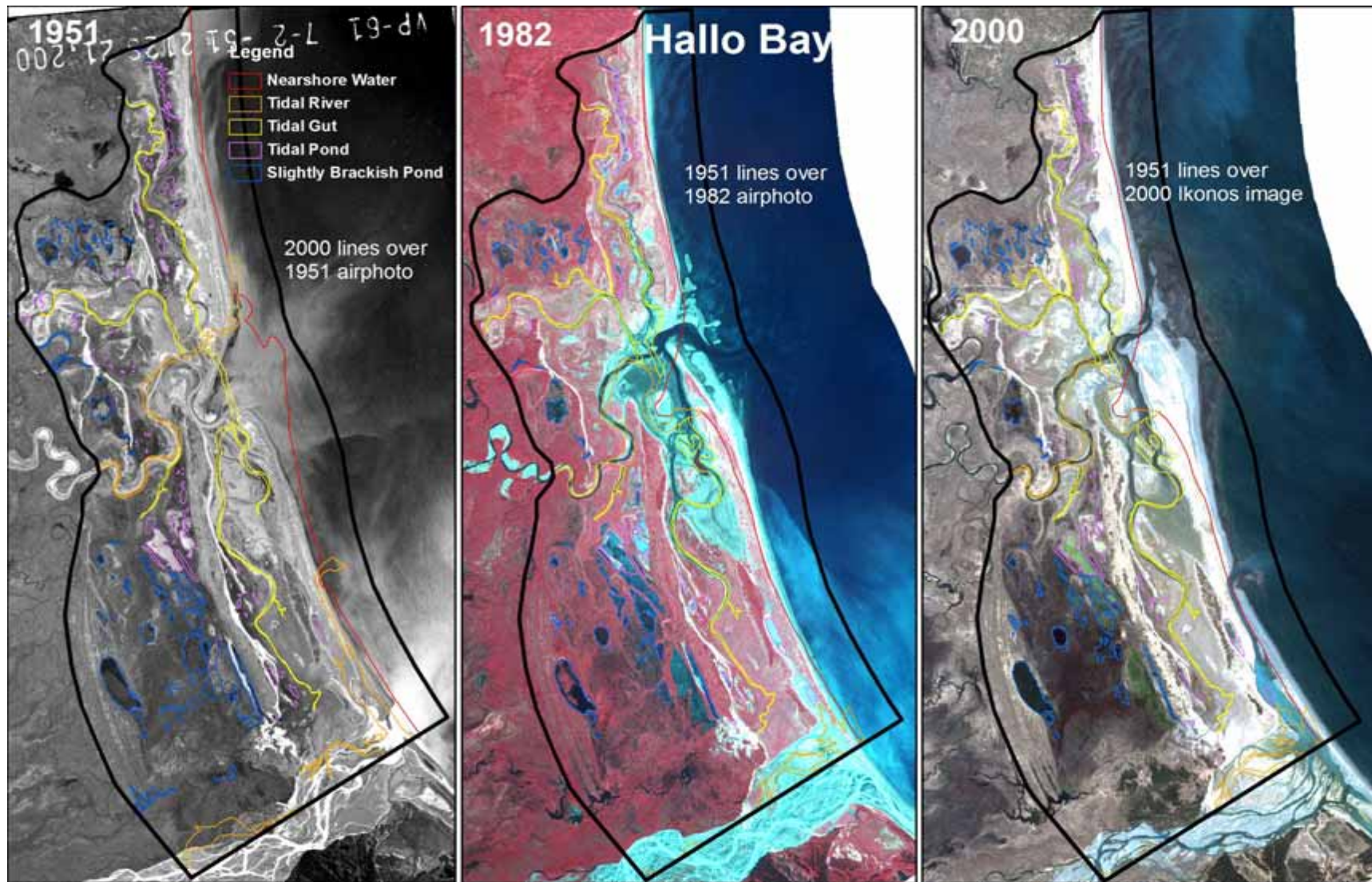


Figure 17. Changes in waterbody distribution evident on a time-series of georectified imagery for Hallo Bay (HABA).

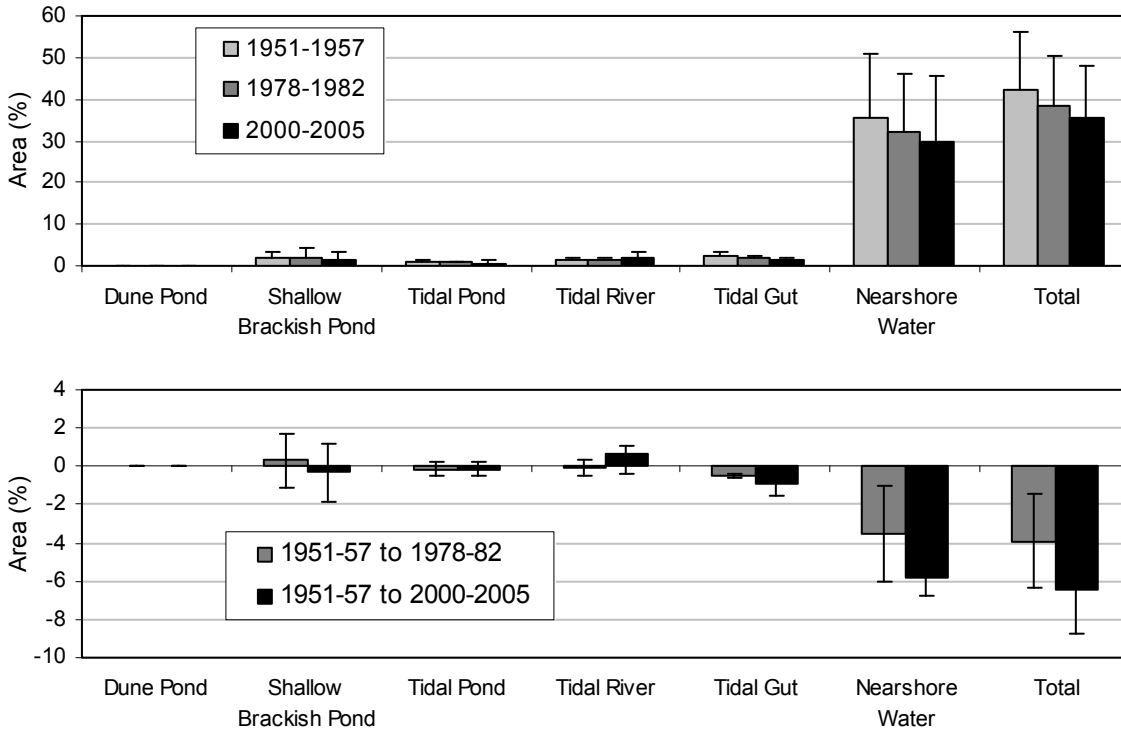


Figure 18. Mean ($\pm 95\%$ CI) abundance (top) and change in abundance relative to the 1951–1957 period (bottom) of waterbody types across three coastal sites within Lake Clark and Katmai National Parks and Preserves.

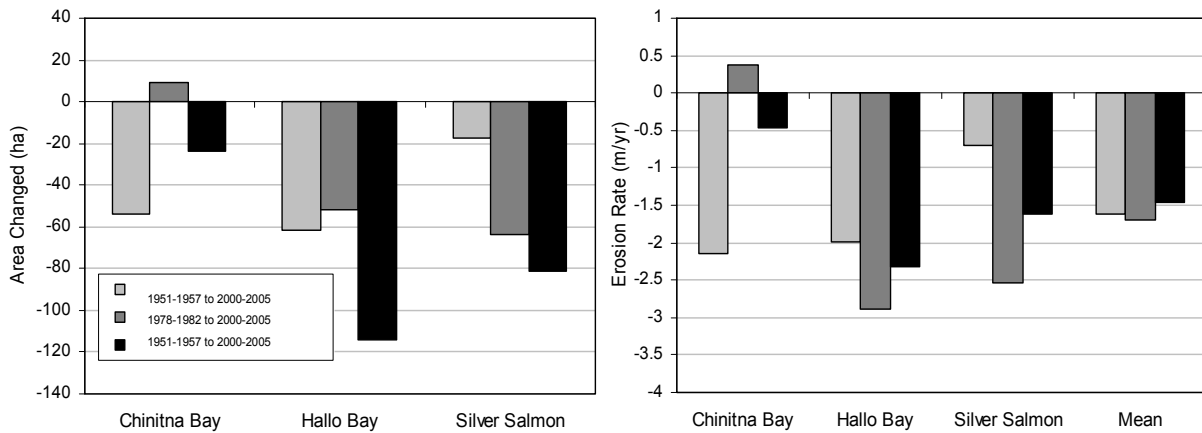


Figure 19. Areal extent of land lost (+) or gained (-)(left) and erosion rates (erosion is negative)(right) for three time intervals across three coastal sites in Lake Clark and Katmai National Parks and Preserves.

A comparison of the methods for mapping waterbodies and point-sampling of ecotypes showed very similar results. For example, the mean percent areas for nearshore water were 35.7%, 32.1%, and 29.8% for the 1951–1957, 1978–1982, and 2000–2005 periods obtained by waterbody mapping, compared to 33.5%, 32.9%, and 30.3% obtained by point-sampling. The larger difference between methods for the 1951–1957 period was mainly due to a spectrally indistinct distribution of muddy water near the tidal river mouth at CHBA, evident on the B&W photography, and to the smaller number of grid points at this site.

Geomorphic and ecological processes responsible for changes in ecotypes were assigned to each grid point based on definitions in Table 2. Erosion and deposition was dramatic around the river mouths at each site, as well as along the shorelines (Figure 21). Sedimentation from storms or reworking of the shoreline can bury vegetation, but assessing this change is not always straightforward because of the contrasting quality of the imagery (Figure 21). A large storm event before 1951 caused large beach ridge overwash deposits (linear barren deposits oriented perpendicular inland from the ridge) at SISA and CHBA. Early successional development of Coastal Sandy Dry Circumacidic Beach-pea Meadow was extensive and easily detected, as was the late successional expansion of Coastal Sandy Circumacidic Moist Sitka Spruce Woodland (Figure 22). Early succession of tidal flats was uncommon on new areas that had developed from accumulating sediments, but was evident by the slightly greenish color visible on color Ikonos imagery (Figure 22). Paludification and infilling of ponds and development of Circumneutral Organic-rich Slightly Brackish Wet Lyngbye Sedge-Herb Meadow was common (Figure 22).

Overall, 20.5% of the landscape changed over the two periods. Most changes were located near the mouths of tidal rivers and tidal guts, and along beach ridges and near the shoreline (Figures 23–25). Processes most responsible for the changes in mean percent area across the three sites for the 1951–1957 to 2000–2005 time interval were Shoreline Deposition (3.9 ± 0.5 , 95% CI, $n=3$), Early Succession (4.1 ± 0.5), Late Succession (3.4 ± 2.1), Sedimentation (2.4 ± 2.1), and Channel Deposition (1.8 ± 0.3) (Figure 26). For all the other processes where mean percent change was $<1.5\%$, the 95% CI overlapped 0, indicating small changes could not be reliably detected.

Analysis of landscape changes was constrained by the spatial resolution and spectral characteristics of the imagery. In our study, the spatial resolution (1.0 m, except 4.0 m for the 2005 Ikonos image for Hallo Bay) was not a major factor. The spectral characteristics, however, were very different. Small differences in vegetation composition or waterbody margins were difficult to discern on B&W airphotos, whereas, differences in vegetation and soil moisture were readily evident on the CIR airphotos. The true-color Ikonos had intermediate spectral variation. Consequently, large changes in vegetation structure (e.g., from meadow to forest) were reliably detected, but small shifts in composition of meadows were difficult to detect and rarely recorded. Similarly, the margins of deep water with vegetated margins could be easily detected and mapped, while the margins of shallow water with muddy margins were indistinct and the accuracy of detecting change was reduced. During the photo-interpretation we were conservative and assumed no change unless the photo-characteristics indicated distinct differences in signatures among years.

Table 8. Percent areas of ecotypes by site and year determined by photo-interpretation of 634 grid points on a time-series of imagery for three coastal sites, Lake Clark and Katmai National Parks and Preserves.

Ecotype	Chinitna Bay			Hollo Bay			Silver Salmon		
	1957	1978	2004	1951	1982	2000	1957	1978	2005
Coastal Gravelly Saline Barrens	5.5	8.3	6.4	6.4	9.6	9.6	4.3	5.8	6.5
Coastal Sandy Dry Circumacidic Beach-pea Meadow	2.8	0.0	1.8	4.0	5.6	8.0	1.4	1.8	3.6
Coastal Sandy Moist Circumacidic Beachgrass-Umbel Meadow	3.7	6.4	3.7	7.2	6.0	5.6	10.9	8.0	8.0
Coastal Sandy Circumacidic Moist Sitka Spruce Woodland	2.8	2.8	5.5	0.0	0.0	0.4	1.8	2.5	4.7
Upland Sandy Circumacidic Moist Bluejoint-Lupine Meadow	0.0	0.0	0.0	5.6	5.2	4.8	1.4	0.0	0.0
Upland Sandy Moist Circumacidic Alder Shrub	1.8	1.8	1.8	5.2	7.2	6.8	1.1	1.1	1.4
Upland Sandy Circumacidic Moist Sitka Spruce Woodland	1.8	1.8	1.8	2.0	2.4	2.4	10.1	11.6	11.6
Coastal Loamy Flat Barrens	6.4	5.5	8.3	3.6	3.6	4.0	2.2	0.4	1.4
Coastal Loamy Channel Barren	1.8	1.8	2.8	2.0	0.8	0.8	1.4	2.5	1.8
Coastal Loamy Saline Wet Ramenski Sedge Meadow	5.5	6.4	4.6	4.4	4.4	4.0	7.2	6.5	5.1
Coastal Loamy Brackish Wet Sedge-Grass Meadow	11.0	10.1	10.1	6.4	5.6	5.6	5.1	4.7	5.1
Coastal Loamy Brackish Wet Elymus-Forb Meadow	0.0	0.0	0.9	1.6	1.6	1.6	0.0	0.0	0.0
Coastal Loamy Slightly Brackish Wet Elymus-Sedge Meadow	1.8	1.8	1.8	0.4	0.4	0.4	1.1	1.1	1.4
Coastal Loamy Brackish Wet Lyngbye Sedge Meadow	3.7	3.7	1.8	0.8	0.8	0.8	0.4	0.4	0.4
C. Organic-rich Slightly Brackish Wet Lyngbye Sedge-Herb Meadow	2.8	2.8	2.8	10.8	11.2	11.2	7.6	8.3	8.7
Lowland Organic-rich Circumacidic Wet Bluejoint Meadow	1.8	1.8	1.8	0.4	0.4	0.4	2.9	2.5	2.2
Lowland Organic-rich Circumacidic Wet Sweetgale Low Shrub	2.8	2.8	4.6	10.0	10.0	10.0	1.4	1.4	1.4
Lowland Shallow Open Water	0.0	0.0	0.0	1.2	1.2	1.2	0.0	0.4	0.4
Lacustrine Circumacidic Maretail Marsh	0.0	0.0	0.0	0.4	0.4	0.4	0.7	0.0	0.0
Riverine Gravel Alkaline Barrens	0.0	0.0	0.0	2.0	1.6	2.0	0.0	0.0	0.0
Riverine Shallow Open Water		0.0	0.0		0.4	0.4		0.0	0.0
Coastal Saline Maretail Marsh			0.0			0.0			0.4
Coastal Brackish Ponds	0.0	0.0	0.0	3.6	3.2	3.2	2.5	2.2	1.4
Coastal Tidal Channels	0.9	0.9	0.0	1.2	1.2	1.2	1.1	1.1	0.4
Tidal River	0.9	0.9	0.0	0.4	0.4	0.8	0.7	0.7	0.7
Nearshore Water	42.2	40.4	39.4	20.1	16.9	14.1	38.2	41.4	37.3

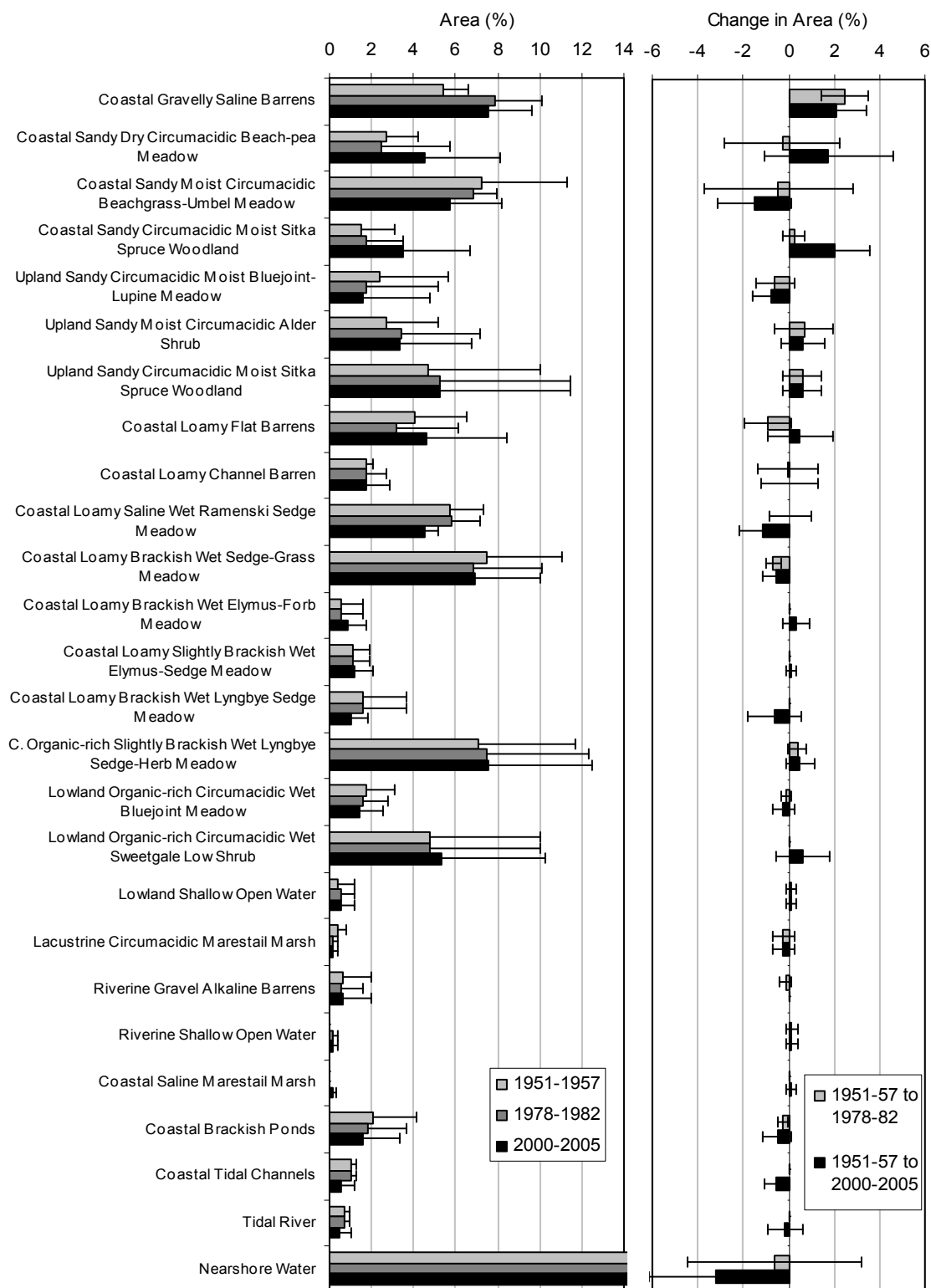


Figure 20. Mean ($\pm 95\%$ CI) abundance (left) and change in abundance from the 1951–1955 baseline period (right) of coastal ecosystems from 1951 to 2005 at three coastal sites in Lake Clark and Katmai National Parks and Preserves.

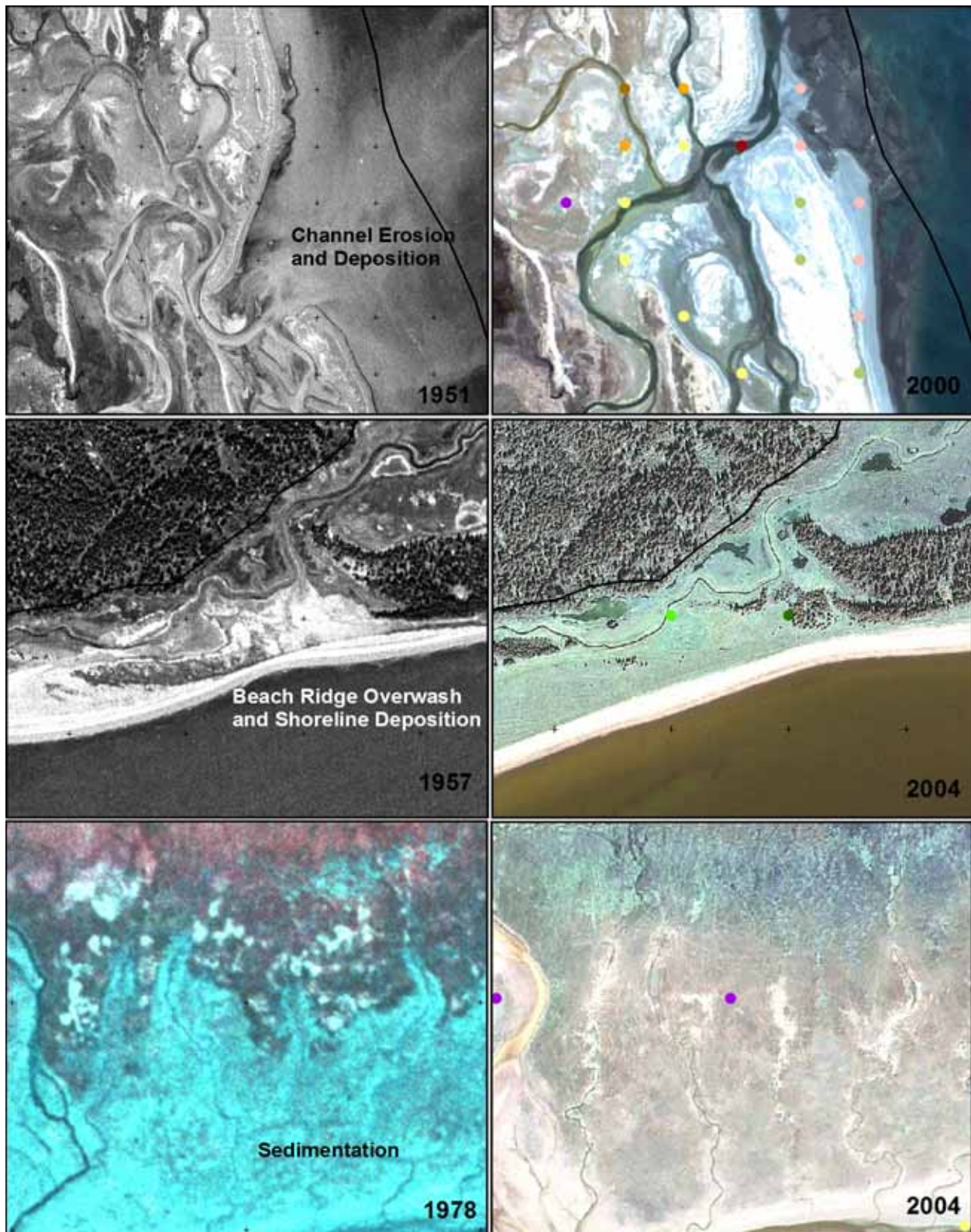


Figure 21. Examples of change associated with channel erosion and deposition, beach ridge overwash and shoreline deposition, and sedimentation in coastal areas of southwestern Alaska. Colored dots indicate areas where change was detected during grid sampling (see Figure 23 for color legend).

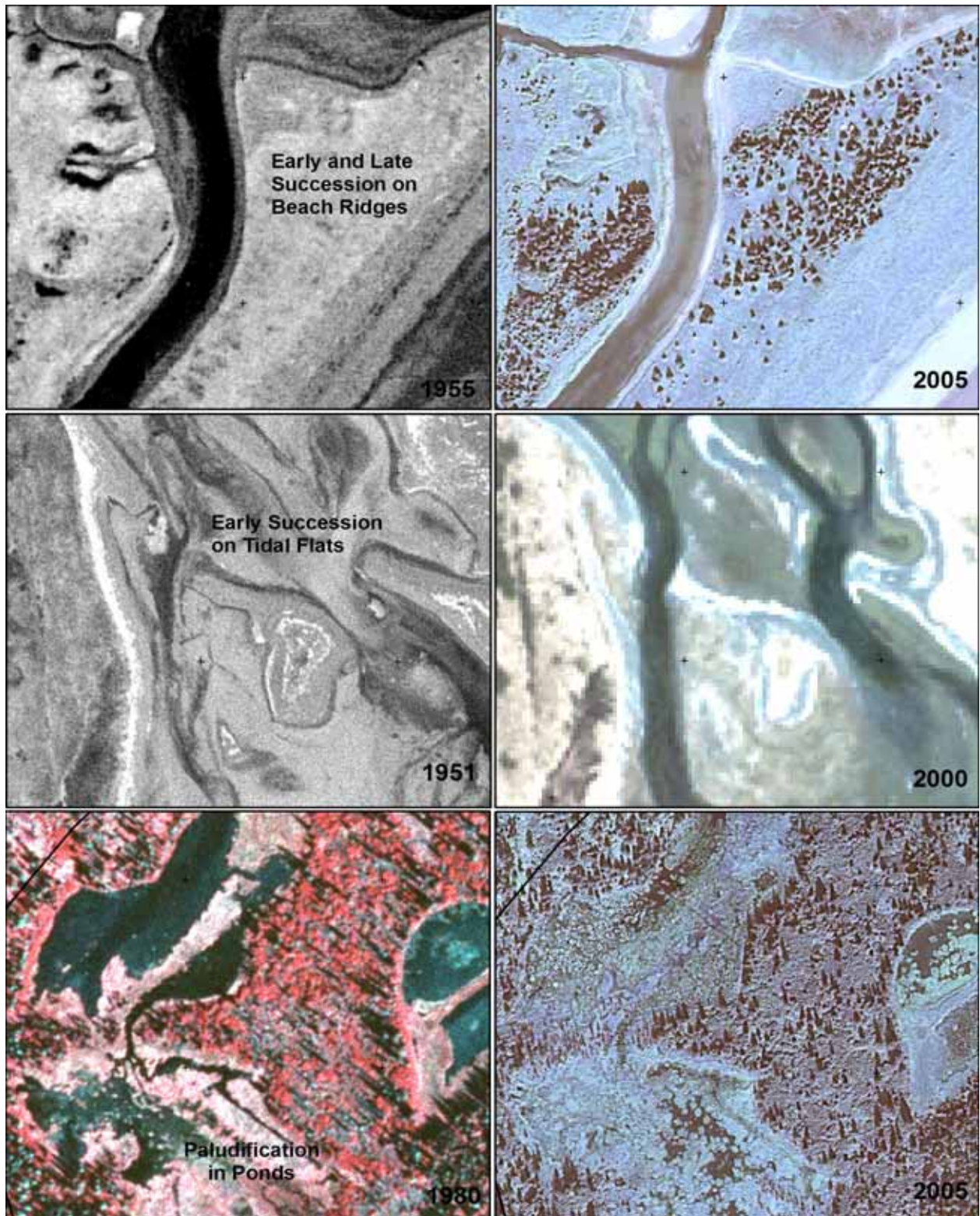
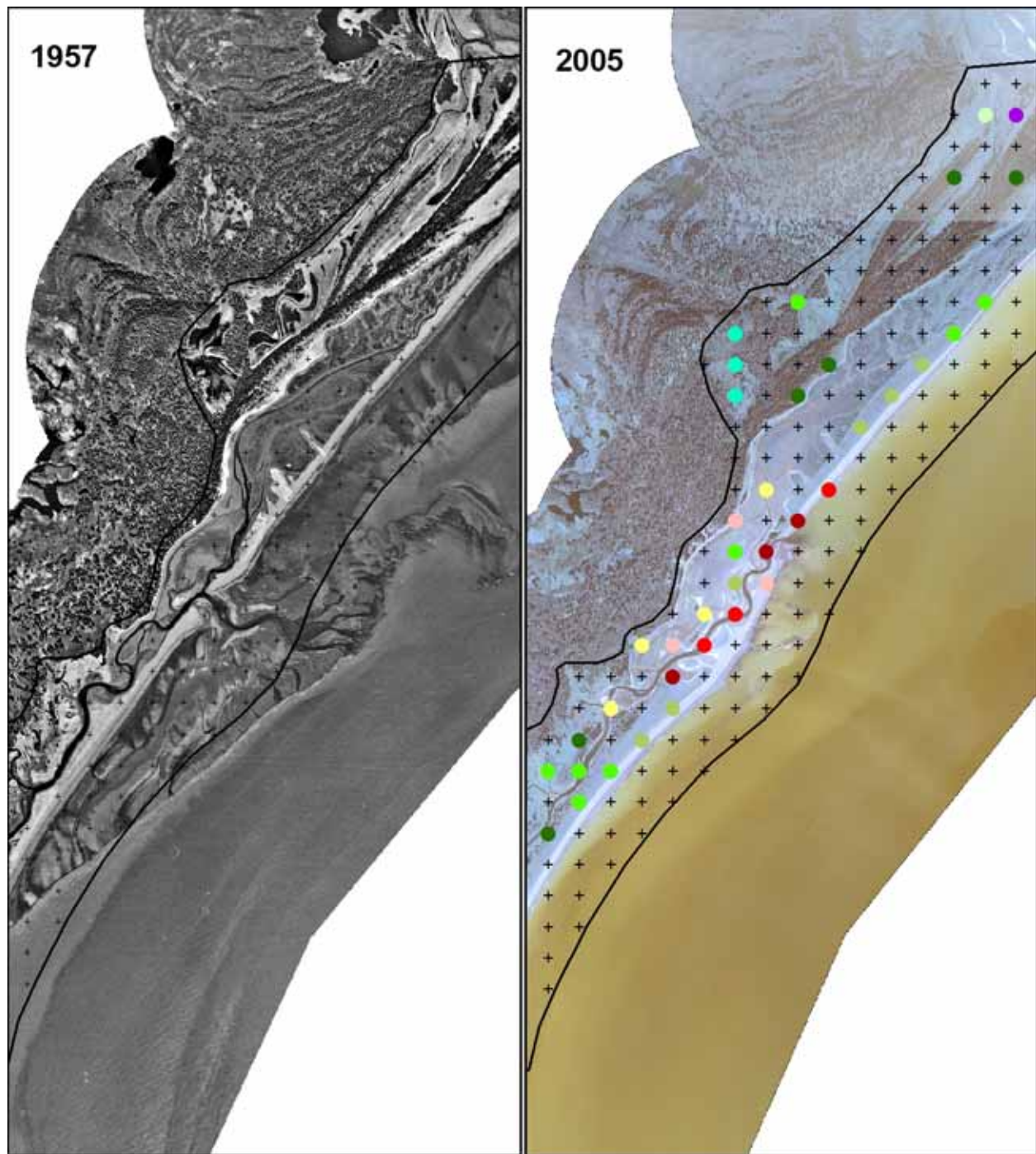


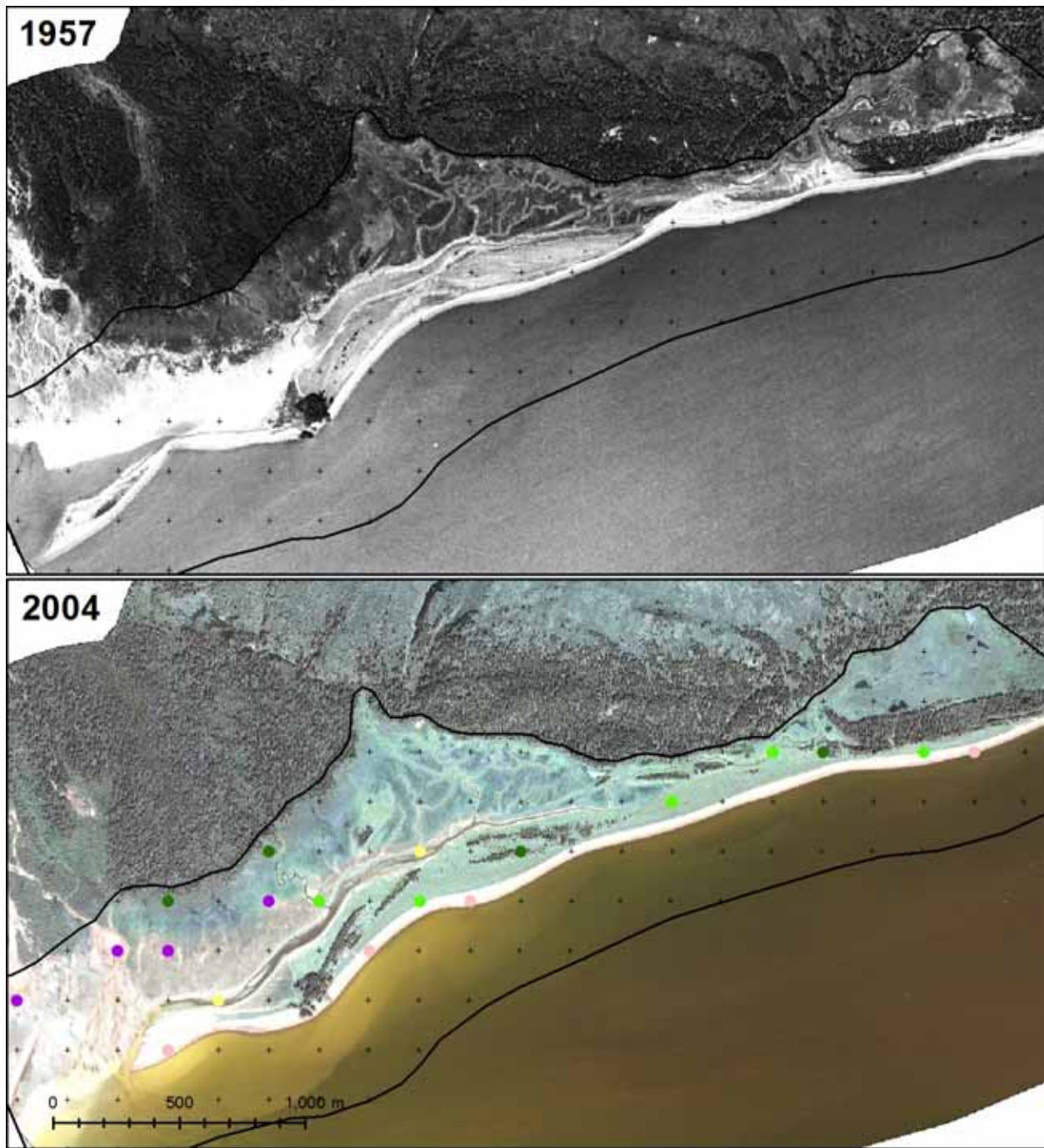
Figure 22. Examples of change associated with early succession on beach ridges and tidal flats and with paludification in ponds in coastal areas of southwestern Alaska. Colored dots indicate areas where change was detected during grid sampling (see Figure 23 for color legend).



Landscape Changes 1957-2005

- | | | |
|------------------------------|--------------------------------|-------------------------------|
| + None | channel erosion and deposition | sedimentation and succession |
| shoreline erosion | channel deposition | shoreline deposition-success. |
| shoreline erosion-deposition | sedimentation | early succession |
| shoreline deposition | beaver dam | late succession |
| channel erosion | paludification | |

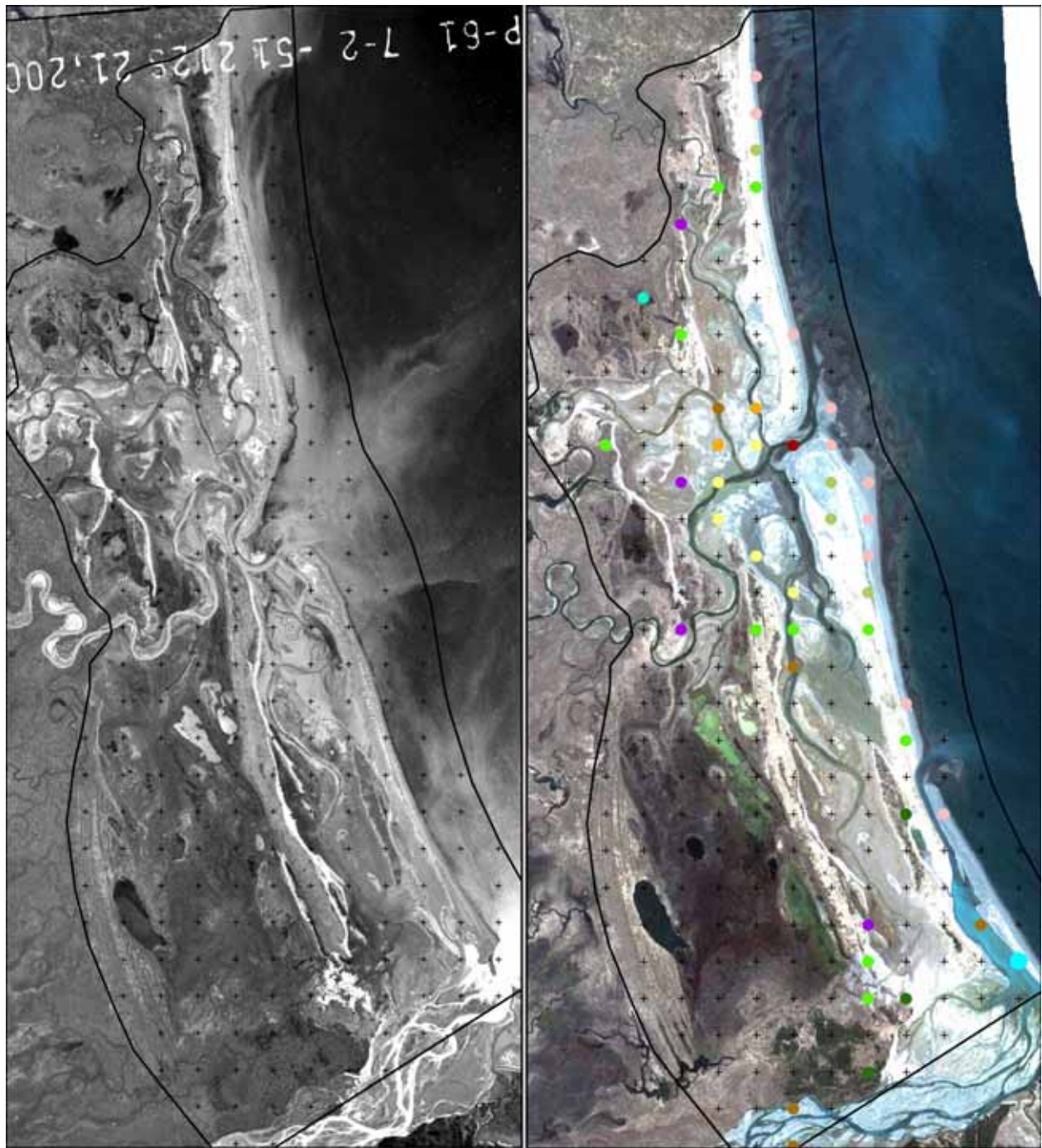
Figure 23. Landscape changes from 1957 to 2005 associated with geomorphic and ecological processes at Silver Salmon (SISA).



Landscape Changes 1957-2004

- | | | |
|----------------------------------|---------------------------------------|---|
| + none | orange channel erosion and deposition | light green sedimentation and succession |
| red shoreline erosion | yellow channel deposition | olive green shoreline deposition-success. |
| red shoreline erosion-deposition | purple sedimentation | light green early succession |
| pink shoreline deposition | blue beaver dam | dark green late succession |
| brown channel erosion | cyan paludification | |

Figure 24. Landscape changes from 1957 to 2004 associated with geomorphic and ecological processes at Chinitna Bay (CHBA).



Landscape Changes 1951-2000

- | | | | | | |
|---|------------------------------|---|--------------------------------|---|-------------------------------|
| + | None | ● | channel erosion and deposition | ● | sedimentation and succession |
| ● | shoreline erosion | ● | channel deposition | ● | shoreline deposition-success. |
| ● | shoreline erosion-deposition | ● | sedimentation | ● | early succession |
| ● | shoreline deposition | ● | beaver dam | ● | late succession |
| ● | channel erosion | ● | paludification | | |

Figure 25. Landscape changes from 1951 to 2000 associated with geomorphic and ecological processes at Halo Bay (HABA).

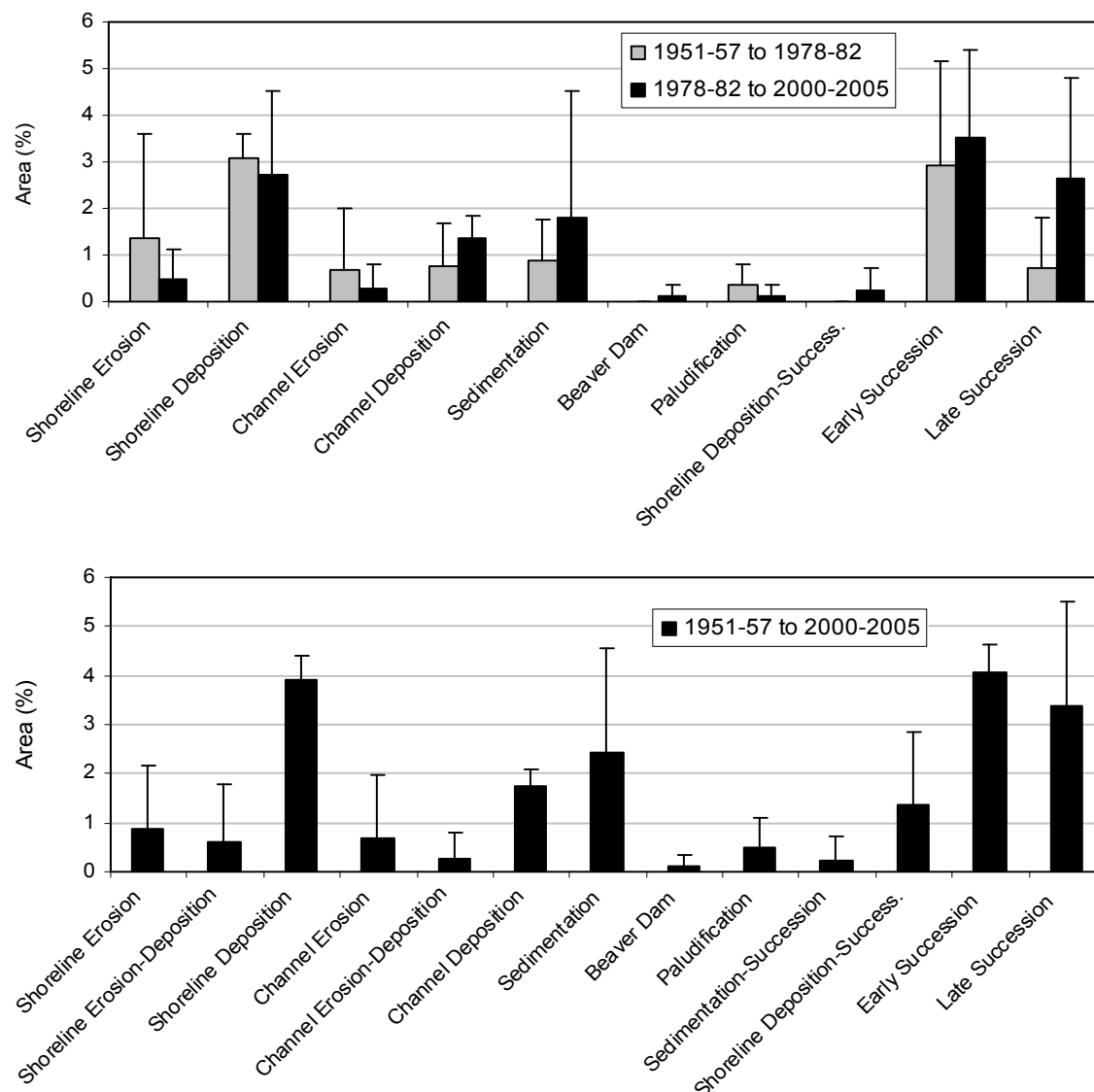


Figure 26. Mean ($\pm 95\%$ CI) areal extent of changes within two intermediate intervals (top) and for the entire five-decade interval (bottom) associated with geomorphic and ecological processes at three coastal sites in Lake Clark and Katmai National Parks and Preserves.

The results reveal substantial changes due to numerous processes that can be put in context of the conceptual model (Figure 1) we developed prior to the monitoring effort. Tectonic activity, and the 1964 earthquake in particular, has been raising the land surface in the region. This has led to shifts from active tidal flats to inactive tidal flats, and to the abandonment of beach ridges inland from the active beaches. Volcanism has left thick tephra deposits at HABA from the 1912 Novarupta eruption, and recent thin deposits at SISA from the ashfall from Mt. Redoubt on 23 March 2009. Storms have led to shifting shorelines, reconfiguration of surficial deposits at river mouths, overwash deposits across the beach ridges, and sedimentation on tidal flats. Vegetation succession has led to substantial changes on the beach ridges, as Sitka spruce continues its late Holocene expansion along the Alaska Peninsula, non-halophytic vegetation colonizes uplifted inactive tidal flats, and vegetation establishes in old waterbodies.

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NPS 188/103147, June 2010

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