Remote Sens. **2014**, *6*, 12447-12477; doi:10.3390/rs61212447

OPEN ACCESS

remote sensing

ISSN 2072-4292

www.mdpi.com/journal/remotesensing

Article

Establishing a Baseline for Regional Scale Monitoring of Eelgrass (*Zostera marina*) Habitat on the Lower Alaska Peninsula

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External Editors: Santonu Goswami, Daniel J. Hayes, Guido Grosse, Benjamin Jones and Prasad S. Thenkabail

Received: 20 May 2014; in revised form: 27 November 2014 / Accepted: 27 November 2014 / Published: 10 December 2014

Abstract: Seagrass meadows, one of the world's most widespread and productive ecosystems, provide a wide range of services with real economic value. Worldwide declines in the distribution and abundance of seagrasses and increased threats to coastal ecosystems from climate change have prompted a need to acquire baseline data for monitoring and protecting these important habitats. We assessed the distribution and abundance of eelgrass (*Zostera marina*) along nearly 1200 km of shoreline on the lower Alaska Peninsula, a region of expansive eelgrass meadows whose status and trends are poorly understood. We demonstrate the effectiveness of a multi-scale approach by using Landsat satellite imagery to map the total areal extent of eelgrass while integrating field survey data to improve map accuracy and describe the physical and biological condition of the meadows. Innovative use of proven methods and processing tools was used to address challenges inherent to remote sensing in high latitude, coastal environments. Eelgrass was estimated to cover ~31,000 ha, 91% of submerged aquatic vegetation on the lower Alaska Peninsula, nearly doubling the known spatial extent of eelgrass in the region.

Mapping accuracy was 80%–90% for eelgrass distribution at locations containing adequate field survey data for error analysis.

Keywords: remote sensing; satellite imagery; Landsat; classification; habitat mapping; isodata; maximum likelihood; *Zostera marina*; eelgrass; monitoring program

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1. Introduction

Seagrass meadows are one of the world's most widespread and productive ecosystems providing a broad range of services that have real economic value [1–3]. They create productive and complex environments [2] that provide sustenance and refuge for a diverse number of species [3–5]. In Alaska, eelgrass (*Zostera marina*) is the dominant seagrass ranging almost continuously from southeast Alaska, west along the Gulf of Alaska and north into the Bering Sea to its upper limit at about 67°N latitude [6]. The seagrass, surfgrass, *Phyllospadix* spp. also occurs along the Gulf of Alaska but is confined to exposed rocky shorelines and sparsely distributed [6]. Eelgrass is likely the most abundant marine macrophyte of protected nearshore waters, forming expansive meadows, some among the largest for the species in the world [7]. Eelgrass is an important source of nutrients for the region's foodweb [8] and serves as critical nursery habitat for many commercially valuable fishery stocks, such as salmon (*Oncorhynchus* spp.), rockfish (*Sebastes* spp.), and herring (*Clupea pallasi*) [9–11].

Despite the importance of eelgrass to the coastal ecosystem of Alaska, we know little about its status and trends within the state. Basic information about the distribution, abundance, and characteristics of eelgrass meadows and their environment is critical for managers to assess and monitor the resource. Such knowledge is lacking for most of Alaska, a significant data gap given the decline in seagrasses worldwide [3,12,13]. A primary driver for this decline is human development of terrestrial systems that increase rates of sedimentation and eutrophication in coastal waters [14–16]. Impacts of sediment loading and eutrophication are a concern in Alaska in places where eelgrass is located near human population centers, mining operations [17,18] and oil and gas development [19,20]. However, most eelgrass beds in Alaska are distant from populated areas and existing commercial development (e.g., mining and offshore oil extraction), so other factors associated with climate change, such as increasing temperatures, sea level rise, and intensified storm activity, may play more important roles in limiting eelgrass distribution and abundance [9,21]. Some impacts of climate change may have a positive effect on eelgrass distribution in Alaskan waters. For example, as sea surface temperature increases in coming years [22,23], coastal waters at higher latitudes may reach optimal ranges for eelgrass germination and survival [24,25], leading to an expansion and enrichment of eelgrass meadows. Under certain conditions of sea level rise eelgrass extent may increase by expanding into high intertidal and other coastal sites currently unavailable to this seagrass [26].

The lower Alaska Peninsula is known for expansive eelgrass meadows [21] that provide food for hundreds of thousands of migratory waterbirds travelling annually between wintering areas in Asia, Oceania, South America, and North America and breeding areas in Alaska, Russia and Canada [27–29]. This region is also likely to transform rapidly as the climate changes because impacts are expected to occur sooner and be more severe at northern latitudes [22,23,25]. Increases in average annual temperature have been associated with reductions in the Bering Sea ice extent [30,31] and ice cover in coastal embayments [32]. Historically, most birds migrate south in the autumn before severe weather and ice conditions restrict access to food resources [33], but as conditions have ameliorated in recent years, an increasing numbers of waterfowl are now overwintering along the Alaska Peninsula, raising questions about the carrying capacity of the eelgrass habitat [34].

The establishment of baseline data detailing the current distribution, abundance, and characteristics of seagrass meadows to serve as a starting point for future comparisons is fundamental to understanding, monitoring, and mitigating changes to this critically important habitat [9,35]. Remote sensing provides an accurate and cost effective approach for mapping and evaluating eelgrass beds for change in spatial distribution over broad areas [16,21,36,37]. Field surveys supply precision data describing internal characteristics of eelgrass meadows, such as canopy height, percent cover and associated species, which can be used to assess condition and predict or explain changes in spatial extent [9,35]. There are major challenges, however, to conducting field research, especially in Alaska, due to the cost in time and money required to reach and survey large meadows in remote locations. An effective way to meet these challenges is to apply a hierarchical approach that uses a three-tier framework of monitoring integrated across decreasing geographic scales to answer increasingly specific questions [35,38]. Tier 1 monitoring applies broad scale data derived using remote sensing techniques to determine spatial extent and distribution of eelgrass meadows. Monitoring at Tiers 2 and 3 uses field survey data collected at progressively smaller scales to assess changes in important internal characteristics of a meadow and their environmental drivers, respectively [35].

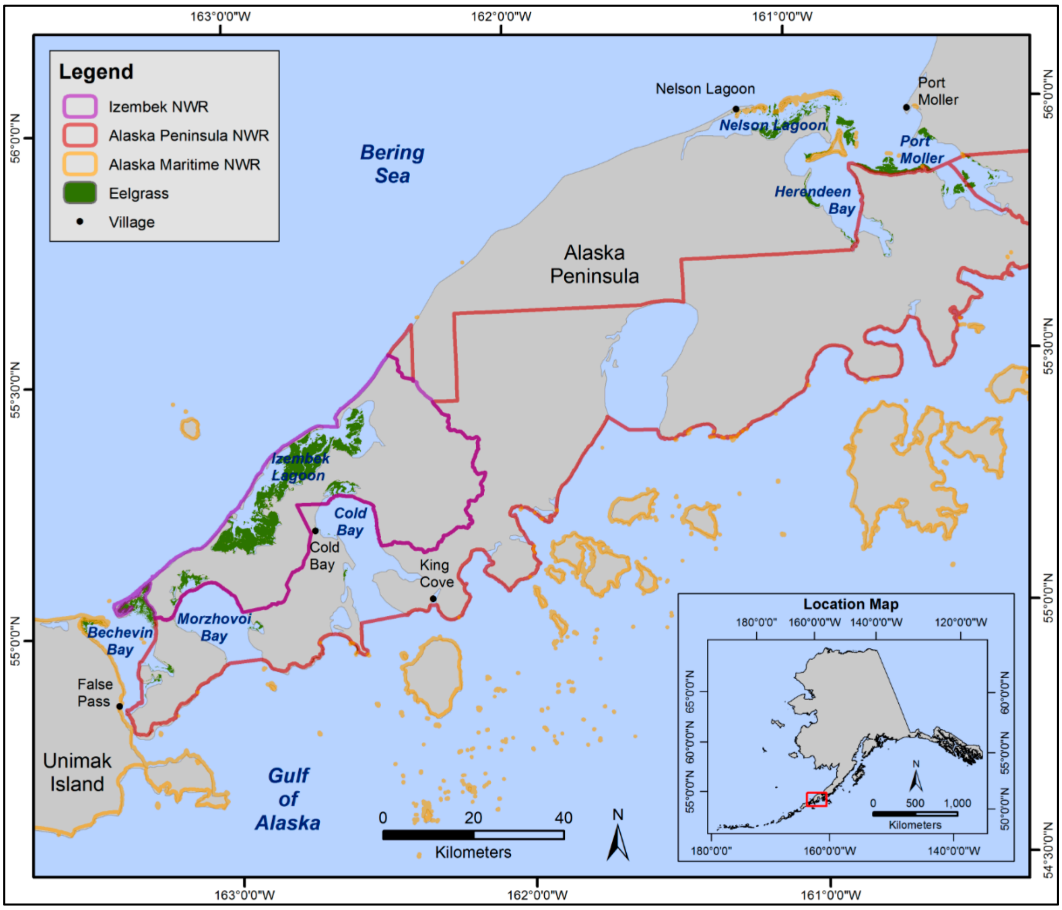
Our goal in this paper was to establish Tier 1 and 2 monitoring for a program to inventory and assess long-term trends in the health and status of eelgrass in southwest Alaska. We developed baseline maps that almost doubled the known spatial distribution of eelgrass meadows (≥5% eelgrass cover) along the lower Alaska Peninsula using Landsat satellite imagery and collected field survey data at a subset of eelgrass locations to both improve map accuracy and describe meadow characteristics. Two well established remote sensing methodologies, unsupervised isodata clustering and supervised maximum likelihood classification, were integrated in an iterative process designed to increase the accuracy of mapped eelgrass distribution. We also applied other GIS tools, interpolation of field survey data, contextual/manual editing and band radiance thresholding to address mapping challenges, such as turbid water, spectral class confusion and poorly defined coastlines inherent to coastal habitat mapping in remote northern high latitudes.

2. Methods and Materials

2.1. Study Area

The study area encompassed coastal waters of the lower end of the Alaska Peninsula from Port Moller on the Bering Sea side to Cold Bay on the Gulf of Alaska side of the peninsula, entailing approximately 1150 km of coastline (Figure 1). This portion of the Alaska Peninsula is largely undeveloped and uninhabited except for five villages (100–2000 residents). Most (73%; 839 km) of the coastline is bordered by three national wildlife refuges (Izembek, Alaska Peninsula, and Alaska Maritime) but lands below the high water line are administered by the State of Alaska and are largely unprotected from development except within Izembek State Game Refuge, which encompasses Izembek Lagoon and its expansive eelgrass meadows [39]. The region is volcanically and seismically active as the North Pacific and North America plates meet along the southern edge of the peninsula. The Bering Sea coast is generally flat and characterized by long straight sandy beaches of gradual slope and extensive shallow-water embayments with broad sand and mudflats. In contrast, the Gulf of Alaska coast is irregular with steep slopes and cliffs that drop to cobble beaches and generally deeper-water embayments consisting of a mixture of cobble, sand and mud bottoms. Water clarity is also better along this coast compared to the Bering Sea side (Secchi disk readings averaging 7 and 4 m, respectively). The climate is moderate polar maritime characterized by cool temperatures (annual range = 4–16 °C), high winds (annual average wind speed = 27 km/h), frequent but not profuse precipitation (annual average rainfall = 91 cm) and nearly constant cloud cover (average of about 12 clear days per year) [33]. Nearshore ice cover and ice scour are important features in the study area during winter, particularly along the Bering Sea coast [32].

Figure 1. Location of study area, mapped eelgrass and National Wildlife Refuge (NWR) lands on the lower Alaska Peninsula, Alaska.



2.2. Data Sources

2.2.1. Landsat Imagery

Imagery from the Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) sensor series was downloaded from the U.S. Geological Survey (USGS), Earth Resource and Observation

Science Center archives. It provided multispectral data at 30 m spatial resolution projected in UTM (Universal Transverse Mercator) Zone 3 or 4 using the WGS 84 (1984 World Geodetic System) datum. To maximize eelgrass detection, we sought imagery for each site with minimal cloud cover, acquired at low tide and during peak vegetative growth (June–August). Seven scenes, spanning a seven year time frame, were required to meet these criteria for all locations across the study area (Table 1). In most cases the spatial extent of the imagery allowed for the use of one scene per location, but this was not possible along the Bering Sea coast where mapping of broad areas across large embayments caused problems with interference from cloud cover (Port Moller) and classification inaccuracies due to variable tidal states (Izembek Lagoon). In both cases these negative effects were addressed by classifying two images per embayment and merging the maps to produce complete estimates of spatial coverage. We believe that any temporal differences in spatial extent between scenes within an embayment were minor relative to the improved spatial estimate for each of these locations. Tides were estimated using Nobeltec Tides and Currents Pro software. Imagery preparation and classification were performed using the ENVI 4.8 software program while map production and accuracy assessment were conducted using ArcMap 10.0.

Table 1. Landsat imagery used to map eelgrass distribution on the lower Alaska Peninsula.

Sensor	Orbital Path/Row	Date [a] (MM/DD/YY)	Tide [b] (m)	Locations Analyzed
L7-ETM+	74/21	08/02/02	+0.48	Port Moller, Nelson Lagoon, Bering Sea Coast
L7-ETM+	74/22	08/02/02	+0.03	Izembek Lagoon
L5-TM	74/21	07/20/06	−0.94	Port Moller, Herendeen Bay, Bering Sea Coast
L5-TM	74/22	07/20/06	−0.27	Izembek Lagoon
L7-ETM+	75/21	06/04/07	−0.30	Kinzarof Lagoon, Cold Bay
L7-ETM+	75/22	06/04/07	−0.37	Bechevin Bay, Morzhovi Bay, Gulf of AK Coast
L5-TM	75/22	08/04/09	−0.30	Hook Bay

[a] All imagery acquired at approximately 12:40 Alaska Standard Time; [b] Predicted tide estimate in mean lower low water datum for the closest station to the location.

2.2.2. Field Surveys

Field surveys were conducted at 7 of the 12 embayments, and one coastal location, in the study area. Izembek Lagoon, Kinzarof Lagoon and the coastal location in Cold Bay were easily accessible from the town of Cold Bay and were surveyed between July and September, 2007–2012. Hook Bay, Hotsprings Bay, Middle Lagoon, Big Lagoon and Littlejohn Lagoon were more remote locations and were surveyed during a research cruise aboard the R/V Aarluk between August and September 2012. For the initial survey at each location, points were evenly distributed across the embayments covering all substrate types and depth ranges using a systematic point sampling design. Points were equally spaced between 125 and 1000 m apart as determined by the size of the embayment. For repeat surveys a subset of points was randomly chosen for reassessment in a random-systematic design. At each point, we estimated water temperature, depth and clarity (20 cm diameter Secchi disk), substrate type and depth, and percent cover of eelgrass and seaweeds (all species combined) within four 0.25 m^2 quadrats placed at each of the cardinal directions around each point. To minimize among-observer differences in estimates of macrophyte cover, a score between 0 and 5 was assigned based on the Braun-Blanquet (BB) visual estimation technique [40]. Percent cover estimates were categorized according to the following BB score: 0- species absent from quadrat; 1- ≤5% cover; 2- 6% to 25% cover; 3- 26% to 50% cover; 4- 51% to 75% cover; and, 5- 76% to 100% cover. At survey points containing eelgrass, a representative sample of 5–10 shoots was collected for morphometric measurements of shoot length and width. Depth measurements were standardized to mean lower low water (MLLW) by subtracting measured depth from predicted depth as determined from the nearest tide station at the time of measurement. Points were located in the field using a Garmin 76 Csx global positioning system (GPS) unit (average accuracy = ±3 m) and sampled by snorkeling in dry suits at moderate to high tides.

Three statistics were computed from the field survey cover estimates for eelgrass and seaweeds at each survey point: density, abundance and frequency of occurrence according to Fourqurean *et al.* [41]. Density was calculated as the mean value of the cover estimates across all four quadrats at a site while abundance was calculated as the mean value of the cover estimates across the quadrats where the species (eelgrass or seaweed) was present, in either case resulting in a value from 0 to 5. Frequency was calculated by dividing the number of quadrats in which a species occurred by the total number of quadrats sampled at a site, resulting in a value between 0 and 1. In order to present the most recent data for this research, field survey data collected in 2010–2012 were used in this analysis.

2.2.3. Alaska ShoreZone Coastal Mapping and Imagery

Coastline eelgrass distribution data and imagery from the Alaska ShoreZone Coastal and Mapping and Inventory Project (hereafter referred to as "ShoreZone") were used to refine maps in six embayments where field survey data were lacking or insufficient (Port Moller, Herendeen Bay, Nelson Lagoon, Hook Bay, Hotsprings Bay, Trader's Cove), and coastal areas along the south side of the Alaska Peninsula. ShoreZone is a standardized habitat mapping system that uses low altitude aerial imagery taken during extreme low tides of the summer months to categorize the physical and biological features of the coast [42]. Helicopters or fixed-wing aircraft are used as a platform to take geo-referenced, oblique angle video and still photographs of the coastline while geologists and biologists simultaneously record commentary about its features. Mappers then use the imagery and commentary to classify substrate type (e.g., seaweeds, seagrasses, salt marsh plants) among other features (e.g., wave exposure, geomorphology, sediment texture) to produce linear GIS data layers of the coast. This dataset provided a simple estimate of coastline length for presence or absence of eelgrass and other substrate types and was insufficient for monitoring areal extent. We used this linear distribution estimate as an ancillary dataset to help differentiate eelgrass from seaweeds in some areas. ShoreZone data and imagery were available for most (86%) of our study area and were accessed via the internet (http://www.shorezone.org/). ShoreZone data for the lower Alaska Peninsula were collected in 2006, from Port Moller to Izembek Lagoon, and 2011, from Izembek Lagoon to western Cold Bay.

2.3. Image Processing, Mapping, and Accuracy Assessment

2.3.1. Preprocessing and Preparation

Each Landsat image was calibrated to at-sensor radiance, corrected for atmospheric path interference and checked for georeferencing accuracy. Radiance calibration was performed following calibration factors and formulas established in Chander *et al.* [43]. The images were corrected for atmospheric interference using dark pixel subtraction [44,45]. We verified the georeferencing of the imagery by comparing the position of prominent landmark features in the images with the position of the same landmarks as indicated by ground control points (GCP) collected with a Garmin 76 CSx GPS unit. We detected only small (<1 pixel) offsets between GCP and their presumed acquisition site (predicted root means squared error = 1.51; range = 0.81–1.4 among all GCP) and between images from different years or adjacent swaths, indicating accurate georeferencing of the imagery. The images were more accurate than USGS topographic maps and National Oceanic Atmospheric Administration nautical charts, which often contain high spatial error [46], so we did not use either as a source for "correction".

The two 2007 images from the Landsat 7 ETM+ sensor were acquired after its scan line correction function failed resulting in data gaps that increase in width toward the edge of the image swath and cover about 22% of the total area of each image. The gaps were filled by applying an algorithm, available through ArcInfo Workstation, which passed a user defined operational window over the image and assigned the mean value for pixels within the window that contained data to the window's central pixel if it lacked data. Three iterations of the algorithm were run on each band of the imagery using a 3 × 5 pixel window to completely close the gaps while emphasizing data from their northern and southern edges. Once the bands were re-composited into a multiband image, these "gap fills" provided a reasonable estimation of the ground cover where gaps were relatively narrow, <6 pixels. Mapping was conducted using this imagery at locations from Trader's Cove to Kinzarof Lagoon, but the gaps did not commence until west of Littlejohn Lagoon. The "gap fill" data accounted for 10% to 14% of the total area of Littlejohn and Kinzarof lagoons, respectively. The eastern portion of Cold Bay was excluded from the analysis because "gap fills" exceeded 6 pixels width and the filled data was deemed unsuitable for reliable estimates of ground cover.

Because of the lack of accurate coastal data for the state of Alaska, coastlines were developed for the study area directly from the imagery using the short wave infra-red (SWIR) data available in Landsat band 5 [47]. SWIR energy is strongly absorbed by water and wet sand but strongly reflected by dry ground and vegetation allowing for the determination of a threshold value of SWIR radiance that indicates a change from dry or vegetated ground to saturated sand or water. The threshold value varies between images due to atmospheric and environmental conditions at the time of image acquisition so this value was determined for each location and a "threshold" function was performed to create a line running between pixels falling above and below this value to derive the coastline.

2.3.2. Initial Distribution Estimates

Of the eelgrass meadows contained in the study area, Izembek and Kinzarof lagoons had been well studied [19,21,48], but eelgrass beds in other locations were known only through observation during waterfowl surveys [28] or other research and had yet to be quantified for areal extent or assessed for condition. Our mapping process was designed without the use of field survey data to create training sites for the classification of satellite imagery which allowed for the production of initial maps for use and improvement during field surveys and for estimates of areal extent at eelgrass meadows that were not visited. This was accomplished by using expert knowledge to indicate likely meadow locations, false color analysis of imagery to confirm the presence of eelgrass, and a simple land-cover classification scheme with three easily discerned categories, eelgrass, bare ground, and water. A tool that we found particularly useful in early mapping stages was the use of false color images, produced by assigning the color red to band 4, green to band 5 and blue to band 1, which displayed exposed eelgrass in a bright maroon color (Figure 2a). Initial runs of the false color analysis were conducted at Izembek Lagoon (Figure 2a), where eelgrass occurs in monospecific stands [21,49], and training classes for eelgrass and other habitat classes could be tested across a wide range conditions (Figure 2b). We then applied the false color analysis to create training classes at the other locations, where eelgrass was suspected to be the dominant marine macrophyte, but not yet known.

Figure 2. (**a**) False color presentation (Red = Band 4, Green = Band 5, Blue = Band 1) of Landsat 5 Thematic Mapper imagery from 20 July 2006; (**b**) Results of ground cover classification in Izembek Lagoon using the combined isodata and maximum likelihood technique with multiple subcategories to refine classification accuracy.

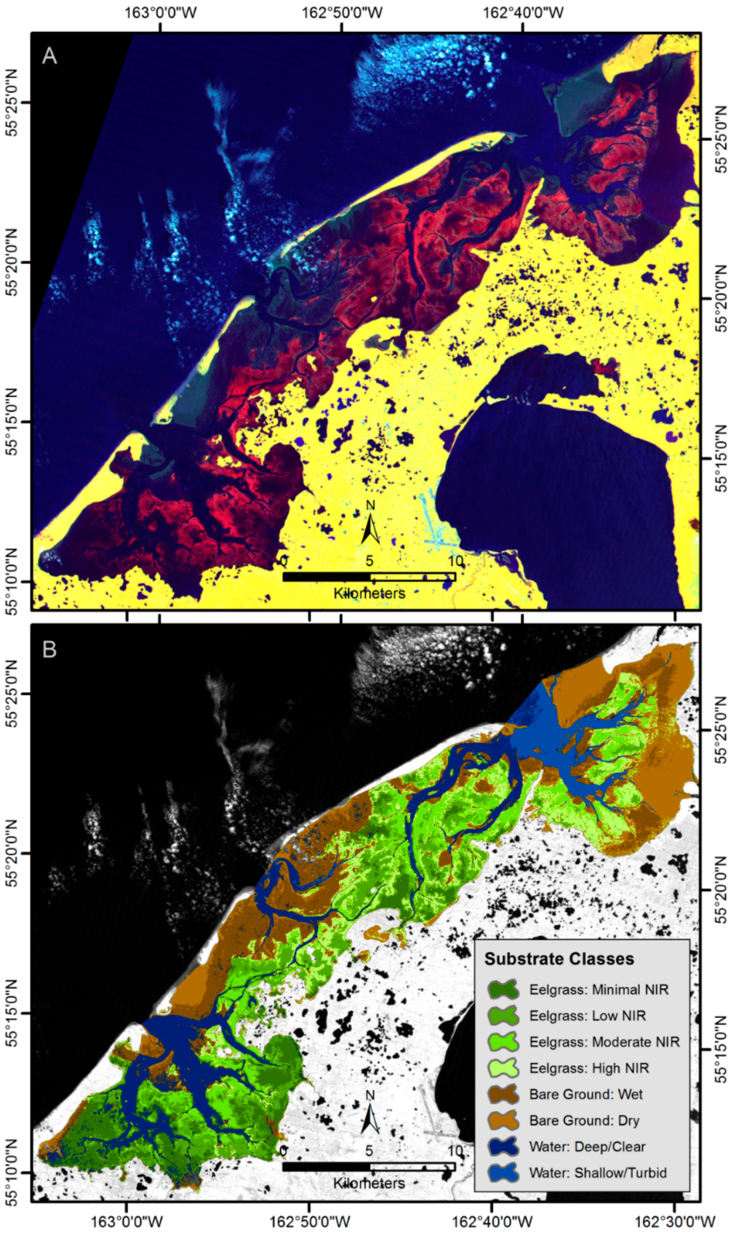
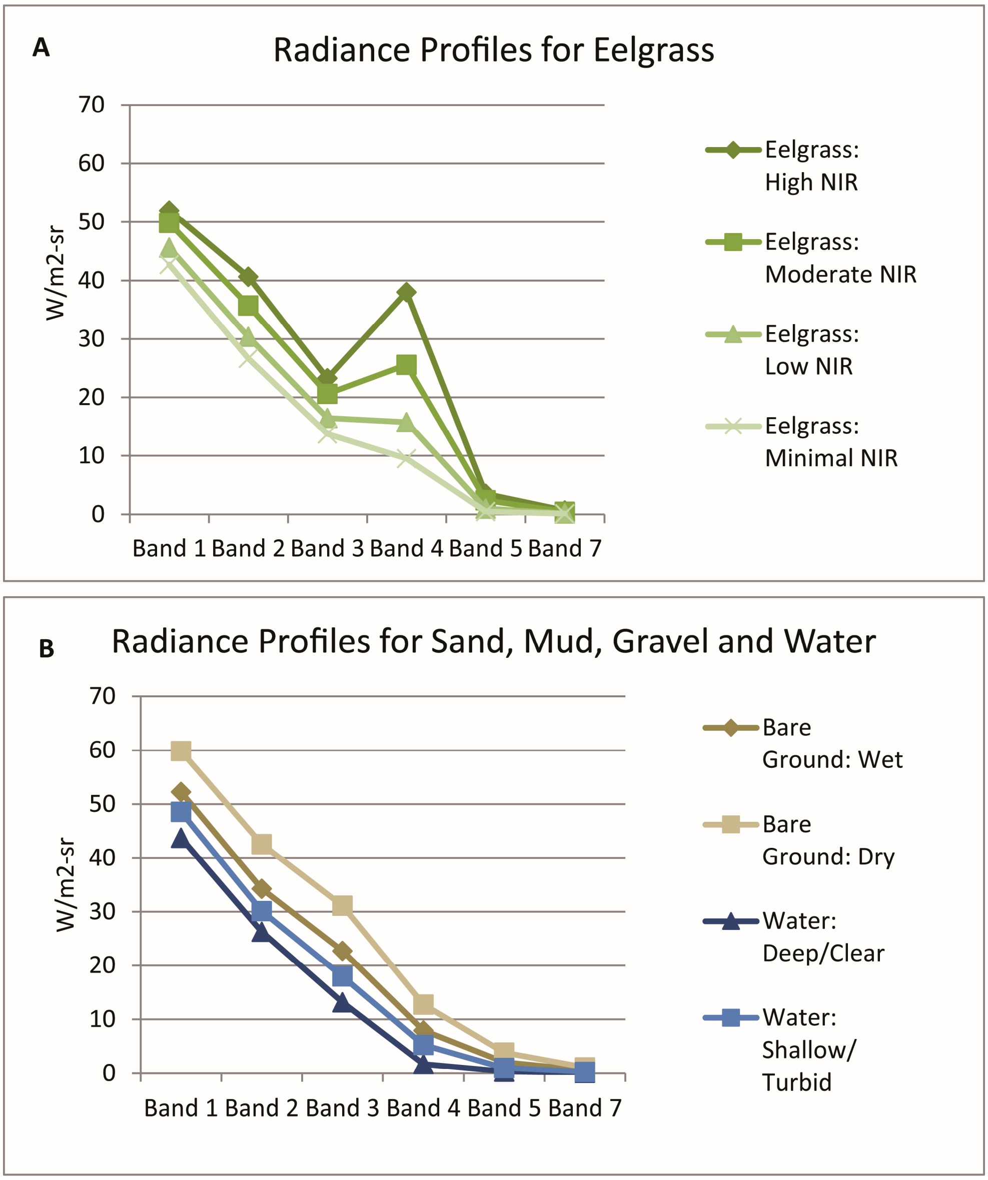


Figure 3. Radiance profiles plotting mean band values for each training class (**a**) differentiating four classes of eelgrass based primarily on strength of the near infrared (NIR) signal (band 4) and (**b**) indicating two classes of bare ground and two classes of water.



Classification of the imagery was conducted using an unsupervised isodata algorithm to identify statistically separable spectral clusters for use in determining training classes in subsequent supervised maximum likelihood analyses [21,50]. Masks were created to exclude clouds and dry land and then an isodata algorithm was run to create 35 spectral clusters. The algorithm was set for a maximum of 25 iterations, a change threshold of 5, 1 pixel per class, maximum standard deviation of 0.5, maximum class distance of 2.5, and a maximum of 2 merge pairs. Clusters were then assigned to one of eight substrate classes to create training regions, four for eelgrass, two each for bare ground and water, or left unassigned. The approach of using eight rather than three training classes resulted in smaller deviations from mean radiance value of each band of the spectral profile reducing confusion between classes and improving the maximum likelihood classification accuracy in differentiating eelgrass, bare ground and water. However, spectral differences between eelgrass sub-classes did not accurately represent real physical differences within meadows and the differences between bare ground and water subclasses were not significant to this study, so final results were collapsed to the three broad classes. Visual interpretation of both false color and real color Landsat imagery was used to assign isodata clusters to the broad substrate classes (eelgrass, bare ground or water), while the spectral profile characteristics of the cluster were used for further sub-categorization. If a cluster was not clearly associated with one of the three substrate classes, it was left unassigned so that the cells it represented were left open and unbiased to the statistical decision making of the maximum likelihood analysis. Clusters that coincided with eelgrass in the false color imagery were assigned to one of four eelgrass classes based on the strength of band 4 (near infrared, NIR) radiance relative to the strength of band 3 (red) radiance: High NIR, Low NIR, Low NIR and Minimal NIR (Figure 3a). The first three subclasses represent the upper, middle and low ranges of NIR values, respectively, in clusters where NIR > Red. In the fourth class NIR ≤ Red, but the cluster is still coincident with eelgrass in the false color image. Since healthy vegetation (*i.e.*, eelgrass) reflects NIR more strongly than red, this reduction in NIR radiance compared to red represents either diminishing eelgrass density (decreased NIR reflectance) or increasing water depth (increased NIR absorption). These subclasses allowed for better isolation of the spectral signal for eelgrass that was either sparse or obscured by water (the minimal NIR subclass) and better differentiation from mud or water. Similarly, isodata clusters representing bare ground (sand, mud, gravel) or water were determined by visual interpretation, verified by the shape of their radiance profile, and further sub-categorized based on the strength of their spectral signal (Figure 3b). A cluster was verified as bare ground if the radiance of band 3 created a convexity in the profile segment between bands 2 and 4 while clusters that created a concavity in that segment were assigned to water. This difference in shape was presumed to be caused by strong red band absorption by water as opposed to red band reflection by bare substrate. All assigned clusters were then merged to create discrete training classes to extract data for a maximum likelihood classification that allocated every pixel in the area of interest to one of the eight substrate classes (Figure 2b).

2.3.3. Accuracy Assessment and Map Rationalization

Mapping accuracy was assessed at locations where field survey data were collected using a two-step process. First, field survey data were simplified to "Eelgrass" (≥5% cover regardless of depth), "Bare ground" (<5% eelgrass cover, <0.5 m depth) and "Water" (<5% cover, ≥0.5 m depth) to match with the three substrate classifications produced by the mapping process while also approximating the minimum cover and maximum depth required to produce a spectral signal for eelgrass. Second, accuracy was evaluated using confusion matrices to compare classified substrate classes to field survey data and determine omission, commission, and total percent accuracy, and a Kappa coefficient (Appendix A). For each substrate class, omission accuracy assessed the percentage of the map data that agreed with the field survey data making the assumption that the survey data were correct, while commission accuracy evaluated the percentage of the field survey data that agreed with the map data making the assumption that the map was correct. The overall accuracy measured the agreement between the two datasets for all three classes as does the Kappa coefficient, but Kappa also accounted for chance agreement between the datasets, so was a more conservative measure of accuracy [51]. We used field survey data from 2007, one year after initial image acquisition, to assess the accuracy of maps of Izembek Lagoon and mean values of field survey data from 2009–2011 to assess map accuracy of Kinzarof Lagoon while minimizing effects associated with the larger temporal offset between field surveys and acquisition of this imagery. Field survey data from 2012 were used to assess accuracy of maps of Hook Bay, Hotsprings Bay, Middle Lagoon, Big Lagoon and Littlejohn Lagoon.

Results of the accuracy assessment were used to rationalize maps of eelgrass distribution in an iterative process where sources of error identified during the assessment were applied to adjust training classes and improve results [51]. Points where the classification did not agree with field survey data were examined and typically the source of error was associated with a small number of isodata clusters that were indeterminate as to which substrate class they covered. Reassignment of these questionable clusters to different training classes, or leaving them unassigned, changed the results of the subsequent maximum likelihood classifications. After each iteration of training class creation and classification, the product was assessed for error, resulting sometimes in decreased accuracy but frequently in its improvement. The best results from this rationalization process were chosen to become the final product and statistical results for the major editing rounds are provided. The map of Hotsprings Bay was not rationalized due to the low number (9) of survey points visited at this location because of time and weather constraints.

2.3.4. Refinement of Final Eelgrass Distribution Estimate

Knowledge gained during field surveys and ShoreZone data were used to differentiate between stands of eelgrass and unidentified seaweeds to refine final maps of eelgrass distribution. Site familiarity acquired during transit to and from survey sites and on specific investigative forays was used to reassign a few areas classified as “Eelgrass” to the class “Seaweeds”. These edits were minimal and did not affect accuracy assessments. Where field survey data were lacking, ShoreZone distribution data were used as an ancillary dataset to differentiate between eelgrass and seaweeds. Using a confusion matrix analysis, ShoreZone data were determined to be highly accurate (90% overall accuracy) in identifying areas of eelgrass as compared to the ground-truthed classified imagery (Appendix B). Therefore, mapped eelgrass spatial extent that coincided with the linear eelgrass distribution of ShoreZone was confirmed, other mapped vegetation was changed to “seaweed”. However, before making such edits, the original oblique aerial photography was also reviewed, and in two locations, Port Moller and Nelson Lagoon, areas of mapped eelgrass were left intact because the photography did indeed show eelgrass as assessed by our operator, contradicting the linear data. Both datasets were used to refine spatial estimates for Hook Bay, field survey data in the north and ShoreZone data in the south where field data were not collected. Field survey and ShoreZone data were not collected for St. Catherine Cove; therefore, we considered all marine vegetation mapped at this location to be eelgrass, an assumption based on the similarity in geomorphology (shallow depths and soft substrate bottoms) between St Catherine Cove and Izembek Lagoon as evident in the imagery and on earlier reconnaissance to the cove.

Finally, field survey data were also used to delineate eelgrass coverage in Kinzarof Lagoon. Detection of eelgrass was problematic in a section of this lagoon where eelgrass occurred in water too deep to detect and map using satellite imagery. We used the percent cover estimates from survey points and the inverse distance weighted (IDW) interpolation method to adjust the estimates of eelgrass spatial extent [41]. The IDW method applies the assumption that point locations in close proximity are more likely to be similar than those farther apart to create a raster surface for the entire area from localized point data [52]. Where water depth did not pose a problem, visual comparisons revealed tight agreement between the eelgrass distribution classified from satellite imagery and areas with >5% cover of eelgrass from the interpolated field data. Therefore, the >5% iso-line was used to estimate eelgrass coverage in areas where water was too deep for a reliable imagery classification in Kinzarof Lagoon.

3. Results

3.1. Regional Eelgrass and Seaweed Distribution: Tier 1 Data

The total spatial extent of eelgrass meadows was estimated to be 30,568 ha within the 12 embayments and 6 sections of coast between Port Moller and Kinzarof Lagoon on the lower Alaska Peninsula (Table 2; Figures 4–7). This areal eelgrass distribution was associated with 406 km of linear eelgrass distribution along the coast as indicated by ShoreZone data. The advantage of areal data for use in a monitoring program is demonstrated by ShoreZone's very similar estimates of linear eelgrass distribution at Port Moller and Herendeen Bay that do not reflect the large difference in areal eelgrass distribution at those locations (Table 2; Figure 5). The largest stands of eelgrass were found within the 6 embayments on the Bering Sea side of the Alaska Peninsula accounting for 90% (27,385 ha) of all eelgrass in the study area. The largest single expanse of eelgrass was found in Izembek Lagoon (55% of all eelgrass in the study area) followed by the Port Moller, Herendeen Bay, and Nelson Lagoon complex (26%) and Hook Bay and St. Catherine Cove (9%). The eelgrass extent along the south side of the Alaska Peninsula accounted for 10% of all eelgrass in the study area and occurred in both embayments (9%) and small patches at outer coast locations (1%). Only two embayments on this side of the peninsula, Big and Kinzarof lagoons, contained eelgrass extents greater than 500 ha. The largest spatial extent of eelgrass along the unprotected outer coast was found between Morzohovi and Cold bays (156 ha).

Eelgrass comprised 91% of the spatial distribution of eelgrass and seaweeds in the study area and was dominant in each of the 12 protected embayments (≥71% of all vegetative cover), but not in each of the 6 unprotected outer coast locations (Table 2). Here, seaweeds comprised the majority (≥56%) of the vegetative distribution when present, except along the west side of Cold Bay, where spatial extent was slightly greater for eelgrass (108 ha) than for seaweeds (90 ha). Seaweeds were present in all protected embayments, but generally were found in relatively low abundance (Table 3). The greatest seaweed extent occurred in the Nelson Lagoon, Herendeen Bay and Port Moller complex, totaling nearly 1760 ha.

3.2. Variation in Characteristics of Eelgrass Meadows: Tier 2 Data

Eelgrass and seaweeds occurred at a majority (88%) of the 444 points in the 8 locations where field surveys were made; however, the characteristics of these meadows varied significantly between locations (Table 3). Eelgrass was more common than seaweeds in all locations, except in Cold Bay and Kinzarof Lagoon. On average, eelgrass was encountered more frequently (82% *vs.* 52% of points, respectively) and occurred at greater densities (BB = 3.54; 50%–75% cover *vs.* BB = 2.11; 25%–50% cover, respectively) in locations on the Bering Sea than on the Gulf of Alaska, a pattern that was consistent with findings of greater eelgrass spatial extent on the north side of the lower Alaska

Peninsula (Table 3). Greatest densities of eelgrass were found in Izembek Lagoon (BB = 3.44; 50%–75% cover) and Hook Bay (BB = 3.46; 50%–75% cover) and lowest density in Cold Bay (BB = 0.15; <5% cover), the only coastal location field surveyed. Seaweeds were present in all surveyed locations, and on average, were encountered at a similar frequency (54%) on either side of the peninsula. Seaweeds occurred at greatest densities in Kinzarof Lagoon (BB = 2.54; 25%–50% cover) and lowest densities in Izembek Lagoon (BB = 0.69, <5% cover). Seaweeds were generally found in greater density and abundance in locations with hard substrates (*i.e.*, cobble, rock).

Table 2. Spatial extent estimates of eelgrass and other substrate classes on the lower Alaska Peninsula.

Location	**Substrate Class (ha)**				**Total Area (ha)**	**ShoreZone Eelgrass (km)**
	Eelgrass	**Seaweeds**	**Bare Ground** [a]	**Water** [b]		
Bering Sea						
Port Moller	4689	473	11,502	27,657	44,321	50
Herendeen Bay	841	347	2224	15,646	19,058	54
Nelson Lagoon	2287	947	13,556	6047	22,837	23
Coast: Nelson Lagoon to Izembek Lagoon	0	0	-	-	-	0
Izembek Lagoon	16,816	153	11,366	5833	34,167	151
Coast: Izembek Lagoon to Hook Bay	0	0	-	-	-	0
Hook Bay	2226	140	317	3878	6562	31
St Catherine Cove	526	0	221	2118	2864	-
Gulf of Alaska						
Hotsprings Bay	217	12	63	1589	1881	15
Trader's Cove	188	11	103	790	1092	19
Coast: Trader's Cove to Morzhovoi Bay	67	243	125	-	-	2
Coast: Morzhovoi Bay	32	170	564	-	-	6
Big Lagoon	938	26	531	249	1744	28
Middle Lagoon	186	1	138	48	373	7
Littlejohn Lagoon	162	2	140	132	436	8
Coast: Morzhovi Bay to Cold Bay	156	202	304	-	-	12
Coast: western Cold Bay to Kinzarof Lagoon	108	90	1239	-	-	-
Kinzarof Lagoon	1129	56	392	479	2055	-

[a] Bare Ground = sand, mud, gravel or rock; [b] Water depth ≤ −0.5 meters, mean lower low water.

Table 3. Variation of eelgrass and seaweed characteristics and environmental parameters in selected embayments on the lower Alaska Peninsula, 2010–2012.

Location	Eelgrass												Seaweed									Year
	Density (BB [a]: 0–5)			Abundance (BB [a]: 1–5)			Frequency (0–1)			Shoot Length [b] (cm)			Density (BB [a]: 0–5)			Abundance (BB [a]: 1–5)			Frequency (0–1)			
	Mean	SE	N	Mean	SE	N	Mean	SE	N	Mean	SE	N	Mean	SE	N	Mean	SE	N	Mean	SE	N	
Bering Sea																						
Izembek Lagoon	3.4	0.2	86	4.3	0.1	73	0.8	0.0	86	49.3	4.9	71	0.7	0.1	86	2.0	0.2	38	0.3	0.0	86	2010
Hook Bay	3.5	0.2	74	4.0	0.2	68	0.9	0.0	74	70.1	7.3	65	2.3	0.2	74	2.8	0.2	67	0.8	0.0	74	2012
Gulf of Alaska																						
Hotsprings Bay	3.3	0.8	9	4.2	0.6	7	0.8	0.2	9	40.9	12.9	6	1.4	0.4	9	2.0	0.3	7	0.7	0.1	9	2012
Middle Lagoon	2.3	0.4	36	3.5	0.4	24	0.6	0.1	36	34.3	7.9	19	1.0	0.2	36	2.2	0.2	20	0.4	0.1	36	2012
Big Lagoon	2.3	0.3	63	3.5	0.3	45	0.6	0.1	63	32.4	4.3	38	1.6	0.2	63	2.5	0.2	48	0.6	0.1	63	2012
Littlejohn Lagoon	2.3	0.4	43	4.3	0.3	25	0.5	0.1	42	60.9	5.0	24	1.0	0.2	42	2.4	0.3	22	0.4	0.1	42	2012
Cold Bay	0.2	0.1	31	2.0	0.4	13	0.1	0.0	31	29.0	4.2	7	0.6	0.2	31	1.9	0.3	13	0.3	0.1	31	2010
Kinzarof Lagoon	2.4	0.2	103	3.6	0.2	75	0.6	0.0	103	54.6	4.6	70	2.5	0.2	103	2.9	0.1	96	0.9	0.0	103	2010

Table 3. *Cont.*

Location	Water			Substrate						Year
	Tidal Depth [c] (m)			Depth (cm)			Type (%)			
	Mean	SE	N	Mean	SE	N	Mud	Sand	Cobble	
Bering Sea										
Izembek Lagoon	0.2	0.1	85	7.0	1.0	84	69	31	0	2010
Hook Bay	−0.2	0.1	71	14.7	2.0	71	54	41	5	2012
Gulf of Alaska										
Hotsprings Bay	0.7	0.1	9	0.8	0.4	9	44	56	0	2012
Middle Lagoon	1.0	0.1	32	8.1	1.8	36	53	47	0	2012
Big Lagoon	0.4	0.2	49	15.3	2.2	62	58	40	2	2012
Littlejohn Lagoon	0.0	0.2	41	1.4	0.2	42	26	45	29	2012
Cold Bay	−1.0	0.1	16	0.4	0.1	22	0	88	12	2010
Kinzarof Lagoon	0.3	0.1	102	3.3	0.4	102	39	39	22	2010

[a] Braun-Blanquet visual estimation scale; [b] Measured from rhizomal mat to tip of longest blade; [c] Datum: mean lower low water.

Figure 4. Distribution of eelgrass and other classified habitats as derived from Landsat imagery (displayed as a black/grayscale backdrop) and field survey points in Izembek Lagoon, Kinzarof Lagoon and northwest Cold Bay. Also shown, highlighted in purple, is the linear coastal eelgrass distribution derived by ShoreZone.

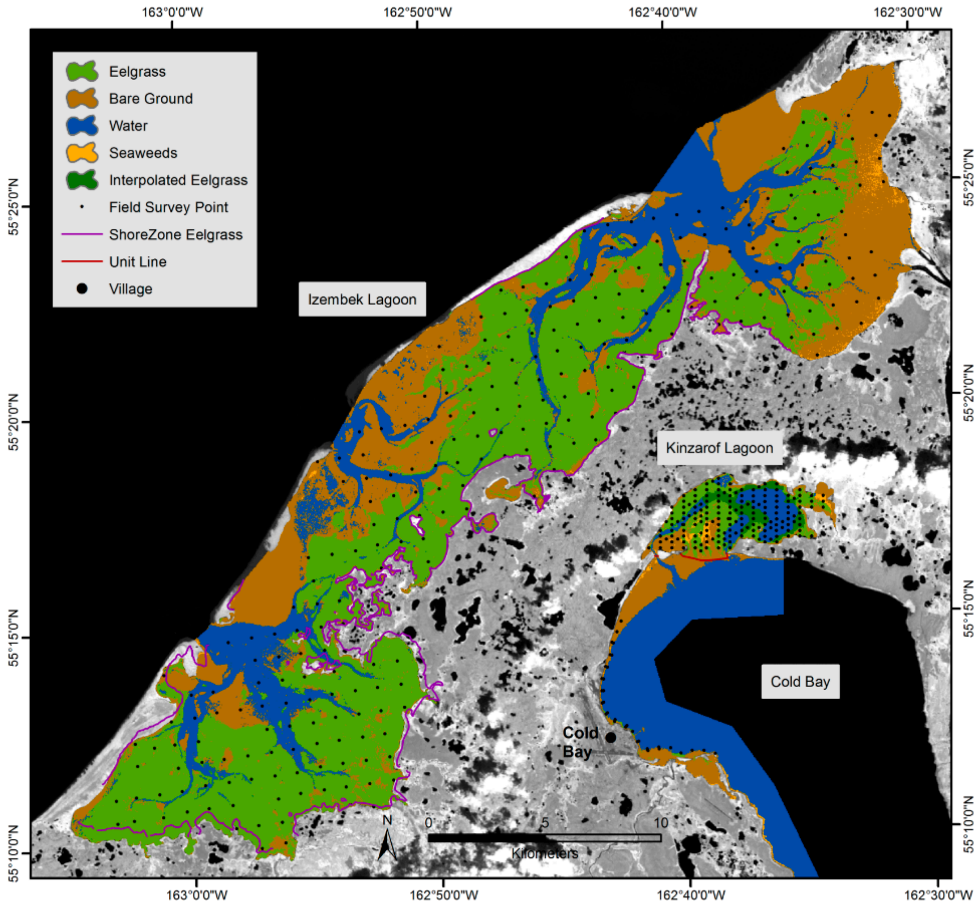


Figure 5. Distribution of eelgrass and other habitats as derived from Landsat imagery (displayed as a black/grayscale backdrop) in Port Moller, Herendeen Bay, and Nelson Lagoon using ShoreZone data to differentiate between eelgrass beds and seaweeds.

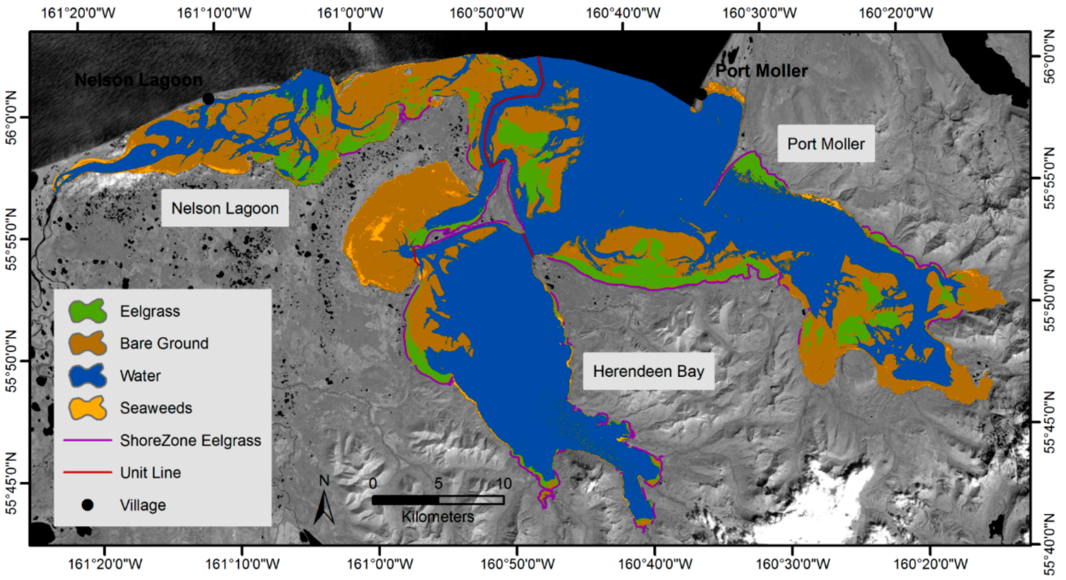
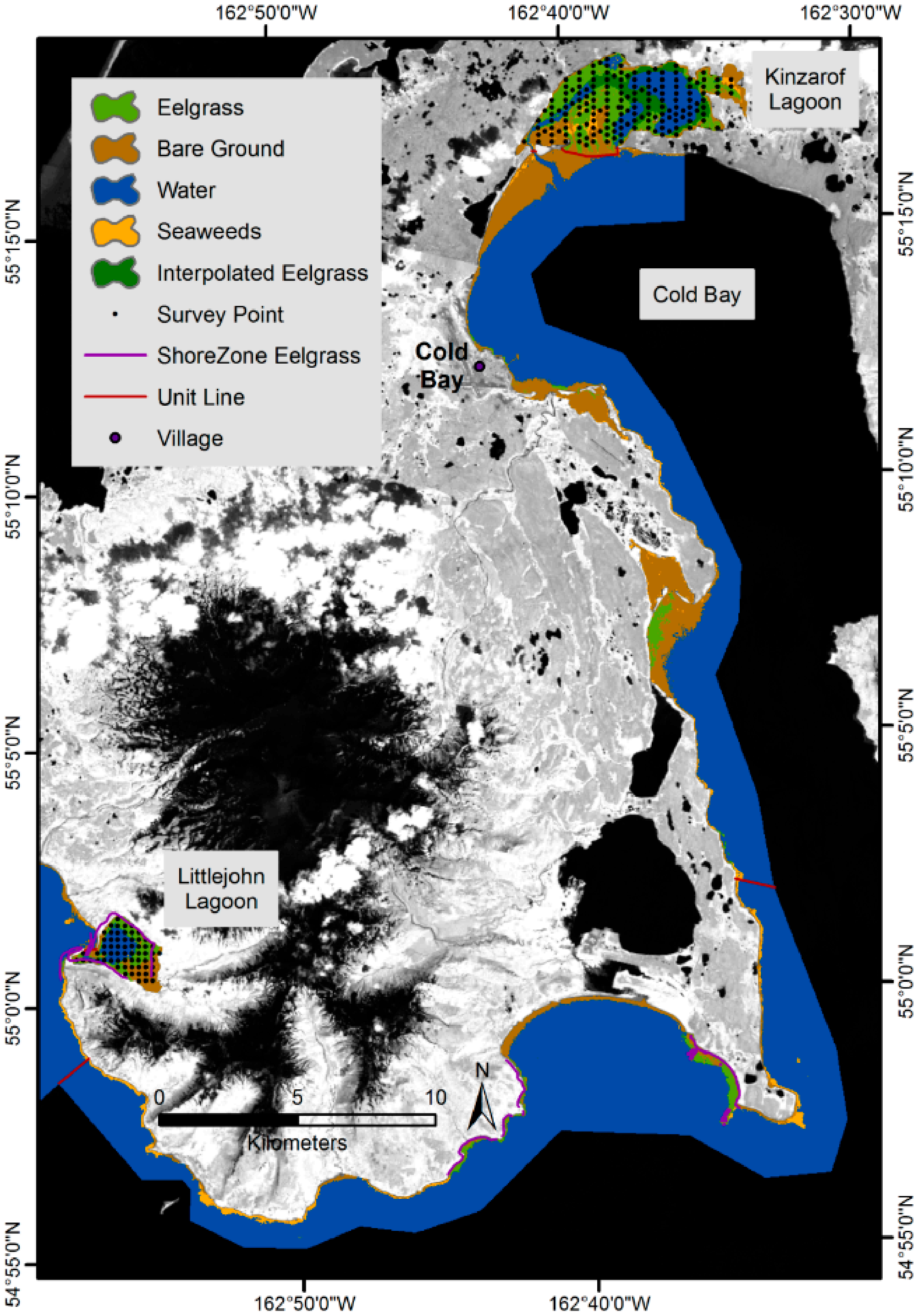


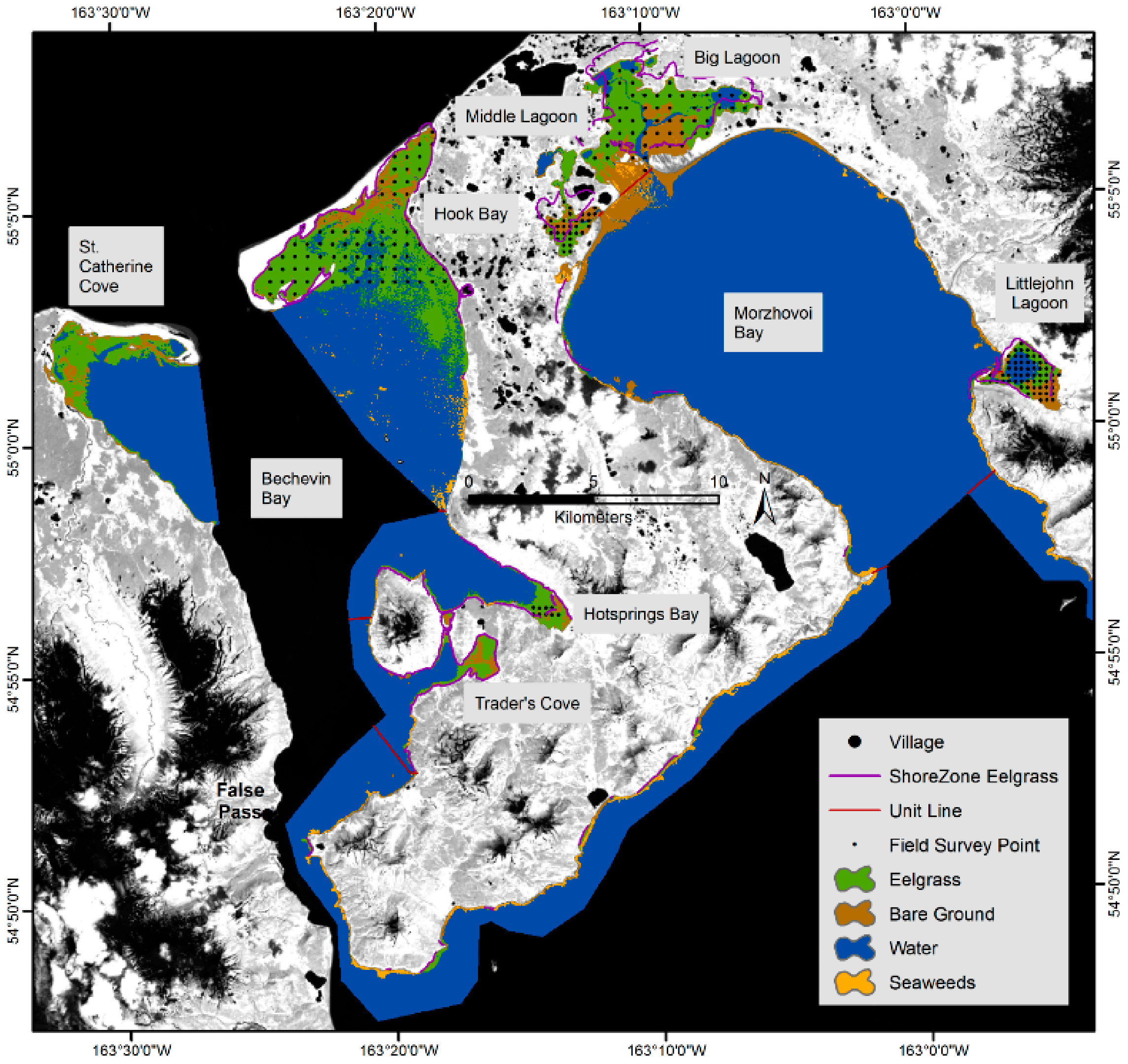
Figure 6. Distribution of eelgrass and other habitats as derived from Landsat imagery (displayed as a black/grayscale backdrop) for coastal areas between Morzhovoi and Cold bays where ShoreZone data were used to differentiate between eelgrass and other seaweeds.



3.3. Accuracy Assessment: Impact of Iterative Process and Final Product Refinement

Field survey data were collected at 6 of the 12 embayments where mapping occurred, allowing for accuracy assessments that could be performed in an iterative process to "rationalize" the initial product and improve results (Table 3; Appendix A). Of the 680 survey points used in accuracy assessment, 60% were eelgrass, 23% were bare substrate and 17% were water as determined by our assessment criteria providing sufficient coverage for a rigorous assessment of each substrate class. The overall accuracy of the initial classifications ranged from 46% to 85% (Kappa ranged 0.19–0.69) while the overall accuracy of the rationalized classifications ranged from 61% to 88% (Kappa ranged 0.41–0.83). The rationalization process improved overall accuracy by an average of 9% (Kappa by an average of 0.21) at five embayments (Izembek, Big, Middle, Littlejohn and Kinzarof lagoons) but caused declines in overall accuracy of 4% (Kappa by 0.1) at one embayment (Hook Bay). These changes in overall accuracy were associated with a decrease in spatial extent of eelgrass at all locations except at Hook Bay, where eelgrass spatial extent increased. Edits made to the final distribution maps to differentiate eelgrass from stands of mixed seaweed species reduced the spatial coverage of eelgrass by 1% to 9% but had minimal or no impact on statistical accuracy. The exception was Kinzarof Lagoon, where inclusion of the eelgrass distribution estimate derived from interpolated field data increased the spatial extent of eelgrass by almost 200 ha and improved overall accuracy from 62% to 75%.

Figure 7. Distribution of eelgrass and other habitats as derived from Landsat imagery (displayed as a black/grayscale backdrop) and field survey points in Bechevin and Morzhovoi bays. In areas lacking field survey points, ShoreZone data were used to differentiate between eelgrass and other seaweeds.



4. Discussion

This study is among the first large-scale, comprehensive assessments of the distribution and abundance of eelgrass in Alaska. The 30,568 ha of eelgrass on the lower Alaska Peninsula represents one of the largest expanses of this critical seagrass habitat in North America [5,7]. While a significant portion (55%) of the total spatial extent occurred in Izembek Lagoon, one of the largest contiguous beds of eelgrass in the world [7,21], our study almost doubles the mapped extent of eelgrass meadows along the Alaska Peninsula into areas where eelgrass was known or suspected to exist, but had yet to be quantified. Further, our estimate of eelgrass extent in Izembek Lagoon (16,816 ha) was consistent with earlier estimates for this location, determined from remotely sensed data, (1978: 15,067 ha; 1987: 15,915 ha) [21], suggesting a stable (≤12% change between years) areal cover of eelgrass in this lagoon over the last 28-year period. Other large beds of eelgrass are known to occur east of the study area in protective embayments along the south side of the Alaska Peninsula (e.g., Chignik Bay [49], Pavlov Bay and Sanak Island, Ward and Hogrefe unpubl. data) but this region remains largely unsurveyed. Eelgrass is thought to be uncommon east of our study area along the north side of the peninsula probably because of the extreme tides (mean tidal range of 4–6 m) and turbid waters of Bristol Bay. Likewise, eelgrass is uncommon west of the study area in the Aleutian Islands probably because shorelines are generally steep and rocky, and largely unprotected from high wave action. The expansive eelgrass meadows of the lower Alaska Peninsula are an important reason for the rich diversity of wildlife that seasonally populates this region [33].

Abiotic factors, such as coastal geomorphology, nutrient availability, substrate quality (grain size and depth), and water quality (temperature, salinity and turbidity), likely drive variation in the abundance and distribution of eelgrass along the lower Alaska Peninsula [48,53]. In this study, most (90%) of the eelgrass distribution occurred on the north side of the peninsula (Table 2) in large protective embayments where soft bottom substrates are ideal for the settlement and growth of eelgrass [4]. These eelgrass meadows were the most dense and abundant in the study area (Table 3). The absence of eelgrass on the outer coast of the Bering Sea is likely the result of high wave exposure along this straight coastline that directly faces the regions prevailing northwesterly weather patterns [32]. In contrast, a subduction zone to the south of the Alaska Peninsula creates a steep and rocky coastline with embayments of various sizes. The outer coast and larger bays have hard (gravel, rock, cobble) bottom substrates while some smaller, shallow inlets with freshwater inputs allow for the accumulation of sand or mud substrates. Significant eelgrass meadows were mapped in such inlets, but generally there was a greater abundance and diversity of seaweeds than eelgrass meadows along the south side of the peninsula [54] in the study area. Along the exposed coast, eelgrass beds were sparse and grew mixed with large expanses of seaweeds, likely because of the high prevalence of rock and cobble substrates that allow for attachment of seaweeds but are unfavorable for root attachment by seagrasses. Eelgrass and seaweeds also occurred at greater water depths (up to at least −3 m) along the south side of the peninsula probably because of the greater water clarity of these waters compared to the Bering Sea.

We cannot rule out that some of the vegetation identified as eelgrass was actually surfgrass along the exposed outer coast on the south side of the peninsula, where environmental conditions are likely suitable (rocky/sandy substrates in a surf zone) for growth of this seagrass [6]. We did not ground-truth this location and relied on ShoreZone data, which has insufficient resolution to differentiate between these two seagrasses where distributions overlap.

The moderate resolution of Landsat imagery is well suited for mapping eelgrass over broad expanses while providing adequate detail for monitoring changes to spatial extent at regional scales [35,37,55,56]. In this study, we used a combination of classification methods, informed by field survey data, to produce distribution maps with an accuracy that generally exceeded accepted standards for the remote sensing field that can be used to monitor trends in eelgrass spatial distribution [51,56]. Excluding Kinzarof Lagoon, the overall accuracies of initial classifications were above, or very close to 70% while those for the final product were >80%, in some cases approaching 90%. In addition to the refinement process, the high accuracy of the final estimates is likely directly related to the relative shallow depth (>−1.0 m) of the majority of the eelgrass meadows in the study area and our choice of a three class scheme appropriate to the detail expected from mapping eelgrass distribution with Landsat spectral data in a near shore environment [54].

4.1. Refining Classification Technique to Address Error Caused by Water

Water is problematic in remote sensing because it attenuates solar energy and distorts the spectral signal of the material that the water covers causing misclassification of substrate types [57,58]. This effect increases with depth until the water completely obscures the signal of the underlying substrate and is more severe in water with high turbidity [57,58]. In our iterative classification process, most errors were located along the substrate margins, associated with just a few isodata clusters and likely related to water cover. This suspicion was supported by field survey data as most of the misidentification occurred within the low and minimal NIR eelgrass sub-classes, the groups most easily confused for water or bare ground because of decreasing eelgrass density and increasing water depth. Without the confounding effects of water, the progressive reduction in NIR radiance in the eelgrass subclasses (Figure 3a) is likely caused by diminishing eelgrass density because vegetation strongly reflects NIR and denser vegetation reflects it more strongly. However, water absorbs all NIR within the first few centimeters of the water column, so, as water depth increases and then exceeds eelgrass length, NIR absorption increases until the signal for eelgrass is completely obscured. Consequently the spectral profile of dense, long (~80 cm) eelgrass in around 50 cm of water might appear similar to sparse eelgrass that is completely exposed and be classified the same. This is a significant source of error when attempting to differentiate eelgrass density classes, or conversely, to differentiate depth classes such as exposed, inter-tidal and sub-tidal eelgrass. The impact of increasing water depth to classification accuracy was heightened by tidal stage variability both across an image and within an individual tidal basin. Most locations with significant eelgrass meadows are broad basins with narrow channels connecting to the open ocean so once a tidal shift occurs, different portions of the basins fill/drain at different rates causing spectral confusion when density/depth class differentiation was attempted. Accuracy was improved among the three broad classes, however, by changing the training class assignment of the isodata clusters in subsequent right class maximum likelihood classifications (Table 4). It is worth noting that some of the error was likely caused by small geographic offsets between Landsat scenes.

Table 4. Accuracy and spatial extent of eelgrass distribution during each step of the mapping process in embayments on the lower Alaska Peninsula.

Location	Number of Survey Points	Processing Stage [a]	Kappa Coefficient	Overall Accuracy (%)	Eelgrass Omission Accuracy (%)	Eelgrass Commission Accuracy (%)	Eelgrass Spatial Extent (ha)
Bering Sea							
Izembek Lagoon	267	Initial	0.693	82.77	88.96	92.36	17357
		Rationalized	0.722	84.60	88.60	94.20	16160
		Final	0.723	84.64	87.95	94.20	16816
Hook Bay	77	Initial	0.570	85.71	89.06	95.00	2469
		Rationalized	0.470	81.82	85.94	93.20	2511
		Final	0.470	81.82	85.94	93.20	2226
Gulf of Alaska							
Hostsprings Bay [b]	9	Initial	0.357	77.78	85.71	85.71	217
Big Lagoon	59	Initial	0.299	67.80	89.19	75.00	1128
		Rationalized	0.719	84.75	89.19	97.06	964
		Final	0.719	84.75	89.19	97.06	938
Middle Lagoon	34	Initial	0.534	73.53	73.68	87.50	230
		Rationalized	0.654	82.35	84.21	88.90	187
		Final	0.654	82.35	84.21	88.90	186
Littlejohn Lagoon	63	Initial	0.663	77.78	43.48	100.00	171
		Rationalized	0.832	88.89	86.96	83.33	163
		Final	0.832	88.89	86.96	83.33	162
Kinzarof Lagoon	171	Initial	0.188	46.78	54.64	71.62	832
		Rationalized	0.413	61.99	64.95	85.14	679
		Final	0.591	75.44	86.60	89.36	1129

[a] "Initial" = results of first maximum likelihood classification, "Rationalized" = best results from iterative classification process, "Final" = rationalized product with edits based on ShoreZone data and field knowledge; [b] This location was not rationalized using field data due to insufficient survey points.

The use of eight substrate classes during maximum likelihood classifications further reduced error along the substrate margins in the three class product, but the four eelgrass subclasses did not reliably differentiate between eelgrass density and depth classes. Early classification attempts using the iterative isodata clustering and maximum likelihood technique with just three classes produced statistically accurate results with overall accuracies around 70%, but a significant amount of "noise" was generated by single pixels classified as eelgrass that were scattered through areas classified as water or bare ground (and vice-versa). This "noise" was caused by radiance profiles for the three target classes that were too generalized to discern the small differences among the profiles of bare ground, sparse eelgrass and eelgrass when covered by water. To produce more tightly defined radiance profiles, eelgrass was subdivided into four classes while bare ground and water were subdivided into two classes (Figure 3). While acknowledging the difficulties caused by water, we tested the hypothesis that the four eelgrass subclasses represented a gradient of either eelgrass density or depth class as this would be valuable information for resource managers. However, field survey data indicated that high eelgrass densities were found in each of the sub-classes and, further, both dense eelgrass in deep areas and sparse eelgrass in shallow areas were included in the low and minimal NIR subclasses. This confirmed that the diminishing spectral radiance in NIR (and in the other bands) was due to the combination of increasing water depth and decreasing eelgrass density, and that the two could not be teased apart with the available datasets. These preliminary tests confirmed other research that documents the low accuracy of eelgrass density and depth subclasses and further suggests that maps with overall accuracy below 70% do not provide information accurate enough to serve as a monitoring tool [51,56], while other studies have established sound monitoring protocols using eelgrass areal extent as a first layer of data to be further informed by field surveys [9,35]. Therefore, we collapsed the eight classes into three (eelgrass, bare ground and water), eliminating almost all of the noise and producing a product that is sufficiently accurate for use by resource managers to detect changes to eelgrass distribution in a monitoring program.

4.2. Spatial Distribution Estimate Derived from Field Survey Data

Turbid coastal Alaskan waters caused detection problems resulting in underestimates of eelgrass in some areas. Even after refinements to methodology, a site depth of about −0.5 m MLLW seemed to be the effective limit for eelgrass detection using Landsat satellite imagery along the lower Alaska Peninsula. In Kinzarof Lagoon, a significant amount of the eelgrass occurred at depths below this threshold leading to poor results even after the rationalization process (Table 4). Review of the series of eelgrass extent estimates revealed that a "noisy" speckled pattern developed in the classified eelgrass distribution where subtidal eelgrass was present beyond detectable depths. We were able to correct estimates of eelgrass distribution in the problem area using interpolated field survey data (Figure 4). This solution may also be applicable in Hook Bay where eelgrass extent was also likely underestimated where this "noisy" speckle pattern was also apparent (Figure 7), especially in the southern portion of the bay where water depths exceeded −0.5 m. Unfortunately, foul weather prevented our survey of southern Hook Bay, causing incomplete coverage of the location and disallowing the use of the survey data for accurate interpolation.

4.3. Differentiation of Eelgrass from Seaweeds

We address the inaccuracy in distinguishing eelgrass from seaweeds, caused by Landsat's relatively coarse spectral resolution [58], through the use of contextual assessment, site familiarity gained during field surveys, and ancillary data obtained from the ShoreZone project. Where coastal morphology produced conditions favorable to the growth of eelgrass meadows, such as shallow waters in protected embayments with soft bottom substrates, we assumed all detected vegetation was eelgrass unless refuted by field knowledge or ShoreZone data. In a few cases we could use knowledge gained during investigative forays and on transit to and from survey sites to correct areas identified as seaweeds but classified as eelgrass based on spectral signal and context. Generally, these vegetated areas were located near embayment entrances, where substrates transitioned from soft to hard bottoms that favor seaweeds or in high (>1.0 m elevation) intertidal sand flats where blue-green algae and detrital eelgrass occurred. Corrections of these errors resulted in fairly minor changes in total eelgrass distribution, ranging from 1% in Middle Lagoon to 9% in Hook Bay (Table 3; Figures 4–7). Overall, these adjustments provided a more complete and accurate habitat description of the spatial relationship among substrate classes that will be more useful to resource managers monitoring for ecological change.

Use of ShoreZone data likely improved spatial estimates of eelgrass in embayments lacking field survey data given the high overall accuracy (90%; Appendix B) to detect the presence and absence of eelgrass. However, because we only tested the accuracy of ShoreZone at one location (Izembek Lagoon), we can only speculate as to its accuracy for differentiating eelgrass from seaweeds in other locations lacking field surveys. We suspect that the level of uncertainty associated with our use of ShoreZone data varied across locations depending on their similarity of physical characteristics relative to Izembek Lagoon, a protected Bering Sea location dominated by soft bottom substrates with high eelgrass densities (Table 3). Therefore, the most accurate use of ShoreZone data probably occurred in other nearby Bering Sea embayments known to have similar soft bottom substrates, shallow depths and high densities of eelgrass, such as Nelson Lagoon. Use of ShoreZone data may have been less accurate in locations with shallow, soft bottoms intermingled with deep areas and rock-cobble shoreline, such as Port Moller and Herendeen Bay, and least accurate in locations along the Gulf of Alaska coast between Bechevin and Cold bays, where hard bottom substrates and exposed beaches predominate and there is an increased likelihood for surfgrass, seaweeds and mixed eelgrass stands dominated by seaweeds (Table 3). ShoreZone data was a good temporal fit with the Landsat imagery we used for mapping our study area and we feel confident in the use of these data as an ancillary dataset. These data may reduce field survey costs associated with additional comprehensive studies to map spatial extent of eelgrass in other portions of Alaska where this seagrass is known to occur but is not mapped.

5. Conclusions

This study establishes baseline data for a program to monitor the distribution and characteristics of eelgrass meadows on the lower Alaska Peninsula. Using a hierarchical approach, we integrate coarse scale, remotely sensed data (Tier 1) that establishes the location and extent of seagrass meadows over broad areas with moderate resolution field survey data (Tier 2) to describe the physical and biological characteristics of a sample of seagrass meadows [35]. In doing so, we double the known spatial extent of eelgrass in the region and demonstrate the ability to accurately estimate the regional distribution and system-wide characteristics of eelgrass meadows. Our use of the hierarchical framework provides for an efficient and flexible monitoring program that takes advantage of the strengths of both remote sensing techniques and field survey data to meet the challenges of difficult access and adverse environmental conditions that persist in remote and undeveloped regions such as the lower Alaska Peninsula. We created eelgrass maps with relatively high overall accuracy (80%–90%) [51], as assessed by *in situ* field survey data, reflecting the practical utility of the maps for large-scale monitoring of eelgrass in the region. The maps were produced using well known classification methods in a unique iterative process that reduces error and dependence on field data in the mapping process, important considerations in a region where access is difficult and costly.

Our assessments of eelgrass meadow distribution and characteristics provide baseline datasets for a conservation monitoring plan for eelgrass in the region. Presuming that the relative long term stability of eelgrass extent in Izembek Lagoon [21] is representative of the study area, our eelgrass areal extent estimates provide an excellent baseline from which to monitor for Tier 1 change. The ability to detect a change in eelgrass spatial extent will depend on the natural variability in the eelgrass system and the accuracy of the Tier 1 assessment. If we assume that the natural variability is represented by the range in estimates of eelgrass spatial extent at Izembek (12%) [21] and the accuracy to detect eelgrass using coarse scale remotely sensed data is characterized by our error assessment (10%–25%), then a threshold of ≥20% in spatial extent at any location would likely indicate a real change in the distribution of eelgrass on the lower Alaska Peninsula. This threshold should not be considered static, but be subject to reassessments informed by the higher resolution Tiers 2 and 3 field survey data collected to better understand the nature and drivers of the change [35,41]. Change detection analyses would also provide maps of the specific location of the change and could serve to inform the design of Tiers 2 and 3 surveys. Given the current stability of eelgrass distribution in this region [21], a 5 to 10-year time interval should be appropriate before repeating large-scale (Tier 1) remote sensing assessments of eelgrass extent while a more frequent, 2- to 3-year time interval before repeating moderate scale (Tier 2) field surveys at a subset of points to detect changes in environmental and eelgrass conditions relative to potential stressors.

Acknowledgments

Funding and logistical support for the project were provided by the Izembek National Wildlife Refuge (NWR), Alaska Peninsula and Becharof NWR, U.S. Fish and Wildlife Service-Region 7 Migratory Bird Management, and U.S. Geological Survey. We are especially grateful to Nancy Hoffman and staff of Izembek NWR, Ron Britton and the crew of the R/V Aarluk, Orville Lind and Kevin Payne. Field collections would not be possible without the generous help of Bruce Casler, Lucretia Fairchild, Pat Harris, Sandra Lindstrom, and Kristine Sowl. The use of trade or product names is for descriptive purposes only and does not constitute endorsement by the U.S. Government. This paper benefited from reviews by John Pearce and Mandy Lindberg.

Author Contributions

Kyle R. Hogrefe was the primary author of this manuscript, conducted much of the field research, analyzed the imagery, created the maps and summarized spatial data. David H. Ward led the research, contributed to the text, and conducted much of the field research. Tyrone F Donnelly and Niels Dau contributed significantly to the field research and data processing and provided editorial comment on the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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Appendix A

Accuracy assessments were conducted using confusion matrix analysis to compare habitat classifications derived from Landsat imagery to field survey information. Four assessments were made: (1) Omission accuracy, or the percent of classified substrates that matched the substrates observed in the field, was calculated by dividing the number of field survey points that agreed with the classified data by the total number of field survey points for that substrate, and mutiplying by 100; (2) Commission accuracy was derived in a similar fashion, but makes the presumption that the classified substrate is correct; (3) Total percent correct (in bold within tables) was calculated by dividing the number of all survey points that agreed with the classified data, regardless of substrate class, by the total number of survey points for the area, and mutiplying by 100; and (4) Kappa coefficient (*k*) is similar to total percent correct but it accounts for potential random agreement between the datasets so that it is a more conservative measure of accuracy (see Foody 2002 for calculation).

Table A1. Initial classification of habitats in Izembek Lagoon.

Map Data	**Field Survey Reference Data**						***k* = 0.69**
	Eelgrass	**Bare Ground**	**Water**	**Total Correct**	**Total Points**	**% Correct (Commission)**	
Eelgrass	145	3	9		157	92.4	
Bare	17	40	9		66	60.6	
Water	1	7	36		44	81.8	
Total Correct				221			
Total Points	163	50	54		267		
% Correct (Omission)	89.0	80.0	66.7			**82.8**	

Table A2. Final product for classification of habitats in Izembek Lagoon.

Map Data	Field Survey Reference Data						*k* = 0.72
	Eelgrass	Bare Ground	Water	Total Correct	Total Points	% Correct (Commission)	
Eelgrass	146	3	6		155	94.2	
Bare	18	41	9		68	60.3	
Water	2	7	39		48	81.3	
Total Correct				226			
Total Points	166	51	54		267		
% Correct (Omission)	88.0	80.4	72.2			**84.6**	

Table A3. Initial classification of habitats in Hook Bay.

Map Data	Field Survey Reference Data						*k* = 0.57
	Eelgrass	Bare Ground	Water	Total Correct	Total Points	% Correct (Commission)	
Eelgrass	57	2	1		60	95.0	
Bare	2	3	1		6	50.0	
Water	5	0	6		11	54.5	
Total Correct				66			
Total Points	64	5	8		77		
% Correct (Omission)	89.1	60.0	75.0			**85.7**	

Table A4. Final product for classification of habitats in Hook Bay.

Map Data	Field Survey Reference Data						*k* = 0.47
	Eelgrass	Bare Ground	Water	Total Correct	Total Points	% Correct (Commission)	
Eelgrass	55	2	2		59	93.2	
Bare	4	3	1		8	37.5	
Water	5	0	5		10	50.0	
Total Correct				63			
Total Points	64	5	8		77		
% Correct (Omission)	85.9	60.0	62.5			**81.8**	

Table A5. Initial classification of habitats in Hotsprings Bay.

Map Data	Field Survey Reference Data						*k* = 0.36
	Eelgrass	Bare Ground	Water	Total Correct	Total Points	% Correct (Commission)	
Eelgrass	6	1	0		7	85.7	
Bare	1	1	0		2	50.0	
Water	0	0	0		0	NA	
Total Correct				7			
Total Points	7	2	0		9		
% Correct (Omission)	85.7	50.0	NA			**77.8**	

Table A6. Initial classification of habitats in Big Lagoon.

Map Data	Field Survey Reference Data						$k = 0.30$
	Eelgrass	Bare Ground	Water	Total Correct	Total Points	% Correct (Commission)	
Eelgrass	33	11	0		44	75.0	
Bare	3	7	3		13	53.8	
Water	1	1	0		2	0.0	
Total Correct				40			
Total Points	37	19	3		59		
% Correct (Omission)	89.2	36.8	0.0			**67.8**	

Table A7. Final product for classification of habitats in Big Lagoon.

Map Data	Field Survey Reference Data						$k = 0.72$
	Eelgrass	Bare Ground	Water	Total Correct	Total Points	% Correct (Commission)	
Eelgrass	33	1	0		34	97.1	
Bare	2	14	0		16	87.5	
Water	2	4	3		9	33.3	
Total Correct				50			
Total Points	37	19	3		59		
% Correct (Omission)	89.2	73.7	100.0			**84.7**	

Table A8. Initial classification of habitats in Middle Lagoon.

Map Data	Field Survey Reference Data						$k = 0.53$
	Eelgrass	Bare Ground	Water	Total Correct	Total Points	% Correct (Commission)	
Eelgrass	14	2	0		16	87.5	
Bare	2	11	0		13	84.6	
Water	3	2	0		5	0.0	
Total Correct				25			
Total Points	19	15	0		34		
% Correct (Omission)	73.7	73.3	NA			**73.5**	

Table A9. Final product for classification of habitats in Middle Lagoon.

Map Data	Field Survey Reference Data						$k = 0.65$
	Eelgrass	Bare Ground	Water	Total Correct	Total Points	% Correct (Commission)	
Eelgrass	16	2	0		18	88.9	
Bare	3	12	0		15	80.0	
Water	0	1	0		1	0.0	
Total Correct				28			
Total Points	19	15	0		34		
% Correct (Omission)	84.2	80.0	NA			**82.4**	

Table A10. Initial classification of habitats in Littlejohn Lagoon.

Map Data	**Field Survey Reference Data**						***k* = 0.66**
	Eelgrass	**Bare Ground**	**Water**	**Total Correct**	**Total Points**	**% Correct (Commission)**	
Eelgrass	10	0	0		10	100.0	
Bare	4	15	0		19	78.9	
Water	9	1	24		34	70.6	
Total Correct				49			
Total Points	23	16	24		63		
% Correct (Omission)	43.5	93.8	100.0			**77.8**	

Table A11. Final product for classification of habitats in Littlejohn Lagoon.

Map Data	**Field Survey Reference Data**						***k* = 0.83**
	Eelgrass	**Bare Ground**	**Water**	**Total Correct**	**Total Points**	**% Correct (Commission)**	
Eelgrass	20	1	3		24	83.3	
Bare	3	15	0		18	83.3	
Water	0	0	21		21	100.0	
Total Correct				56			
Total Points	23	16	24		63		
% Correct (Omission)	87.0	93.8	87.5			**88.9**	

Table A12. Initial classification of habitats in Kinzarof Lagoon.

Map Data	**Field Survey Reference Data**						***k* = 0.19**
	Eelgrass	**Bare Ground**	**Water**	**Total Correct**	**Total Points**	**% Correct (Commission)**	
Eelgrass	53	27	1		74	71.6	
Bare	9	5	0		24	20.8	
Water	35	19	22		73	30.1	
Total Correct				80			
Total Points	97	51	23		171		
% Correct (Omission)	54.6	9.8	95.7			**46.8**	

Table A13. Rationalized product for classification of habitats in Kinzarof Lagoon.

Map Data	**Field Survey Reference Data**						***k* = 0.41**
	Eelgrass	**Bare Ground**	**Water**	**Total Correct**	**Total Points**	**% Correct (Commission)**	
Eelgrass	63	10	1		74	85.1	
Bare	3	21	0		24	87.5	
Water	31	20	22		73	30.1	
Total Correct				106			
Total Points	97	51	23		171		
% Correct (Omission)	64.9	34.4	95.7			**62.0**	

Table A14. Final product for classification of habitats in Kinzarof Lagoon.

Map Data	**Field Survey Reference Data**						***k* = 0.59**
	Eelgrass	**Bare Ground**	**Water**	**Total Correct**	**Total Points**	**% Correct (Commission)**	
Eelgrass	84	9	1		94	89.4	
Bare	5	23	0		28	82.1	
Water	8	19	22		49	44.9	
Total Correct				129			
Total Points	97	51	23		171		
% Correct (Omission)	86.6	45.1	95.7			**75.4**	

Appendix B

The accuracy of ShoreZone data to detect presence or absence of eelgrass was assessed at Izembek Lagoon because no other location had coincidental field survey and ShoreZone data with a tightly matched coastline (offset <90 m). To prepare the data sets we initially converted the classified eelgrass distribution derived from ground-truthed Landsat imagery from raster areal data to vector point data and created a 60 m buffer around the linear eelgrass distribution downloaded from ShoreZone. We then compared habitat classification between ShoreZone and Landsat data using a confusion matrix analysis (see Appendix A) where the datasets were considered in agreement if a linear segment contained at least one eelgrass point in common with its buffered area and in disagreement if no points fell within the buffer. We also assumed that eelgrass distribution did not change significantly between the collections of the ShoreZone (May 2011) and the Landsat data (two images: August 2002 and July 2006) in Izembek Lagoon.

Table B1. Accuracy assessment of ShoreZone eelgrass detection in Izembek Lagoon.

ShoreZone Data	**Classified Landsat TM Data**					***k* = 0.74**
	Eelgrass Present	**Eelgrass Absent**	**Total Correct**	**Total Points**	**% Correct (Commission)**	
Eelgrass Present	148	9		157	94.3	
Eelgrass Absent	14	50		64	78.1	
Total Correct			198			
Total Segments	162	59		221		
% Correct (Omission)	91.4	84.7			**89.6**	