



Coastal Change Maps of Bering Land Bridge National Preserve and Cape Krusenstern National Monument, 1980 - 2014

Natural Resource Report NPS/ARCN/NRR—2020/2152



ON THE COVER

Eroding permafrost bluff along the north coast of the Bering Land Bridge National Preserve (BELA) between Espenberg and the Kitluk River. This is the shore with most actively eroding coastal permafrost bluffs in BELA. Note the ice (whitish colors) at the bottom of the escarpment, and the shaded notch below where waves have undermined the sediments by thermoerosion (combined erosion and thaw). The beach is narrow here, allowing constant wave action against the scarp. Ice-wedge polygons are visible on the tundra flat above the escarpment. Shorezone photo (www.shorezone.org) nw12_kz_05183 (latitude 66° 35' 9" N, longitude 164° 16' 15" W, 19 July 2012).

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Abstract

The Bering Land Bridge National Preserve (BELA) and Cape Krusternstern National Monument (CAKR) have about 350 km (220 miles) of coastline. These coastal areas are rich in natural and cultural resources, and they are the most frequently visited parts of the parks. The National Park Service (NPS) Arctic Inventory and Monitoring Network (ARCN) monitors coastal change in BELA and CAKR with aerial photographs and satellite images. Rates of coastal erosion, and associated threats to resources, vary greatly from place to place. A set of 35 maps at a scale of 1:40,000 on 8.5” x 14” pages has been created to portray in detail the rates of coastline erosion or accretion, and areas where vegetation has been gained or lost, in the time period leading up to our most recent imagery of the area, 2013-2014. The maps are available for download in pdf file format from <https://irma.nps.gov/DataStore/Reference/Profile/2260273> (Swanson 2020). These maps provide a summary of coastal change that is readily accessible to park managers for assessment of threats to resources. Annotations on the maps highlight significant changes and explain the processes involved.

Acknowledgments

This study was funded by the NPS Inventory and Monitoring Program. The geographic data used in this report was prepared by multiple people at different times. Leanne R. Lestak and William F. Manley of the University of Colorado orthorectified the imagery used in the first three time periods, set up the Digital Shoreline Analysis System (DSAS) database for the outer coastline, and digitized the water lines for the first three time periods. The DSAS tools were created by the Woods Hole Coastal and Marine Science Center of the U.S. Geological Survey. Louise M. Farquharson originated our concept of the coastal “erosion line” and digitized it for the outer coast, using imagery orthorectified by Manley and Lestak plus satellite images obtained free of charge through the Commercial Remote Sensing Space Policy (CRSSP). Celia Miller assisted in orthorectification and analysis of the most recent imagery. Thanks to Peter Neitlich, Katie Cullen, and Guadalupe Zaragoza for review comments.

Introduction

The coastlines of Bering Land Bridge National Preserve (BELA) and Cape Krusenstern National Monument (CAKR) are extensive, and they are the most heavily used and culturally important parts of these National Park Units (Figure 1). The outer coast alone (not counting lagoon shores or inlets) is about 250 km (156 miles) long in BELA and 100 km (63 miles) long in CAKR. These coastlines have always been dynamic systems, and in connection with the reduction in the length of time each year when the coastline is protected from wave action by sea ice (Farquharson et al. 2018), park managers are concerned that erosion rates could be increasing and threatening cultural and natural resources. The National Park Service (NPS) Arctic Inventory and Monitoring Network (ARCN) monitors changes in the coastline of these two parks as a part of its Coastal Change vital sign (Manley and Lestak 2012).

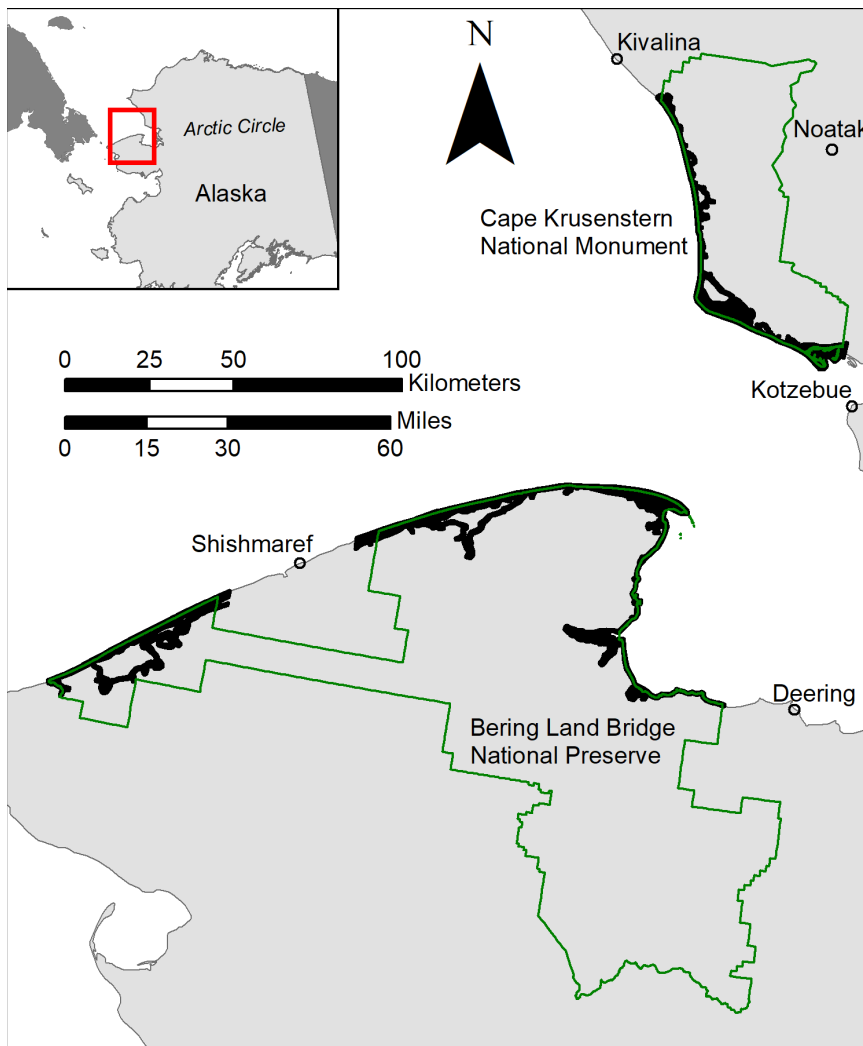


Figure 1. The study area is the coastlines of Bering Land Bridge National Preserve and Cape Krusenstern National Monument. The study area, highlighted in black, includes recent marine-deposited sediments and the wave-eroded escarpments of adjacent uplands.

Much of the coastlines of BELA and CAKR consist of sandy or gravelly barrier island-spit complexes that front the open ocean of the Chukchi Sea, with lagoons behind (Figure 2). In some places the outer coast is a beach in front of low bluffs consisting of permanently frozen sediments (Figure 3). The lagoons are mostly bordered by salt marshes (Figure 4), though along the shore of the mainland the marsh is a very narrow fringe that is bordered by low bluffs made of sediments with permafrost (Figure 5). Bedrock is exposed along the shoreline in BELA only on the far southeastern coast (Figure 6). In CAKR bedrock is present the north side of Krusenstern Lagoon, and one bluff on the outer shoreline north of Tasaychek Lagoon. Estuaries with salt marsh that grade upstream into brackish marshes and then freshwater riparian wetlands and moist tundra are present at the mouths of river and creeks (Figure 7). The photos in Figures 2 through 7 are from the Shorezone (2019) coastal mapping project (www.shorezone.org).

The information generated by the ARCN coastal change monitoring program has to date consisted of digital shoreline positions for the outer coast: shores that front on open ocean, as opposed to the lagoons. These data are stored in the form of geographic information system (GIS) digital files, and have been summarized in journal articles (Gorokhovich and Leiserowiz 2012, Farquharson et al. 2018).

NPS managers and scientists have expressed interest in coastal change along shorelines of lagoons, in addition to the outer coast. They have also expressed interest in detailed maps depicting the erosion rates at all locations in the two parks.



Figure 2. Barrier island shoreline of BELA. Bordering the sand beach are sand dunes partly covered by grass. Behind these is salt marsh, and Cowpack lagoon is visible in the background. Shorezone (2019) photo nw12_kz_05508.jpg (latitude 66° 29'23" N, longitude 165° 2' 4" W, 19 July 2012).



Figure 3. Eroding permafrost bluff along the north coast of BELA between Espenberg and the Kitluk River. This is the shore with most actively eroding permafrost bluffs in BELA. Note the ice (whitish colors) at the bottom of the escarpment, and the shaded notch below where waves have undermined the sediments by thermoerosion (combined erosion and thaw). The beach is narrow here, allowing constant wave action against the scarp. Ice-wedge polygons are visible on the tundra flat above the escarpment. Shorezone (2019) photo nw12_kz_05183 (latitude 66° 35' 9" N, longitude 164° 16' 15" W, 19 July 2012).



Figure 4. Salt marsh behind barrier island, along Cowpack Lagoon in BELA Shorezone (2019) photo nw12_kz_00986 (66 26' 19" N, 165 11' 37" W, 18 July 2012).



Figure 5. Inland margin of Cowpack Lagoon in BELA. A narrow band of salt marsh is present along a low vegetated escarpment. The tundra behind is above the reach of salt water and has ice-rich permafrost, as shown by the ice-wedge polygons. A pair of tundra swans (*Cygnus columbianus*) is visible on the marsh. Shorezone (2019) photo nw12_kz_01596 (latitude 66° 26' 7" N, longitude 165° 8' 3" W, 18 July 2012).



Figure 6. Coastline with bedrock cliffs in Goodhope Bay in BELA. The light-colored birds in the air and on the rocks are black-legged kittiwakes (*Rissa tridactyla*), a seabird in the gull family. Shorezone (2019) photo nw12_kz_03504, latitude 66° 3' 58" N, longitude 163° 12' 25" W, 19 July 2012.



Figure 7. The Goodhope River estuary (BELA). The main channel of the river (right) winds through intricately patterned salt marsh. Shorezone (2019) photo nw12_kz_03907 (latitude 66° 4' 31" N, longitude 163° 44' 11" W, 19 July 2012).

The present report has two purposes: 1) to augment the data that has been collected to date with some additional measures of coastal change that NPS managers and scientists have requested, and 2) to present the data in the form of pre-formatted maps that can be easily referenced by managers and other interested people. The new measures of coastal change presented here are digital shorelines for lagoons (previously we digitized only the outer coast), and maps documenting the change in area covered by vegetation in the coastal zone. Our results are presented in the form of maps in portable document format (pdf), with annotations that point out and discuss important features.

Methods

Imagery

This study is based on four groups of imagery: 1) 1:43,000-scale panchromatic aerial photographs taken from 1949 to 1956 and orthorectified by Manley and Lestak (2012); 2) 1:60,000 Alaska High-Altitude Program (AHAP) color-infrared aerial photographs taken between 1978 and 1985, and orthorectified by Manley and Lestak (2012); 3) 1:24,000-scale color photographs taken and orthorectified by AeroMetric Inc. in 2003; and 4) Worldview-2 satellite imagery from 2013 and 2014 (by Satellite Imaging Corporation, <https://www.satimagingcorp.com/>; 1.86 m resolution in red, green, blue, and near-infrared; 0.46 m resolution pan-sharpened), orthorectified by NPS using the IfSAR 5 m resolution digital elevation model (Alaska Geospatial Council 2016). The quantitative analyses portrayed on the maps were based on the latter three image groups, and the locations covered by each year are given in Fig. 8. For brevity's sake the 1978-1985 AHAP imagery is referred to as “c. 1980” and the 2013-2014 Worldview-2 (mostly 2014) as “2014”.

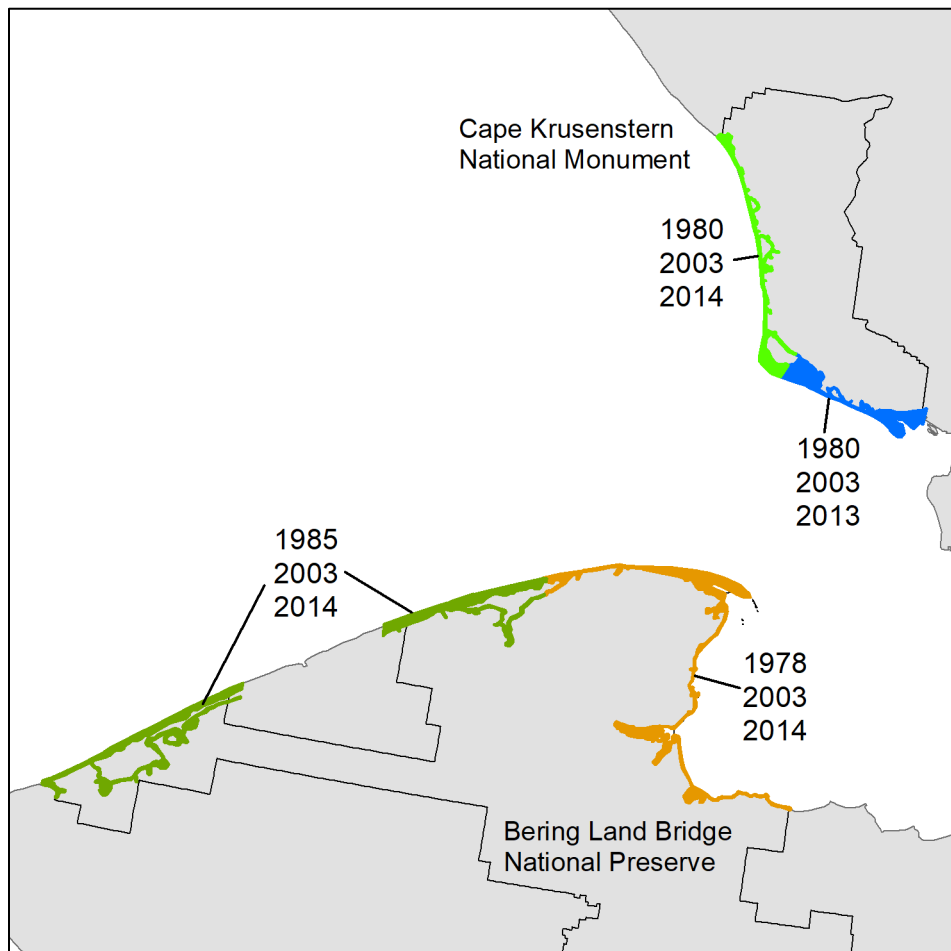


Figure 8. Years of imagery used in this study.

Shorelines

The rates of shoreline change portrayed on the maps are based on the most recent two imagery dates, 2003 and 2013-2014. Along the outer coast, the shoreline used was the “erosion line” developed by Farquharson (2017 and Farquharson et al. 2018). The erosion line was, where possible, identified by the distinct topographic escarpment between the beach and higher ground behind, usually a dune or low bluff of frozen sediments. Where a distinct scarp was absent but there was an obvious break between beach and vegetated land that could be attributed to erosion, the shoreline was defined there. Care was taken to be consistent about the feature used to define the shoreline in different years at any given location. No erosion line was defined where there was a gradual transition to vegetation, or an irregular vegetation boundary associated with tongues of deposited sediment. The erosion lines were digitized by hand by Farquharson (2017) and D. Swanson, with the screen display zoomed to a scale of 1:3,000.

Along the lagoon shores, the shoreline was defined as the boundary between dense vegetation and either water or mud. This boundary was distinct in most areas and digitized by D. Swanson at a screen display scale of 1:3,000.

The change in position of these shorelines between 2003 and 2013-2014 was analyzed by intersecting the shoreline with transects oriented perpendicular to the shore using DSAS software (Himmelstoss et al. 2018). The transects were spaced at intervals of 50 m. The distance of shoreline change along the transects was converted to meters per decade, and used to create color-coded bars that were plotted on the maps with length proportional to the rate of change.

Previous studies of ARCN shoreline change (Manley and Lestak 2012, Gorokhovich and Leiserowiz 2012, Gibbs 2019) used the position of the waterline on the beach, digitized from the imagery from the first three available image dates (c. 1950, c. 1980, and 2003). I chose to use the erosion line after Farquharson et al. (2018) because it is less subject to temporary differences in water level, and it better portrays the reach of erosional forces that are of interest to management of coastal resources. I used the vegetation line rather than water line in the lagoons for the same reasons. Erosion rates changed between time periods (Farquharson et al. 2018), and thus to most accurately estimate the current rate of change, I portrayed on the maps rate computed from change between the two most recent image dates (2003 and 2013-2014). All three shoreline types, the “water line” and “erosion line” on the outer coast, and the “vegetation line” on the lagoons, are available for all imagery dates as GIS files (<https://irma.nps.gov/DataStore/Reference/Profile/2263667>).

Vegetation change

I created maps of vegetation presence/absence using the c. 1980 AHAP color-infrared orthophotos and the 2013-2014 satellite images. I differenced the maps from the two dates, and areas that gained or lost vegetation cover between the two dates are portrayed on the downloadable maps (Swanson 2020). I used the c. 1980 AHAP photos rather than the 2003 aerial photos because the c. 1980 photos are color-infrared photos, which are more reliable for recognizing vegetation than the “true-color” (red-green-blue) 2003 photos. The vegetation presence/absence maps were created from the imagery by 1) segmentation (locating small homogenous areas on the images); 2) training (identifying example segments that were vegetated or un-vegetated - sand, mud, water); and 3) classification

(labeling the unknown segments by matching them to training segments). The classification technique used was k-nearest neighbor (knn). By this method, the training segments that are spectrally most similar to an unknown segment were located; these were the “nearest neighbors”. I used the 3 nearest neighbors, weighted by the inverse of the distance: the Euclidean distance in spectral space for 3 dimensions (the green, red, and near-infrared spectral bands) for the AHAP photos and 4 dimensions (blue, green, red, and near-infrared) for the Worldview-2 images. Then the majority classification, either vegetated or not, of the 3 nearest neighbors was assigned to each unknown segment. To avoid false change detection, I only used segments where the probability of the “winning” class was at least 0.8. See the Results for discussion of how this value was chosen.

The detailed steps are given below. The scripts referred to are available for download at the same location as the maps (<https://irma.nps.gov/DataStore/Reference/Profile/2260273>). The asterisks (*) in the script names listed below are replaced by “BELA_AHAP”, “BELA_WV2”, “CAKR_AHAP”, or “CAKR_WV2” to cover all combinations of park and imagery. All analyses were completed in ArcGIS, and in R (R Core Team 2017) using the Raster package (Hijmans 2015) and the kkn package (Schliep and Hechenbichler 2016).

1. Mask the images to the study area (a strip along the coast). See `Rcode_mask*.txt`.
2. Segment the images using the ArcGIS mean shift segmenting tool with spectral detail of 20, spatial detail of 18, and minimum segment size of 200 m². The spatial and spectral detail values are internal ArcGIS parameters that are not defined in relation to the standard parameters of the mean-shift algorithm. They were chosen by trial and error to produce segmented images that were somewhat finer than the desired final product, and adjacent segments with the same class were merged in the final output. See `run_arcpy__segment*.py`.
3. Compute segment attributes using the ArcGIS Compute Segment Attributes tool. See `run_arcpy_compute_seg_attr*.py`. This operation overlays the segments onto the original image and computes the average of the 3 (AHAP) or 4 (WV2) wavelength bands for the segment, saving the result in the raster attribute table.
4. Digitize training points representing the range of vegetated and non-vegetated segments on all of the images, and label them as vegetated or unvegetated.
5. For each segmented image, extract the data for the segments with training points and use these to classify the remaining segments using the k nearest neighbor classifier from the R `kkn` package (Schliep and Hechenbichler 2016) with $k=3$, Euclidean distance, and inverse distance weighting. The class and probability value were saved to the attribute table. The classification routine runs on the raster attribute table created in step 3. See `Rcode_veg*.txt`.
6. Run the Spatial Analyst lookup tool to write the classification to rasters, masking out the pixels with less than 80% certainty as No Data (0). The rasters were coded -1 for unvegetated (land or water) and +1 for vegetated). See `run_arcpy_lookup_vat*.py`.

7. Create ArcGIS mosaics for all of the WV2 and AHAP scenes, and then difference the two using ArcGIS Raster Calculator. The possible results are: -2 changed from vegetated to non-vegetated; -1 change from no-data to non-vegetated; 0 no change, or no-data on both dates; +1 change from no-data to vegetated; and +2 change from non-vegetated to vegetated.
8. Generalize the change raster by aggregating from 1 m resolution to 2 m resolution and computing the sum of the 4 aggregated pixels. The result ranged from -8 (all four pixels went from vegetated to unvegetated) to +8 (all four pixels went from unvegetated to vegetated). A sum of 6 could result from a sum of $2 + 2 + 2 + 0$ (three pixels changed from non-vegetated to vegetated, the fourth did not change) or $2 + 2 + 1 + 1$ (two pixels changed from non-vegetated to vegetated, two from uncertain status to vegetated).
9. Reclassify the sums on the 2 m resolution raster as follows: sum of 6, 7, or 8 to +1 (vegetation gain); sum of -6, -7, or -8 to -1 (vegetation loss); all others to no data.
10. Smooth the raster with the ArcGIS Boundary Clean tool, using the “NO_SORT TWO_WAY” option.
11. Convert the raster to polygons.
12. Delete all polygons with areas of less than 400 m².

Error Analysis

I used leave-one-out cross-validation to choose the classification parameters and estimate the error rate. By this technique, each training segment is removed from the training set and classified by the knn method using the remaining segments. I tested values for k of 1 to 5, and inverse distance weighting vs. no distance weighting. This error analysis is present in the Results below.

Map Production

I created pre-formatted maps at 1:40,000 scale and 8.5” by 14” page size that cover the coastline of both park units. The rates of shoreline migration, in meters per decade between 2003 and 2013-2014, are shown using color-coded bars along the shoreline wherever shoreline data from both times was available. The bars are plotted along the DSAS transects where the measurements were made; the transect are spaced at intervals of 50 m. The lengths of the bars are proportional to the rate of change: the bar lengths in meters are 100 times the annual rate of change in meters. Yellow to red colors indicate loss of land (erosion) while green and blue colors indicate gain of land (accretion).

The areas with vegetation gain or loss between the c 1980 AHAP aerial photographs and the 2013-2014 Worldview-2 satellite images are portrayed as color-coded polygons. The vegetation change mapping covers all of the barrier islands and spits, and extends about 400 inland from the edge of the lagoons or outer ocean if there was no lagoon. I added comments to point out features of interest on the maps and provide explanation of the features.

The backdrop layer for the maps is a natural color statewide satellite mosaic (Alaska Geospatial Council 2011).

Results

The coastal processes of erosion and deposition, and vegetation loss and vegetation gain, have been active in both parks. The dominant process is highly specific by location, and few generalizations can be drawn. To see the results for an area of interest, consult the index map for BELA (Figure 9) or CAKR (Figure 10) to locate the map sheet that covers the area of interest, downloadable from <https://irma.nps.gov/DataStore/Reference/Profile/2260273> (Swanson 2020). Coastal retreat rates of over 20 m (66 feet) per decade were present on some portions of the outer coast in both parks, and erosion could locally affect park resources. Rates of coastal change were generally lower in the inner shores of lagoons and salt marshes. In spite of widespread coastal retreat, there was apparently a net gain in vegetation area in BELA: the sum of area of vegetation loss depicted on the maps was 530 ha, compared to 707 ha of vegetation area gained. In CAKR, vegetation loss (388 ha) exceeded vegetation gain (101 ha).

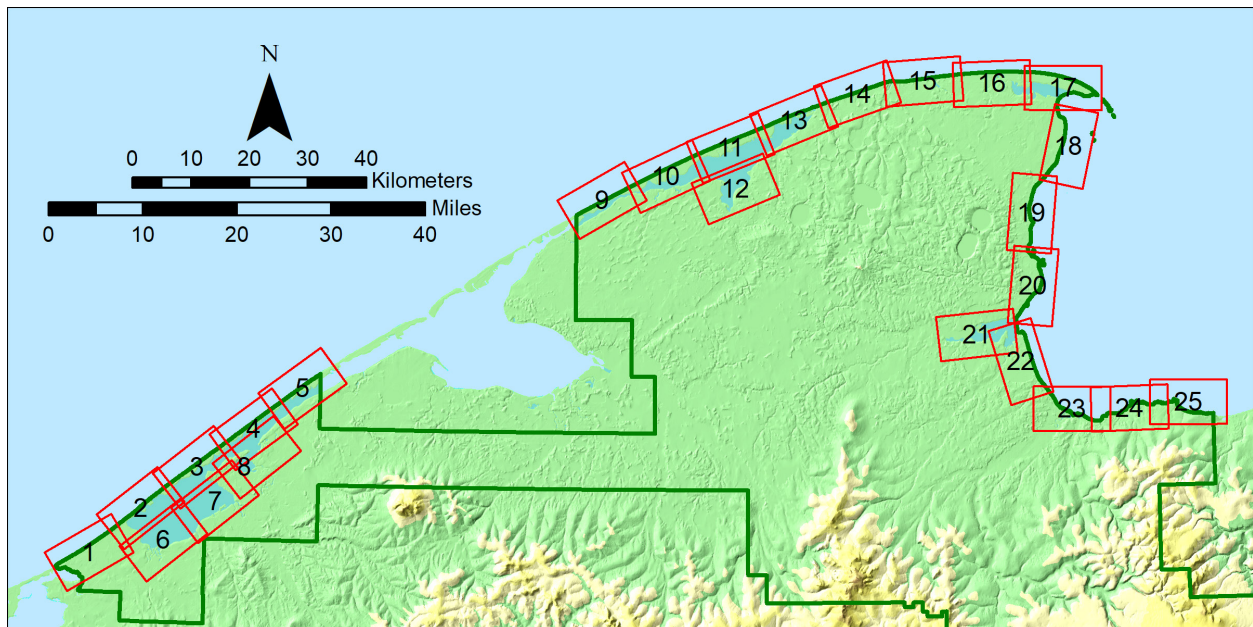


Figure 9. Index map for the 1:40,000 scale map sheets of Bering Land Bridge National Preserve coastal change, available for download at <https://irma.nps.gov/DataStore/Reference/Profile/2260273>.

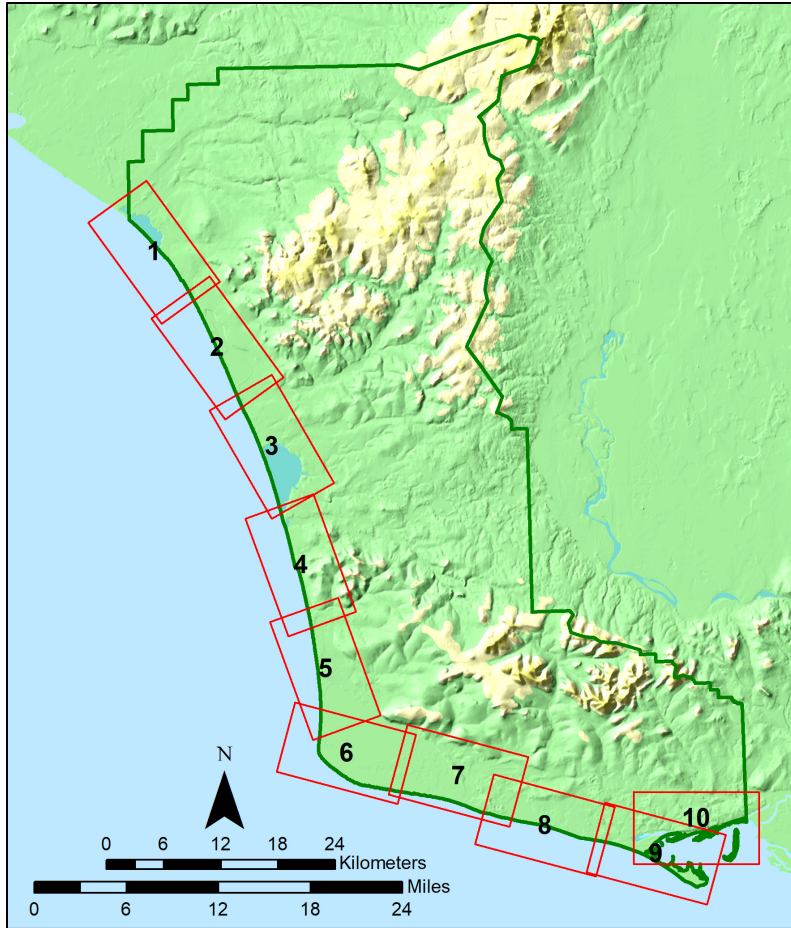


Figure 10. Index map for the 1:40,000 scale map sheets of Cape Krusenstern National Monument coastal change, available for download at <https://irma.nps.gov/DataStore/Reference/Profile/2260273>.

Error analysis

Error rates, based on leave-one-out cross-validation of the training data and averaged across all the images used, ranged from 0.1 to 1.2% for the various combinations of NPS unit, image source, k , and distance weighting method (Table 1; k is the number of nearest neighbors used in the classification). Inverse distance weighting produced equal or better results than no weighting (“rectangular” weighting) in all cases. The error rate generally decreased slightly from $k = 1$ to $k = 5$ for AHAP and increased from $k = 1$ to $k = 5$ for Worldview-2. I chose $k = 3$ as a compromise value. A k greater than one was needed to produce probability values, which were useful for screening out uncertain classifications, as will be shown below.

Table 1. Average error rate (%) with different k nearest neighbor (knn) classification parameters

Image Set	k^1	Distance Weighting Method ²	
		Rectangular	Inverse
BELA AHAP	1	0.89	0.89
BELA AHAP	2	1.09	0.89
BELA AHAP	3	0.88	0.80
BELA AHAP	4	1.02	0.80
BELA AHAP	5	0.97	0.77
BELA AHAP	All	0.97	0.83
BELA WV2	1	0.19	0.19
BELA WV2	2	0.40	0.19
BELA WV2	3	0.44	0.24
BELA WV2	4	0.46	0.31
BELA WV2	5	0.64	0.34
BELA WV2	All	0.43	0.25
CAKR AHAP	1	0.13	0.13
CAKR AHAP	2	0.34	0.13
CAKR AHAP	3	0.30	0.07
CAKR AHAP	4	0.41	0.07
CAKR AHAP	5	0.35	0.13
CAKR AHAP	All	0.31	0.11
CAKR WV2	1	0.62	0.62
CAKR WV2	2	0.53	0.62
CAKR WV2	3	0.91	0.79
CAKR WV2	4	1.24	0.79
CAKR WV2	5	1.12	0.87
CAKR WV2	All	0.88	0.74

¹Number of nearest neighbors used by the knn classifier

²Rectangular – all nearest neighbors receive the same weight; Inverse – nearest neighbors are weighted by $1/d$ where d is the Euclidean distance to the neighbor in spectral space. Values in boldface type are the settings used to produce the maps: $k = 3$ and Inverse distance weighting.

The k nearest neighbor classifier of Schliep and Hechenbichler (2016) provides a probability value for each class. Because the “votes” of the three nearest neighbors are weighted by distance, p -values

are not restricted to 0, 1/3, 2/3, and 1 as they would be with an unweighted classifier. For example, if the two nearest neighbors are very similar to the test segment (i.e. very close in spectral space) and have the same class “vegetated”, while the third nearest neighbor is less similar and has a conflicting class “unvegetated”, the p -value for “vegetated” could be more than 0.9. Inspection of misclassified training segments revealed that many of them had probability values that suggested uncertainty in the classification (i.e. a p of less than 1.0, because the three nearest neighbors were not all the same), while the correctly classified segments were usually unanimous ($p = 1$, all three neighbors were the same). I chose a p -value of 0.8 as a threshold value: segments where the probability of the most likely class was less than 0.8 were removed from the change detection analysis, i.e. treated like “no data”. I chose 0.8 rather than 0.95 or 1 because I did not want to force too many Type II errors (failure to accept segments that were properly classified). Adding the $p > 0.8$ criterion reduced the Type I (simple misclassification) error rates by about half or better, at the cost of excluding less than 2% of properly mapped segments (Table 2). A trial with the more stringent condition of $p = 0.95$ did not improve the Type I error rates, while slightly increasing the number of properly mapped segments that were excluded.

Table 2. Error Rate in percent for training data, with and without removal of low-probability segments

Image Set	All segments Type I errors, %		Segments with $p > 0.8$ Type I errors, %		Segments with $p > 0.8$ Type II errors, %	
	Unvegetated	Vegetated	Unvegetated	Vegetated	Unvegetated	Vegetated
BELA AHAP	0.98	0.75	0.25	0.30	1.34	1.01
BELA WV2	0.16	0.21	0.00	0.21	0.96	0.36
CAKR AHAP	0.18	0.10	0.00	0.00	0.18	0.10
CAKR WV2	0.64	0.59	0.00	0.30	1.50	0.74

While this error analysis suggests the vegetation maps could be as much as 99% accurate, users should bear in mind that false changes are still portrayed on the maps. Sources of error include: 1) the training areas were manually photo-interpreted to represent good examples of unvegetated and vegetated areas, while the set of all segments undoubtedly includes various transitional areas or types that are not well represented in the training sets. 2) Some wet areas were mapped as unvegetated (water) in at one time and vegetated at the other time actually were marshy vegetation in both cases, with minor changes in water level or differences in optical characteristics of the imagery were responsible for the apparent vegetation change. 3) Map registration error produced false vegetation change. For example, a registration error resulting in a shift of a few meters could cause an island to show “loss” of a strip of vegetation on one side and “gain” on the other. 4) Differencing two maps compounds the errors. For example, if an area of vegetation that showed no change between two dates is mapped with a 1% error rate (i.e. 1% of the area was erroneously classified as unvegetated), and we overlay a map from the second date with the same error rate, and if the errors are randomly distributed, the difference map will show $0.99 \times 0.99 = 0.9801$ (98%) as unchanged vegetation

(correct), $0.01 \times 0.99 = 0.0099$ (1%) as changed from vegetated to unvegetated (error), $0.01 \times 0.99 = 0.0099$ (1%) as changed from unvegetated to vegetated (error), and $0.01 \times 0.01 = 0.0001$ (0.01%) as no change due to an error at both times. Thus about 2% of the landscape would erroneously show vegetation change. In an area where vegetation is rather stable and real change amounts to only a few percent of the landscape area, the area of falsely mapped changes could thus rival the “real” vegetation change, even if the underlying maps are very accurate (i.e. error rates of only 1%).

Thus even given the high accuracy of these maps, it is important to avoid assuming every small mapped patch of vegetation change on the map is “real”. Larger patches of vegetation loss or gain, particularly if they coincide with areas where digitized shorelines indicate coastal change, probably represents true vegetation gain or loss.

Conclusions

Mapping of coastline movement by the USGS DSAS system yielded estimates of rates of coastal advance or retreat that will be useful in assessing threats to resources due to erosion. Mapping of vegetated and unvegetated areas using color-infrared aerial photographs from c. 1980 and high-resolution multispectral satellite images from 2013-2014 revealed areas of both vegetation loss by erosion and gain by vegetation expansion onto newly deposited sediments.

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