UNIVERSITY OF PUERTO RICO
MAYAGUEZ COLLEGE CAMPUS
FACULTY OF ARTS AND SCIENCES
DEPARTAMENT OF GEOLOGY

Spatial and Temporal Analysis of Shoreline Changes with AMBUR on Arecibo, Puerto Rico

Héctor M. Crespo Jones
GEOL 4055: Undergraduate Research II
Advisor: Fernando Gilbes
May 9, 2014

Abstract

A previous study shows that Arecibo is undergoing coastal erosion. That zone is very important because of its proximity to Cueva del Indio Natural Reserve and its potential for dune preservation. The Analyzing Moving Boundaries Using R, (AMBUR) software was used to create transects and statistical analyses of the coastline and the dune foot. Coastline analyses revealed a dominant erosion rate of 0.11 m/yr while the eolian deposit was also eroding at a rate of 0.15 m/yr. While DSAS showed in a previous study values of erosion of 0.10 m/yr and 0.21 m/yr in the coastline and dune foot. Spatially the shoreline was erosion was dominant factor while the eolian deposits dominant factor was also erosion. At the temporal scale, a combination of erosion and deposition or a change in the magnitudes of the two factors were displayed for the shorelines. The eolian deposits mostly experienced a change in the magnitudes of the erosion and accretion was very slight with the exception of the eastern end.

Keywords: Shorelines, GIS, AMBUR, Eolian Deposits, DSAS, Aerial Photographs

1. Introduction

Shoreline changes have large importance for coastal communities and people living from the resources of the coastal environment (Rodríguez *et al.,* 2009). These changes in Puerto Rico due to erosion and deposition are occurring nowadays and have been documented in the past (Thieler *et al.,* 2007). This affects the resources available in the area and quantifying the evolution of these systems through transects enhances the probabilities of a better understanding of coastal dynamics (Jackson *et al.,* 2012). Transects are small segment areas that quantify the change of the shoreline at the same spatial interval (Thieler *et al*., 2007). The study of these changes can be done by different tools, but a remote sensing approach has proven to be more efficient and cost effective (Jackson *et al.,* 2012; Avinash et al., 2010).

Also, improvements in Geographical Information Systems (GIS) and hardware capabilities have led to more analyses of coastal areas leading to a widely use and recommended by coastal researchers (Andrews *et al.,* 2002; Rodríguez *et al.,* 2009). GIS software has a variety of capabilities and its importance is based on the amount of layers or information that can be stacked-up to create further analyses (Rodríguez *et al.* 2009). The possibility of reconstructing historical shorelines of the study area into a single map is one of the strongest tools that GIS allows for analysis and interpretation (Rodríguez *et al.,* 2009). The stack of informational layers is one of the best methods in this project to identify if the shoreline has any direct relation with the dunes. Also it will be useful in order to compare the results of both GIS extension tools AMBUR and DSAS.

Shoreline change is mostly associated with the change of the high and low water levels (Stive *et al*., 2002). But the dune foot is also used as a proxy of shoreline evolution (Stive *et al.,* 2002). The dune foot is considered as the end of the backshore in a beach environment, a place where the ocean water does not reach (Del Rio *et al*., 2013; Stive *et al*., 2002). Morelock and Barreto (2003) state that the dune foot can be seen at the vegetation line. Stive (2002) shows a relationship between the dune baseline and the high and low water levels. The shoreline changed at a faster rate than the eolian deposits, but a clear association between both systems remained (Stive *et al*., 2002).

Thieler et al. (2007) used GPS data and ArcGIS software to produce a shoreline analysis on the coast of Rincón. In this project, AMBUR was the extension tool that will be used to determine boundary changes (Jackson *et al*., 2012). The meaning of the acronym is Analyzing Moving Boundaries using R and it is a tool that can be used in any GIS platform to analyze any kind of boundary similar to the Digital Shoreline Analysis System or DSAS (Jackson *et al*., 2012; Thieler *et al*., 2009). AMBUR is the result of the improvements of a similar program called Shoreline Change Analysis of Retreating and Prograding Systems or SCARPS (Jackson *et al*., 2012). The innovative capabilities of AMBUR include its extensive statistic database, increased graphical capacity, novel transect system, detailed review of stats and graphics and forecast ability (Jackson *et al*., 2012).

Erosion has been observed in Arecibo coasts as in other regions of the island due to natural and anthropogenic factors (Morelock 1984; Thieler *et al*., 2007). Although in Arecibo the erosion has been severe due to construction of jetties and ports in the shoreline, leading to a halt of the longshore transport (Morelock, 1984). Also, a dam on the Río Grande de Arecibo upstream stops the supply of sediments from the river affecting the dynamics of the coast (Morelock, 1984). Still Morelock (1984) does not explain what happens in the eastern coast of Arecibo and he was focused in the area close to Río Grande de Arecibo and to Caño Tiburones. This leads to the question of what changes have occurred to the coastline and eolian deposits in the last 60 years over that area. Also it is important to determine which research tool represents better changes in the area.

This study conducted a remote sensing survey of the coastline changes of Barrio Islote, Arecibo, Puerto Rico. The survey used aerial photographs of the last 60 years (from 1950 to 2010) with the ESRI ArcGIS 10.1 software and the ArcGIS-based extensions from the United States Geological Survey (USGS) known as Digital Shoreline Analysis System (DSAS) and the Analyzing Moving Boundaries Using R (AMBUR) developed by Dr.

Chester W. Jackson Jr. The work also compared both extensions and determined if AMBUR is a better tool for correcting and manipulating the transects.

Similar projects have been done in other coastlines of Puerto Rico to determine shoreline changes (e.g. Thieler et al., 2007). In a previous work of coastline changes in Arecibo, problems were observed due to the transect orientation and length in the curved areas (Crespo-Jones, 2013) (Figure 1 and 2). This led to the test of AMBUR software, a program that according to its authors resolves these problems. Transects were operated to focus on the desired area avoiding previously observed crossovers and overshoots (Figure 2). This new software avoided most crossovers and overshoots from adjacent transects through its features (Figure 3). Therefore, the specific objectives of this study were to: 1) use AMBUR to determine shoreline changes (in space and time) in two beaches of Barrio Islote, Arecibo during the last 6 decades, 2) evaluate the erosion or deposition in the coastline with AMBUR, 3) compare AMBUR results with the data gathered from DSAS, 4) create a baseline using the current shoreline of year 2014, 5) evaluate shoreline changes in shorter time periods.

2. Study area

Barrio Islote is located in the northern coast of Puerto Rico at the municipality of Arecibo. The total area is enclosed in a polygon covering approximately in the latitude 18°29’40 N and longitude 66°38’30” W and, latitude 18°29’15” N and longitude 66°36’00” W (Figure 3). This town is bordered by the Atlantic Ocean and the shore is oriented mostly on an East-West direction. Geologically the area is formed of various Quaternary deposits including beach deposits, beach rock, sand dunes and eolianites (Briggs, 1968). The beach deposits are mainly composed of carbonates by the presence of calcite and other fossiliferous fragments and small amounts of volcanic sediments and quartz (Briggs, 1968). The dunes are composed mainly of the materials in the near beach deposits (Briggs, 1968).

3. Methodology

3.1. Sample Description

This study used 5 mosaics of georeferenced vertical aerial photographs from 1950, 1963, 1971, 1977, 1998 provided by the Departmento de Recursos Naturales y Ambientales (DRNA) in tif format and a georeferenced vertical aerial photograph of 2010 provided by the Geological and Environmental Remote Sensing Laboratory (GERS Lab) of the Geology Department in the University of Puerto Rico at Mayaguez with a spatial resolution of 0.30 m. Photos from 1950 to 1971 are in black and white and the last two photos from 1998 and 2010 are in true color (Figures 4-9). The analyzed area comprehends approximately 4.3 km of coastline in Barrio Islote, Arecibo, Puerto Rico.

3.2. Methods

Shoreline changes in Arecibo (Figure 3) were analyzed through ESRI ArcGIS. Each photograph was reviewed through ArcGIS to confirm the shoreline position from Crespo-Jones (2013) previous work. The shoreline proxy was the boundary between the land and water seen in the aerial photographs. Henceforth, the stacking of the different shorelines can be inserted into the latest photograph. Subsequently, analytical graphs and region maps depicting the rate of change of the coastline were produced through AMBUR. The AMBUR tool allowed to make corrections to the transects by selecting an outer and inner boundary or baseline, leaving the transects inside said boundaries (Jackson *et al.*, 2012) (Figure 10). The selected boundaries were buffers from all the shorelines. Furthermore, a forecast of the shoreline was created to observe the future evolution of the coastline. Then, temporal analyses were done at a shorter time scale using the statistics between each consecutive shoreline to observe if there is a different evolution between each year and the general trend. Also the spatial analysis was done dividing the area in regions of similar background to have a better understanding of the evolution of the area. Lastly, the AMBUR tool was utilized to verify the results from DSAS obtained in the last semester project.

The current shoreline was mapped through GPS data. The instrument used was the GPS Pathfinder Pro XRS Receiver (Figure 11). It is a GPS in a waterproof backpack to be able to work in any kind of conditions. The GPS data was acquired in real time and the instrument has an accuracy of 50 cm. The data attained through GPS was easily shared with GIS software through the computers from the GERS Lab.

A new set of boundaries were accurately delineated with GIS to establish the change of the eolian deposits between 1950 and 2010 (Figures 5-10). The new boundaries represent the dune baseline toward the sea indicated by the backshore line (Del Río *et al*., 2013). Transects displaying the rate of change can be done too for the eolian boundaries, because AMBUR is able to work with different kinds of boundaries (Jackson *et al*., 2012). Analytical graphs and a region map were produced to observe the eolian changes.

The shoreline and eolian deposits boundaries created and revised with AMBUR were compared with DSAS to look for similarities and discrepancies. Finally, the advantages and disadvantages of each tool were analyzed.

4. Results and Discussion

4.1. Long Term Shoreline Changes

Two analyses were made to analyze the long term change of the shorelines, the 1950-2010 analysis and an analysis using the 6 shorelines together. The analysis only using two shorelines from 1950 to 2010 was characterized by erosion from most transects (Figure 12). There was a total of 1173 transect with a 5m spacing. The accretion areas were found in transects 190-199, 250-300, 560-570, 760-765, 815-830 and 1150-1168 approximately.

In the analysis using all shorelines, the results were very similar. The only differences were found at the eastern and western ends of the study area, where the quantity of accretion was larger than in the previous result. Erosion was also higher than accretion. Maximum erosion was 58.74 m while maximum accretion was 42.06 m (Figure 13). Mean erosion and mean accretion values were of 12.15 m and 6.43 m, respectively. It is observed that erosion doubles the amount of accretion. The mean erosion and accretion rates follow a similar path, with 0.2 m/yr and 0.11 m/yr, respectively.

4.2. Short Term Shoreline Changes

The analysis from 1950 to 1963 displayed a higher amount of erosion than accretion, although both were very similar (Figure 14A). Maximum erosion was of 43.01 m and maximum accretion was of 43.01 m (Figure 15). The mean erosion and accretion values were of 13.46 m and 11.78 m, respectively. The mean erosion rate was also slightly higher than the mean accretion rate with values of 1.04 m/yr and 0.91 m/yr. From the previous results we start to observe a trend, where the erosion and accretion values of different products remain fairly similar between each other. In other words, any extreme difference can be taken as an error. The mean overall change is of -1.2 m/yr and the mean overall rate is of -0.9 m/yr.

In the period between 1963 and 1971 erosion is also higher than accretion (Figure 14B). Mean erosion is observed of 8.47 m and mean accretion is of 9.24 m (Figure 16). An important factor that is present is how these parameters are behaving between them across time. The previous map compared to this period shows a transformation in the beach area. Those erosion areas turn into accretion similar to a cardiograph. This phenomenon makes sense, because there should be some continuity on the availability of the sediments present in the area. The overall change is of -0.22 m/yr and the overall mean rate is of -0.03 m/yr.

The 1971 to 1977 period had the smallest amount of data processed due to the missing section in the vertical aerial photograph of 1977. AMBUR flagged this section and did not process it in the graphs, although in the map of net change it shows that area as erosion, which is wrong because the analysis cannot be done in that section. This period had a higher accretion values than the previous sections. Maximum erosion was of 42.61 m and maximum accretion of 41.57 m (Figure 17). Mean erosion and accretion values were of 12.4 m and 10.76 m, respectively. The erosion and accretion rate were of 7.1 m/yr and 6.93 m/yr. The overall change was of 0.13 m and the overall mean rate is of 0.04 m/yr.

The second period with the smallest amount of data was between 1997 and 1998. This is to be expected from the 1977 aerial photograph and what has been stated in the last paragraph. Accretion was also slightly higher than erosion in this time period. The overall mean change was of 0.45 m and the overall mean rate was of 0.03 m/yr. Even though, accretion is observed in this values, the erosion and mean rate of erosion, 12.32 m and 0.59 m/yr, is higher than accretion, 11.51 m and 0.55 m/yr (Figure 18). The maximum accretion was definitely higher than erosion with values of 60.52 m and 52.48 m.

In the last time period evaluated, 1998 to 2010, erosion was the dominant process in the area again. All the erosion parameters were higher than the accretion ones. The values from the mean, maximum and mean rate erosion were 12.17 m, 57.25 m and 1.01 m/yr, respectively (Figure 19). The values for the mean, maximum and mean rate accretion were 10.24 m, 45.7 m and 0.85 m/yr. The latter values are obviously lower than the first ones. This resulted in an overall mean change of -2.31 m and an overall mean rate of -0.19 m/yr.

The temporal distribution of the changes observed in the shoreline present zones of transition between erosion and accretion. An understandable change because of mass continuity in the area, but mostly changes in the magnitude of erosion or accretion were observed. The most changes in erosion magnitude were observed between transects 750 to 950 with peak change in 1971. In the other years there are slight changes in magnitudes, but they are comparable to the net rates of erosion at long term.

4.3. Long Term Eolian Deposit Changes

In the eolian deposit section analysis, similar procedures to the shoreline change analysis were followed. The analysis of the 1950 to 2010 dune foots indicated regions of accretion at the east end of the study area (Figure 20). Other accretion spots were found at transects 180, 300 and 400. Erosion values for each statistic were two times higher than the accretion values. This indicates that erosion is dominant in the eolian deposits. The maximum erosion found was of 94 m and the maximum accretion of only 44 m (Figure 21). The mean erosion and accretion values were of 12.18 m and 6.64m, respectively. The mean erosion rate was of 0.2 m/yr and the mean accretion rate is of 0.11 m/yr; overall mean change was of -9.4 m and overall mean rate of -0.16 m/yr.

Accordingly, the analysis of all the historical dune foot positions together had similar results to only using the 1950 and 2010 dune foots. Accretion is mostly seen toward the extremes of the study area. The other spots are similar to the 1950 to 2010 dune foot analysis. The reason is probably because there are more usable transects, that were not flagged by AMBUR seen from the EPR graph. The EPR graphs are fairly similar if not alike by the extra transects.

4.4. Short Term Eolian Deposit Changes

Observing the map of net changes, erosion dominates on the 1950 to 1963 dune foot analysis, but in the next periods accretion seems to dominate with longer regions undergoing it (Figure 22). Accretion mainly dominates on the eastern half of the map of net changes for the years 1963-1998, while erosion mostly dominates the western side. The 1998 to 2010 map is dominated by erosion on the eastern side and accretion on the western side. The 1950 to 1963 period is characterized by erosion with a distinct peak at transect 400; accretion dominates in the eastern and western ends of the study area (Figure 23). Max erosion was of 92.88 m and max accretion of 19.86 m. The mean erosion and mean accretion were of 11.95 m and 4.84 m, respectively. The mean erosion rate was of 0.92 m/yr and the mean accretion rate was of 0.38 m/yr. The overall mean change from this period was of -8.38 m and the overall mean rate was of -0.66 m/yr.

In the period extending from 1963 to 1971, there is missing data at the western end of the study area (Figure 24). Maximum erosion is observed on the EPR graph (Figure 24A). Erosion has higher values and this is closely related to what is seen in the map of dune foot net change. Maximum erosion was of 88.4 m and maximum accretion was of 67.81 m. The mean erosion and accretion was of 13.5 m and 8.83 m. The mean erosion rate was of 1.69 m/yr and the mean accretion rate was of 1.1 m/yr. The overall mean change was of -0.78 m an expected value by observing that the previous parameters indicated higher erosion quantities. On the other hand, the overall mean rate was of -0.11 m/yr.

Between 1971 and 1977 there is missing data up to transect 350 (Figure 25). Erosion and accretion are observed at almost the same rate, but accretion is higher because there is missing data in the 1977 dune foot. Maximum erosion was of 22.16m and maximum accretion of 61.41 m. The mean erosion and mean accretion values were of 5.42 m and 6.77 m, respectively. Mean erosion rate was lower, with a value of 0.9 m/yr, while the mean accretion value was higher this time with 1.13 m/yr. The overall mean change was of 1.45 m and the overall mean rate was of 0.36 m/yr, which indicates a period of accretion dominant processes.

The analysis of the historical dune foot position for the 1977 to 1998 period also displays missing data up to transect 350, by the 1977 aerial photo. Although erosion is slightly higher than accretion the overall mean change and rate indicate accretion is dominant for the time period. The maximum erosion was found to be 44.42 m and the maximum accretion of 51.43 m (Figure 26). The mean erosion and accretion were of 10.14 m and 8.37 m, respectively. Also the mean erosion rate was of 0.48 m/yr and the mean accretion rate was of 0.4 m/yr. In the overall mean change, accretion of sediments in the area dominates with 0.34 m and with the overall mean rate of 0.02 m/yr.

In the last evaluated period of time, accretion was higher than erosion in the EPR graph (Figure 27). This is also observed in the results of the statistics. Maximum erosion was of 26.98 m and maximum accretion of 29.66 m. Mean erosion and accretion were found to be 8.73 m and 8.31 m, respectively. The mean erosion rate and the accretion rate, were the exception to accretion being higher, with an erosion of 0.73 m/yr and an accretion of 0.69 m/yr. The overall mean change was of -0.1 m and the overall mean rate was of -0.01 m/yr which indicate erosion. This is different to what is observed from the graph and statistics were accretion seemed to be higher.

The temporal changes for the eolian deposits were different from the shoreline. Mostly changes in the magnitude of erosion occurred, but there weren't significant changes between each year in the hotspots. In the other areas, the erosion and accretion changes were slight.

4.5. Shoreline and Eolian Deposit Forecasts

AMBUR forecast tool allows the observation of a possible outcome depending on the current trend of the shoreline. It is done by using the EPR, linear regression rate (LRR) or weighted linear regression (WLR) changes from the statistics provided by AMBUR (Jackson *et al*., 2012). The forecast of the shoreline at 50 years was very helpful on understanding how the coast could change and which areas are prone to have a severe change. The shoreline seemed to stay technically the same at the rocky areas (Figure 28). This result is expected, knowing how much weathering the water and air can cause into solid rocks. However, the sandy areas were different, and changes were observed. In the western side, the coast is pretty stable; it is possible that the location of this area prevents extensive loss of sediment to the sea, because it is hidden by rocks at both sides. Nevertheless, this phenomenon does not occur in the beach in the central section where severe erosion is expected to happen. Nonetheless, there are houses build almost in the coastline and rocks, walls and floors were thrown close to the house to prevent erosion of the area. Jackson *et al*., (2012) addresses this problem in the forecast product because AMBUR is not able to recognize the structures and types of shorelines it is analyzing. The eastern side is mostly stable, but in the easternmost area erosion is more pronounced.

The dune foot forecast for the year 2060 appears to be pretty stable at most points of the study area (Figure 29). The major difference was observed in the central section, where there is pronounced erosion spot seen. At this point, the problem mentioned above with the forecast product is also observed. Currently, the dunes on this spot are being preserved; there are signs and barriers protecting them. Also, the main street is behind the dunes.

4.6. Spatial Trend of Shoreline and Eolian Deposit

The spatial trend displayed the most erosion inside the small bay in the central area among transects 482 and 524 (Figure 30). In the eastern side, moderate erosion is observed intermittently with regions of slight erosion. At the end of the eastern side, the region with the most accretion is found. More depositions spots are observed toward the western area of the coast. In the case of the eolian deposits, the region with the peak erosion is in the central area, in the small bay and in the end of the rocky area to the east (Figure 31). The western area is almost totally dominated by slight erosion of the dunes with exceptions at the west end with severe erosion and other small deposition spots. The east side is mainly dominated by moderate erosion.

The trend of both samples follows a similar path. The eastern side dominated by erosion in the shorelines is also dominated by erosion in the eolian deposits. However, the west side is combined with erosion and deposition, but the eolian deposits are mainly eroding slightly in the area. This is understandable because the rocks are protecting the dunes behind them, inhibiting the intrusion of water. Although it is curious that the section not protected by rocks is also being accreting, but the high relief of this zone could be the factor protecting the eolian deposits behind them.

4.7. Comparison between AMBUR and DSAS Extension Tools

AMBUR and DSAS uses different methods to construct and modify transects for analysis. The AMBUR tool casts three different types of transect from which you can select one to filter, as a result obtaining a better distribution of transects along the coast. Especially, this is useful in tight curved areas where transects may overshoot and crossover other transects. On the other hand, DSAS does not have this capabilities, it can only cast perpendicular transects and there is an option to smooth the transect distribution. This option creates overshooting and crossover of transects, which brings errors into the statistics (Figure 1 & 2).

The EPR results of the shorelines from DSAS were -0.10 m/yr (Crespo-Jones, 2013). AMBUR gave a result of -0.11 which is higher than the past value, but it is still lower to the rate observed by Morelock (2003) of -0.21 m/yr (Table 1). It is possible that in the last decade, after Morelock results there have been more accretion, reducing the erosion in the area. Also there is the possibility of errors introduced while digitalizing the shoreline in ArcMap. The NSM for the shoreline had almost the same mean values with a difference of only 0.3 m between each tool. However, the standard deviations had a 2.7 m difference. The shoreline change envelope had the highest difference from the models with a 10 m difference between AMBUR and DSAS. Nevertheless, the standard deviations had a 1.1 m difference between each other.

In the case of the eolian deposits, the EPR values were higher than the shorelines values (Table 2). These results are bit strange considering that the shoreline should erode faster than the eolian deposits because it is behind it (Stive et al., 2002). The wave action is stronger and more recurrent in the shore than in the dune foot. Consequently, the NSM for the dune foot was two times higher than the shoreline in DSAS. While in AMBUR the NSM had a difference of 2.6 m. The standard deviations between the two tools were high, with a difference of 12.9 meters. The SCE difference between both tools was of 16 m, although while comparing that result with the shoreline, both results were lower.

4.8. *2014 Shoreline and Eolian Deposit*

The 2014 shoreline appears to be very steady compared to the 2010 shore. The western side looks to be eroding at a very slow rate (Figure 32). In the eastern side, the shoreline appears to be accreting toward the easternmost part, especially after the curve (Figure 33 & 34). It is possible that the orientation of the coast there allows a more efficient deposition of sand. This is considering the dominant wind and wave direction of the area which is from the East and Northeast.

5. Conclusion

AMBUR creates more analyses, tables and graphs in approximately two to three minutes. Longshore transport appears to dominate the coastal dynamics of Arecibo. The use of remote sensing techniques facilitates the process of obtaining accurate data from risky places as it is more accessible and cost-efficient. Aerial photographs of an instant are ideal for the collection of data in-situ by many natural and anthropogenic factors. Shoreline changes were similar with both AMBUR and DSAS, except for the SCE statistic. These results do not go in accordance with what was expected to occur on the beach environment. Therefore, the introduction of errors in the digitalization of the shoreline is possible. Temporal analyses indicate the presence of erosion and deposition is intertwined through time or the difference in magnitudes of erosion and/or deposition either for the shoreline and eolian deposit. Spatially, erosion hotspots and accretion spots were observed in particular areas.

Acknowledgements

Thanks to the Geology Department for their input in the proposal stage of the research. Special thanks to Prof. Fernando Gilbes for answering all my doubts and concerns about the project. Thanks to the GERS Laboratory and the DRNA for the aerial photographs of the study area. Thanks to Prof. Chester Jackson from Georgia Southern University and creator of AMBUR for teaching how to use the program. Thanks to my mother and sister, Iris Jones and Mileidy Crespo for accompanying me to do the field work. Lastly, thanks to Samuel Rosario for helping me in retrieving the GPS data.

Cited References

Andrews, B. D., Gares, P. A., Colby, J. D., 2002, Techniques for GIS Modeling of Coastal Dunes, Geomorphology, vol. 48, Issue 1-3, p. 289-308.

Avinash, K., Narayana, A. C., and Jayappa, K. S., 2010, Shoreline Changes and Morphology of Spits along Southern Karnataka, West Coast of India: A Remote Sensing and Statistics-Based Approach, Geomorphology, vol. 120, Issue 3-4, p. 133-152.

Briggs, R. P., 1965, Geologic Map of the Barceloneta Quadrangle, Puerto Rico, U. S. Geological Survey.

Briggs, R. P., 1968, Geologic Map of the Arecibo Quadrangle, Puerto Rico, U. S. Geological Survey.

Crespo-Jones, H. M., 2013, Shoreline Changes during the last 60 years in Arecibo, Puerto Rico, unpublished research, 35 p.

Del Río, L., Gracia, F. J., and Benavente J., 2013, Shoreline change patterns in sandy coasts. A Case Study in SW Spain, Geomorphology, vol. 196, Special Issue, p. 252-266.

Jackson, C. W., Alexander, C. R., and Bush, D. M., 2012, Application of the AMBUR R package for spatio-temporal analysis of shoreline change: Jekyll Island, Georgia, USA, vol. 41, Issue 2, p. 199-207.

Morelock, J., 1984. Coastal Erosion in Puerto Rico, Shore and Beach, p. 18-27.

Morelock, J., and Barreto, M., 2003, An Update on Coastal Erosion in Puerto Rico, Shore and Beach, v. 71, p. 7-11.

Rodríguez, I., Montoya, I., Sánchez, M. J., and Carreño, F., 2009, Geographic Information Systems Applied to Integrated Coastal Zone Management, Geomorphology, vol. 107, Issue 1-2, p. 100-105.

Stive, M. J. F., Aarninkhof, S. G. J., Hamm, L., Hanson, H., Larson, M., Wijnberg, K. M., Nicholls, R. J. and Capobianco, M., 2002, Variability of Shore and Shoreline Evolution, Coastal Engineering, vol. 47, Issue 2, p. 211-235.

Thieler, E. R., Rodríguez, R. W., and Himmelstoss, E.A., 2007, Historical Shoreline Changes at Rincón, Puerto Rico, 1936-2006: U.S. Geological Survey Open-File Report 2007-1017, 32 p. Available at http://pubs.usgs.gov/of/2007/1017/.

Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L., and Ergul, Ayhan, 2009. Digital Shoreline Analysis System (DSAS) version 4.0 — An ArcGIS extension for calculating shoreline change: U.S. Geological Survey Open-File Report 2008-1278. *current version 4.3

Figures

Figure 1: Image displaying problems with transect orientation and coverage, leading to errors in previous work by Crespo-Jones. Image taken from Crespo-Jones (2013).

Figure 2: Image displaying another example of problems found by the transects overshoots and crossovers that lead to unforeseen results. Image taken from Crespo-Jones (2013).

Figure 3: Aerial photograph of the specific area where the shoreline and dune foot in Arecibo, Puerto Rico will be analyzed. The photo was taken in 2010 by the US Army Corps of Engineering and provided by the GERS Lab. Yellow pin on the island image indicates the study site. Puerto Rico image taken from Google Earth (2013).

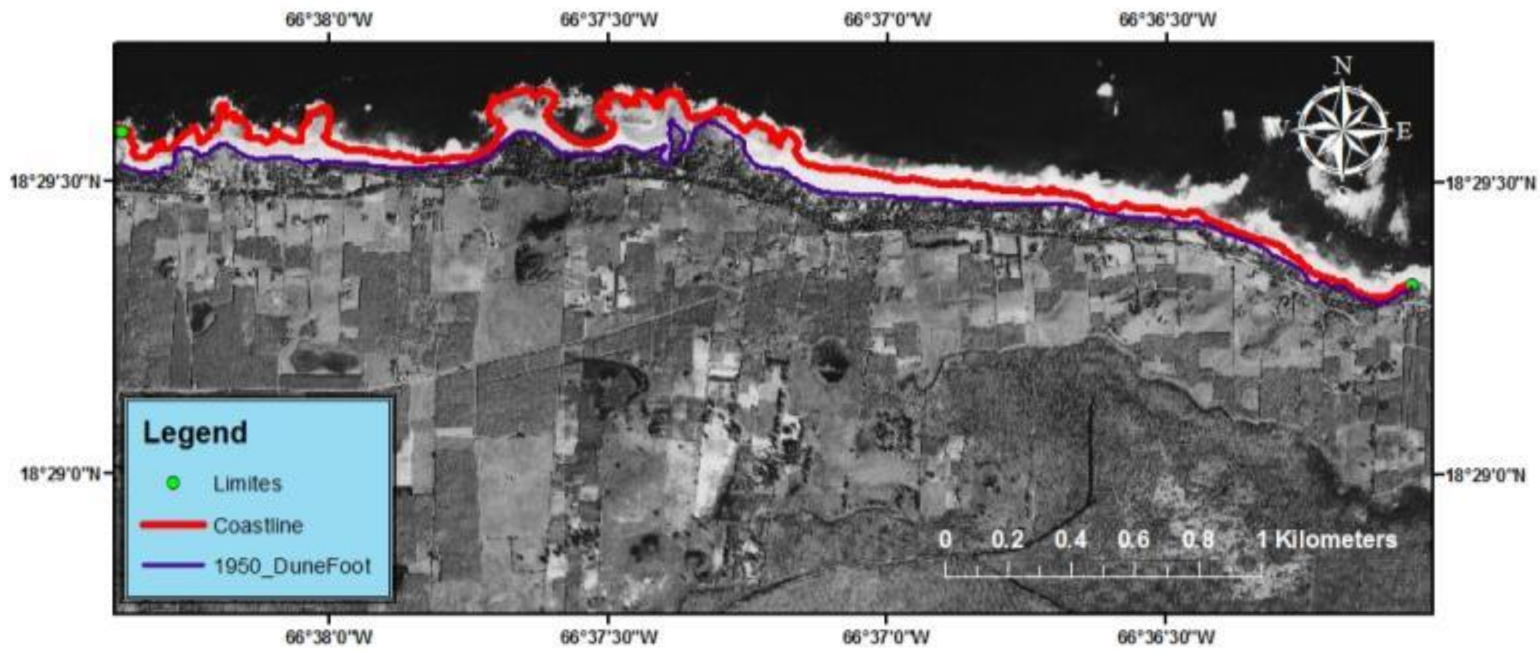

Figure 4: Black and white aerial photograph of Barrio Islote, Arecibo, Puerto Rico in 1950. Image provide by DRNA (1950).

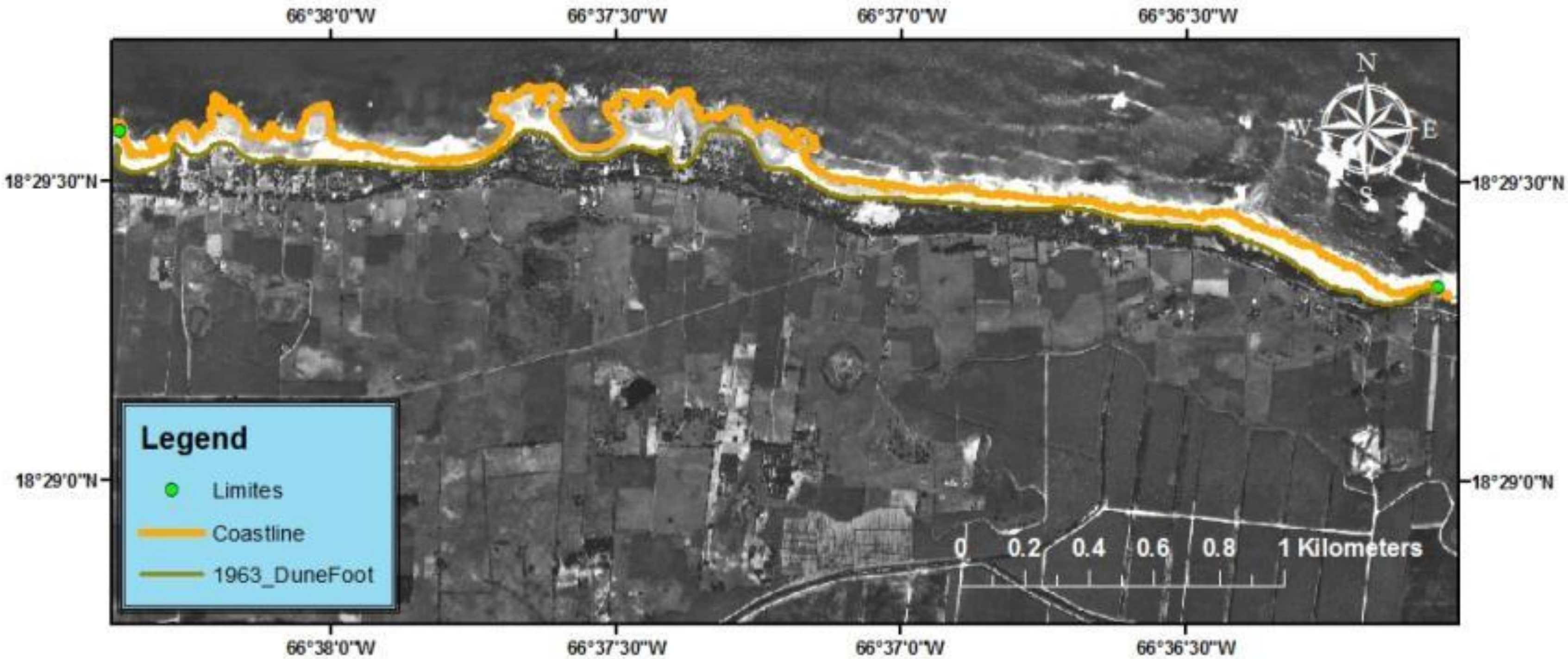

Figure 5: Black and white aerial photograph of Barrio Islote, Arecibo, Puerto Rico in 1963. Photo provided by DRNA (1963).

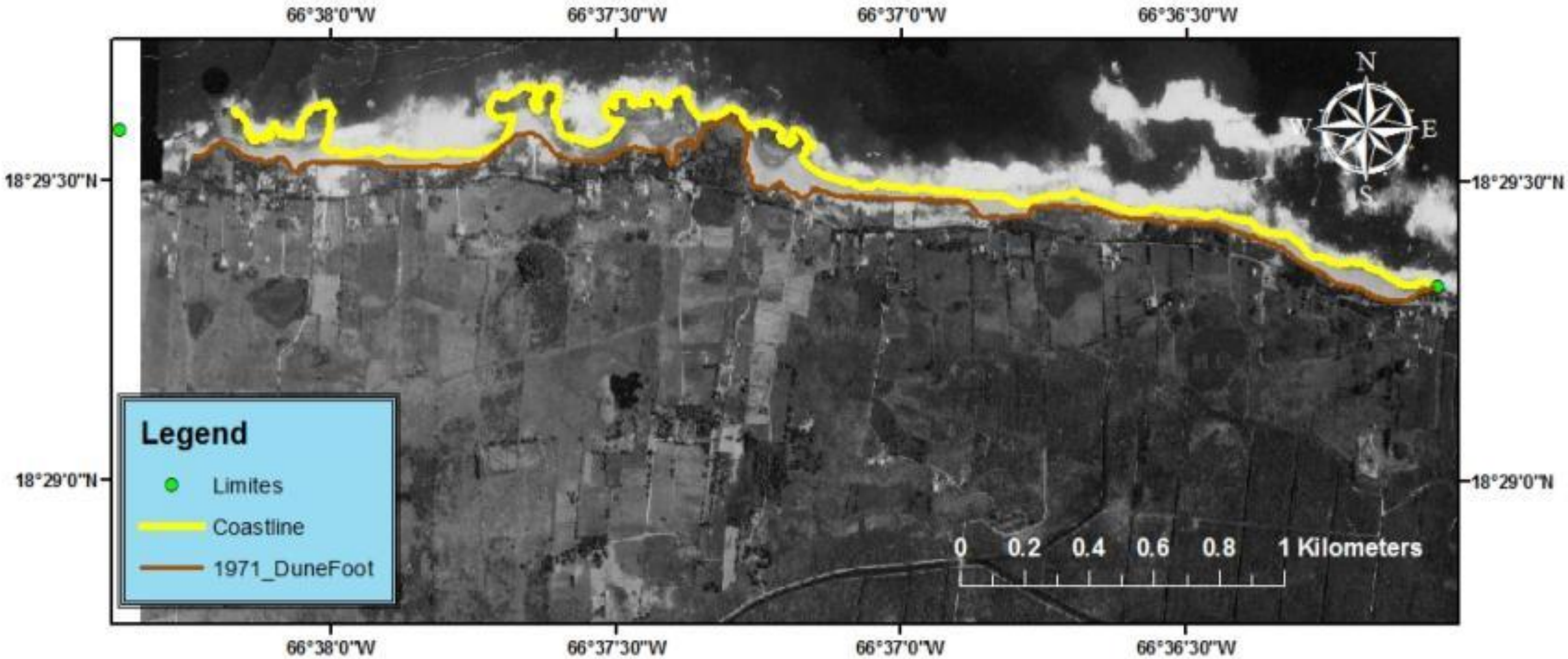

Figure 6: Black and white aerial photograph of Barrio Islote, Arecibo, Puerto Rico in 1971. The photo is damaged in the Northwest corner which impede the digitizing of the coastline and dune foot in that end. Aerial photograph provided by the DRNA.

Figure 7: Black and white aerial photograph of Barrio Islote, Arecibo, Puerto Rico in 1977. A small section of the photo was missing and attempts to find the missing section were in vain. Image provided by DRNA.

Figure 8: True color aerial photograph of Barrio Islote, Arecibo, Puerto Rico. Image provided by DRNA.

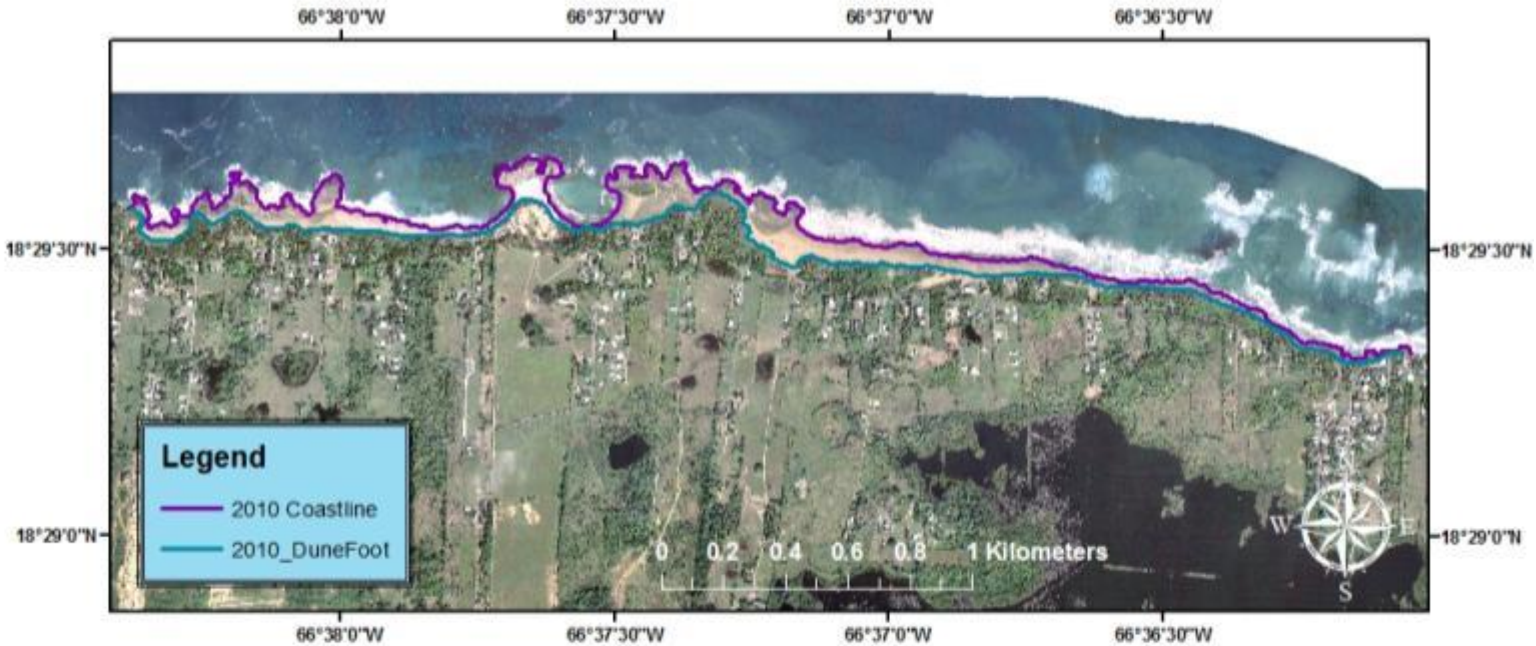

Figure 9: True color aerial photograph from Barrio Islote, Arecibo, Puerto Rico. This photo contains the latest coastline and dune baseline. This photo was provided by the GERS Lab.

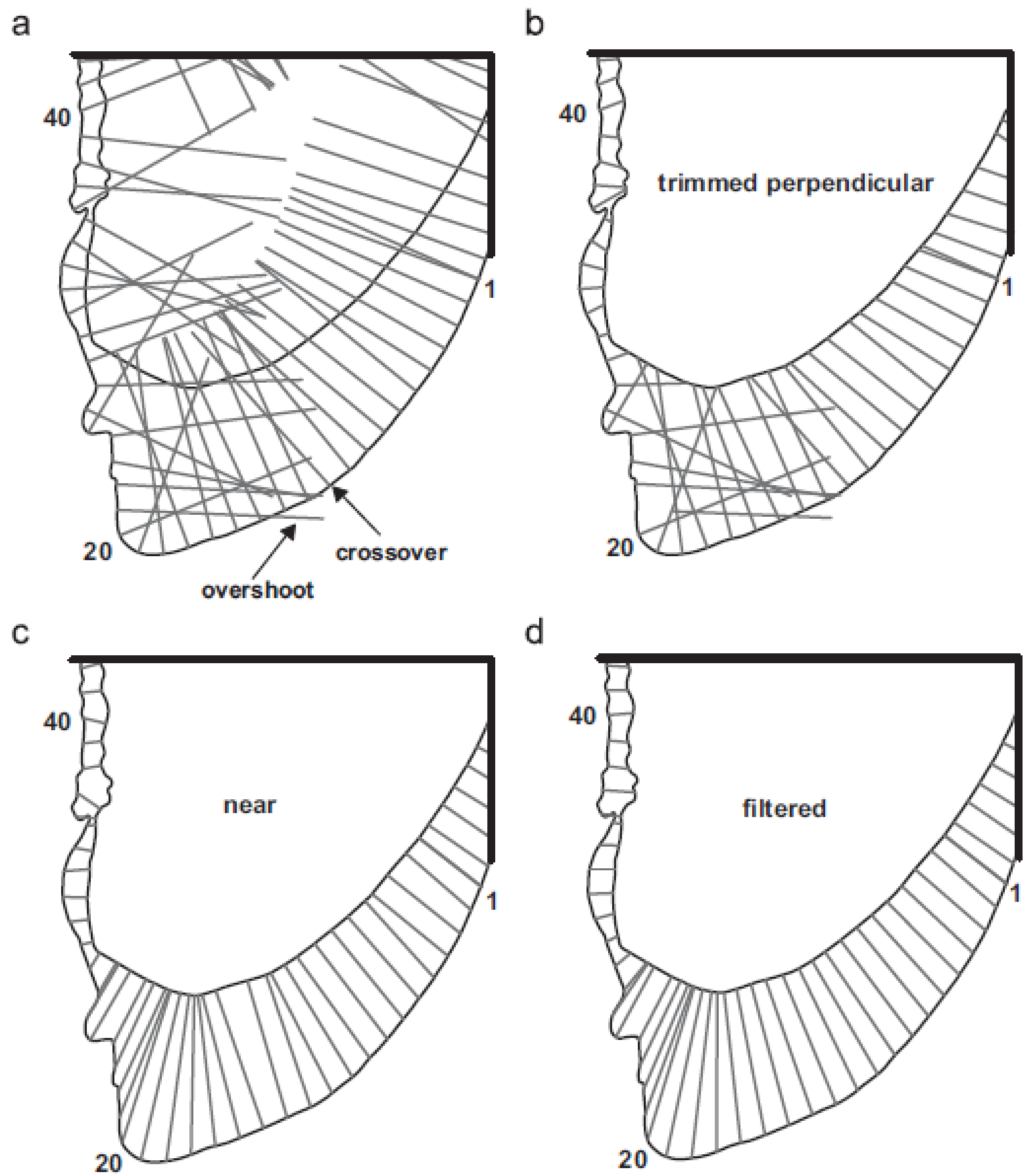

Figure 10: The diagrams above represent the new transect techniques to be used in the project. A) In the top left, the diagram represents an example of using only a minimum of shoreline to analyze leading to overshoots and crossovers. B) In the top right shows the trimmed feature for the transects, it cuts the transect segments outside the boundaries. C) In the lower left, the near feature is used to avoid the crossover between transects. D) In the lower right, the filtered method corrects the gaps left by the near feature. Figure taken from Jackson et al., 2012.

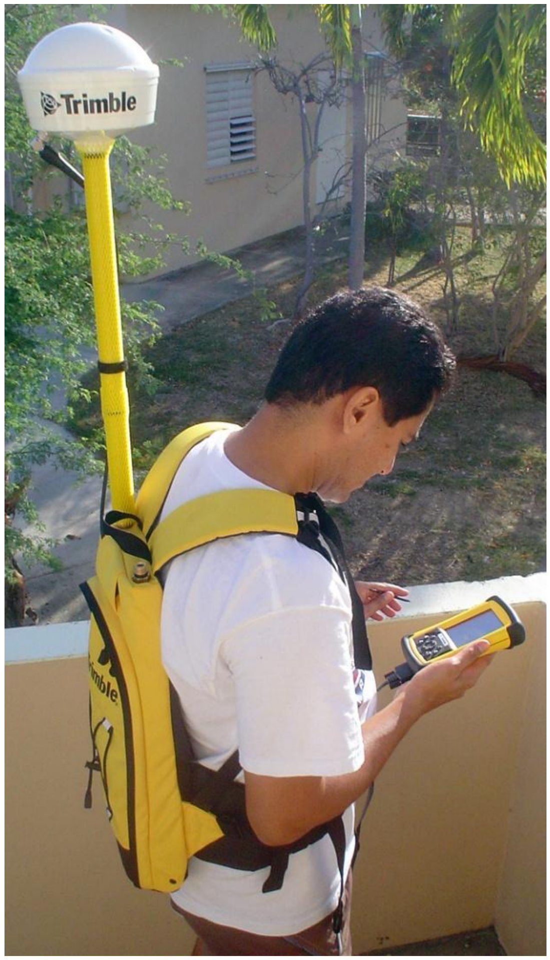

Figure 11: GPS backpack instrument to be used to map the shoreline in Arecibo. Image taken from GERS Laboratory website.

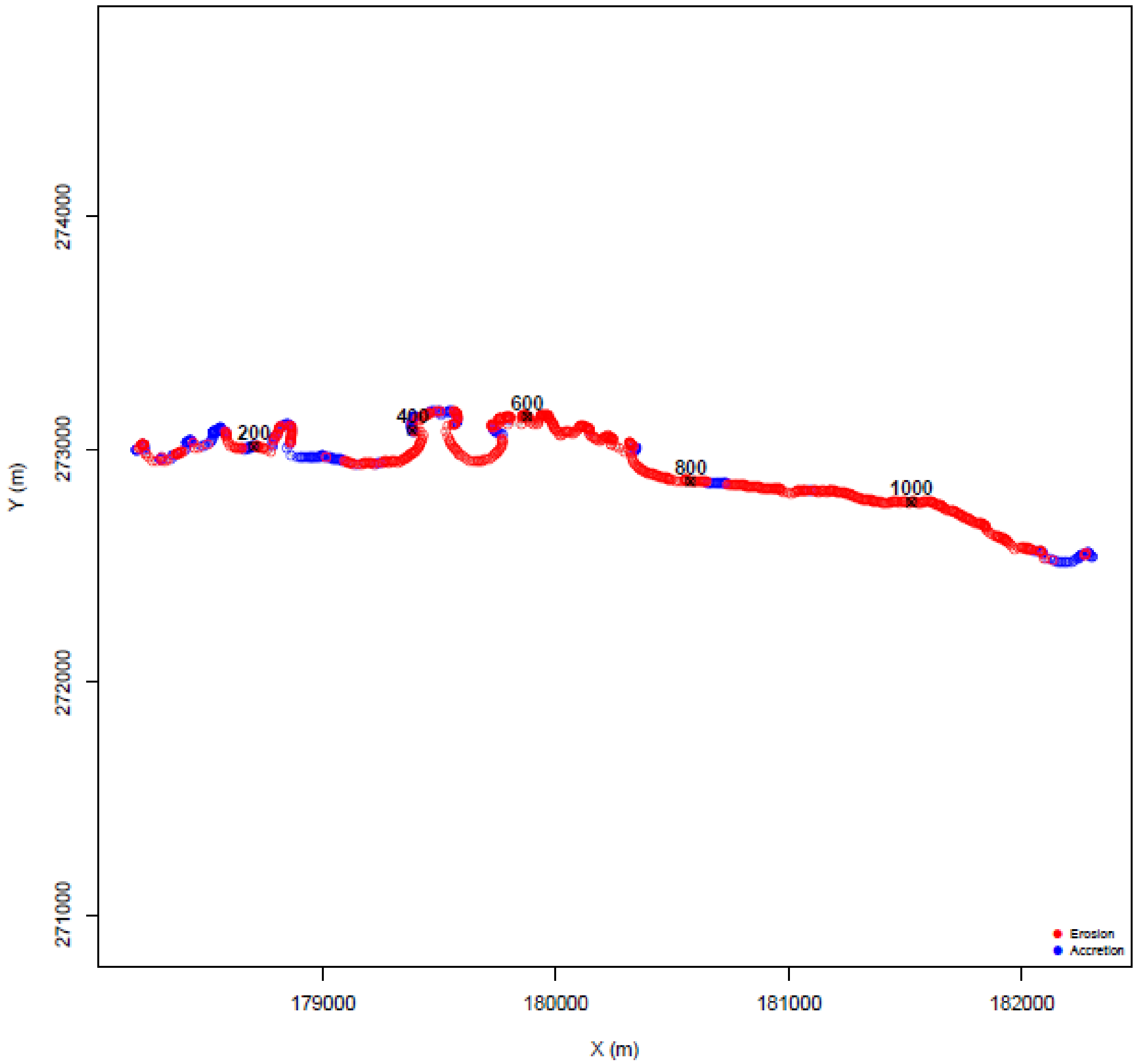

Figure 12: Map of net shoreline changes from all samples 1950-2010.

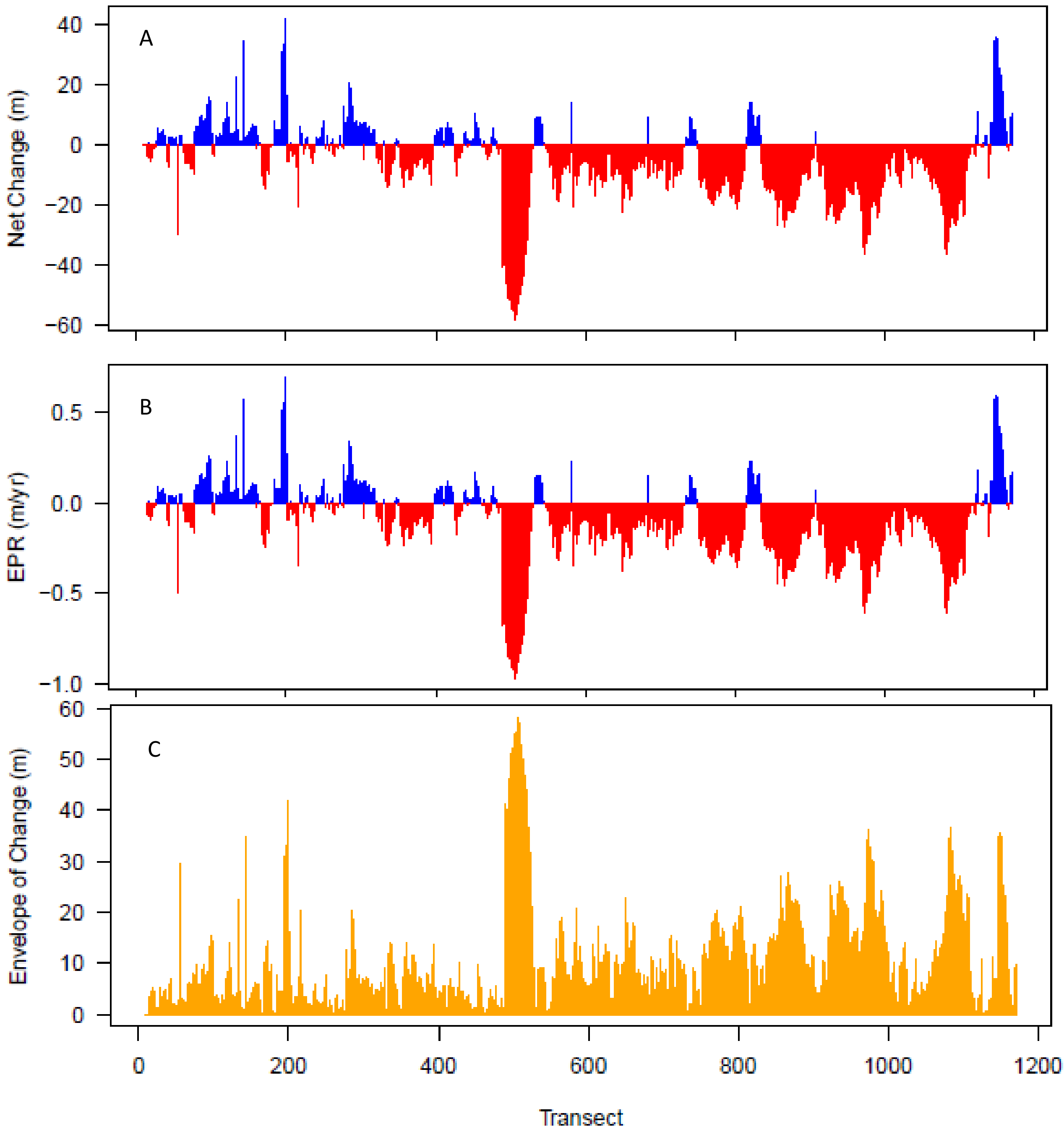

Figure 13: Shoreline change statistics from 1950-2010. A. Graph displaying the net shoreline changes in meters. B. Graph displaying the end point rate in meters per year. C. Graph displaying the shoreline change envelope in meters.

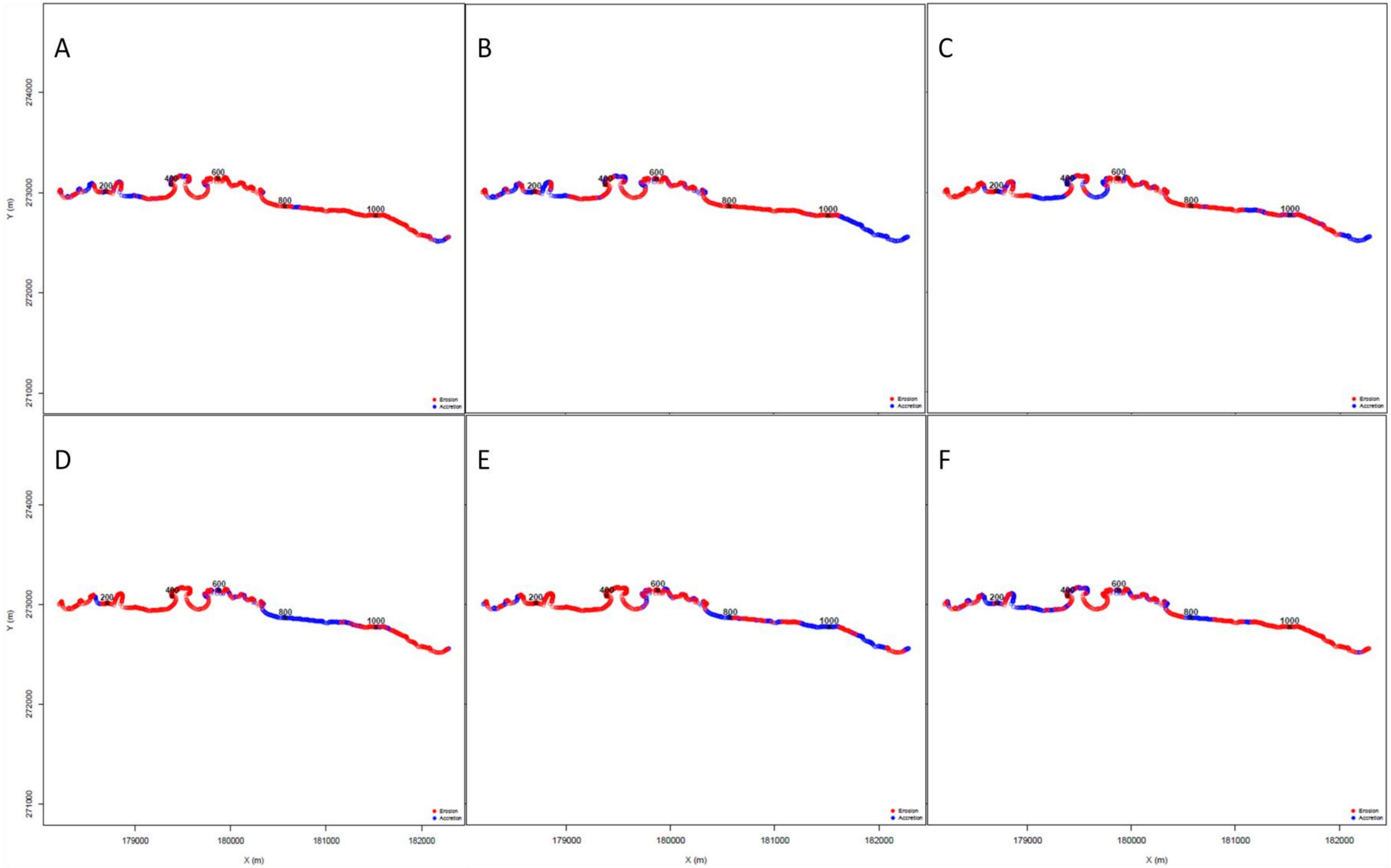

Figure 14: Net shoreline changes by decade through AMBUR. A. Net shoreline changes from 1950 to 2010. B. Net shoreline changes from 1950 to 1963. C. Net shoreline changes from 1963 to 1971. D. Net shoreline changes from 1971 to 1977. E. Net shoreline changes from 1977 to 1998. F. Net shoreline changes from 1998 to 2010.

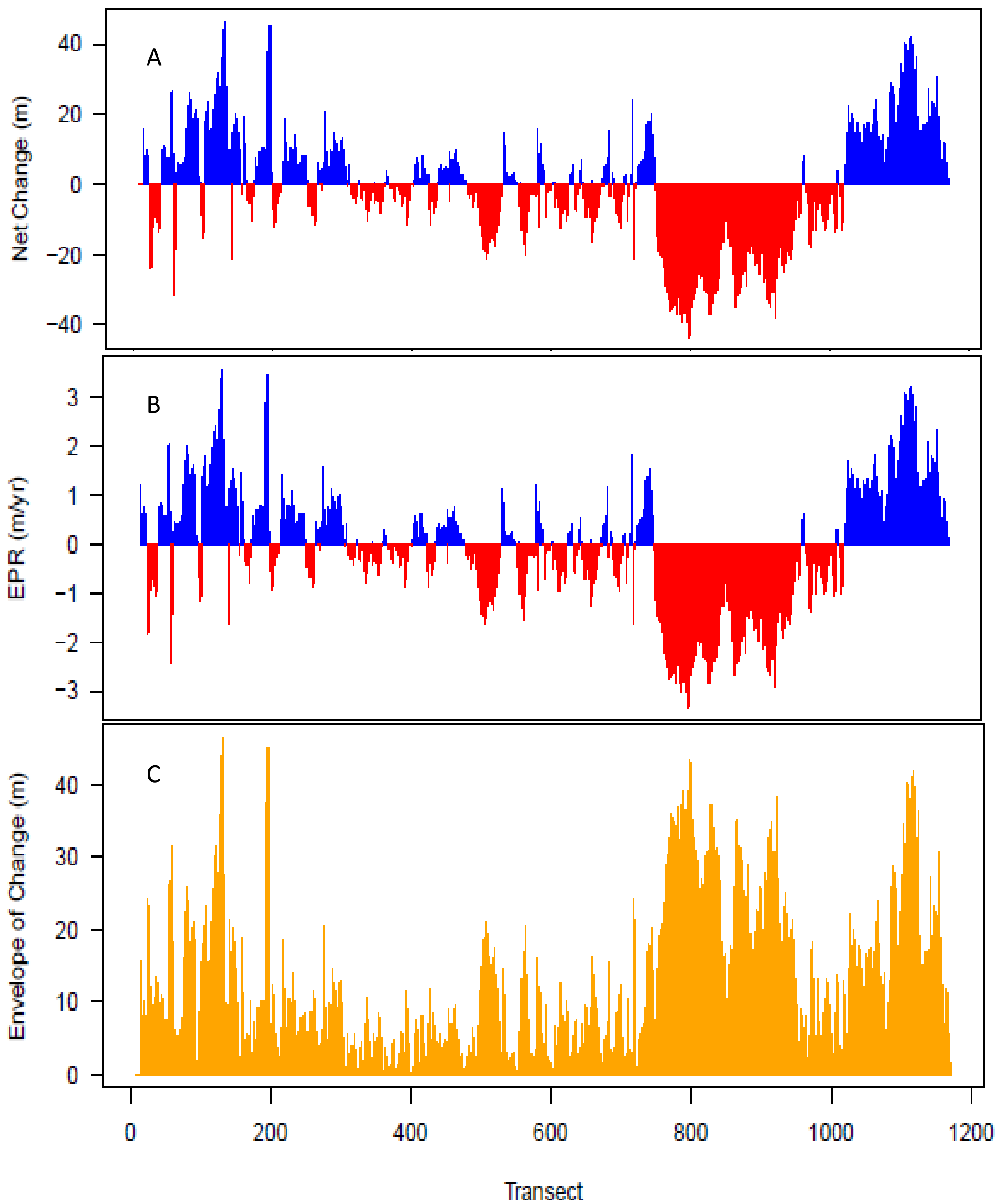

Figure 15: Decadal Shoreline Change 1950-1963. A. Net shoreline change in meters. B. End point rate in meters per year. C. Shoreline envelope of change in meters.

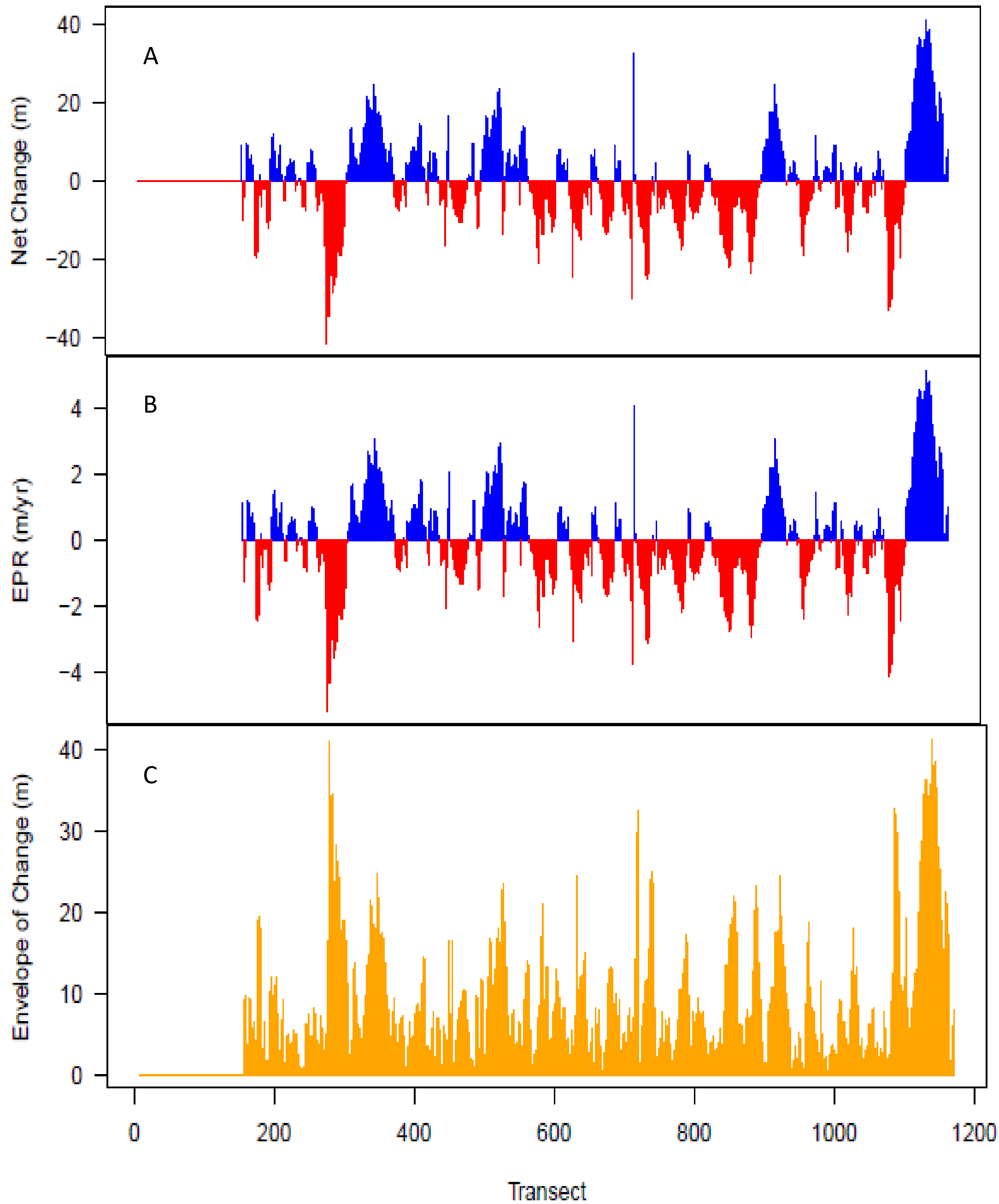

Figure 16: Decadal Shoreline Change 1963-1971. A. Net shoreline change in meters. B. End point rate in meters per year. C. Shoreline envelope of change in meters.

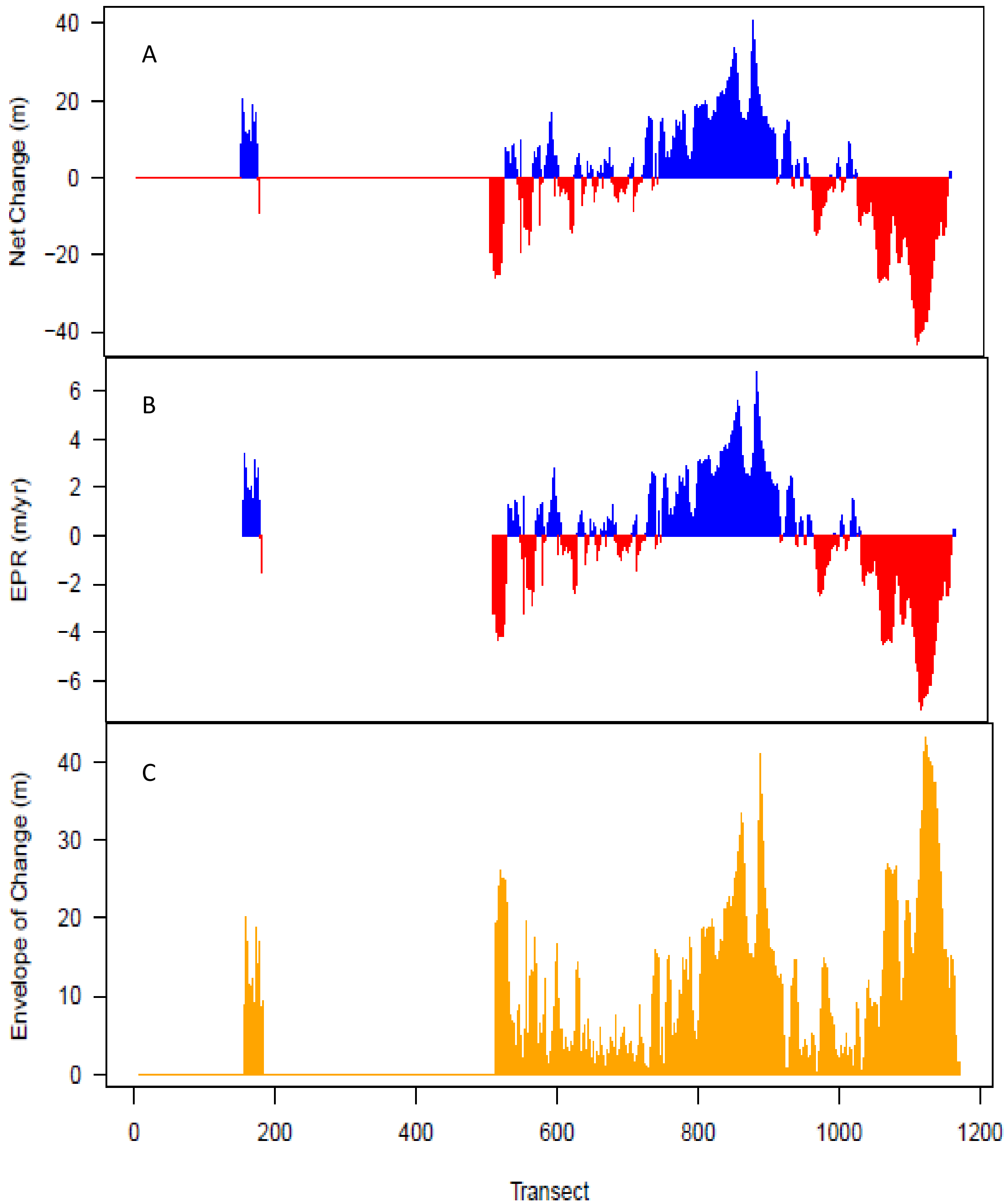

Figure 17: Decadal Shoreline Change 1971-1977. A. Net shoreline change in meters. B. End point rate in meters per year. C. Shoreline envelope of change in meters.

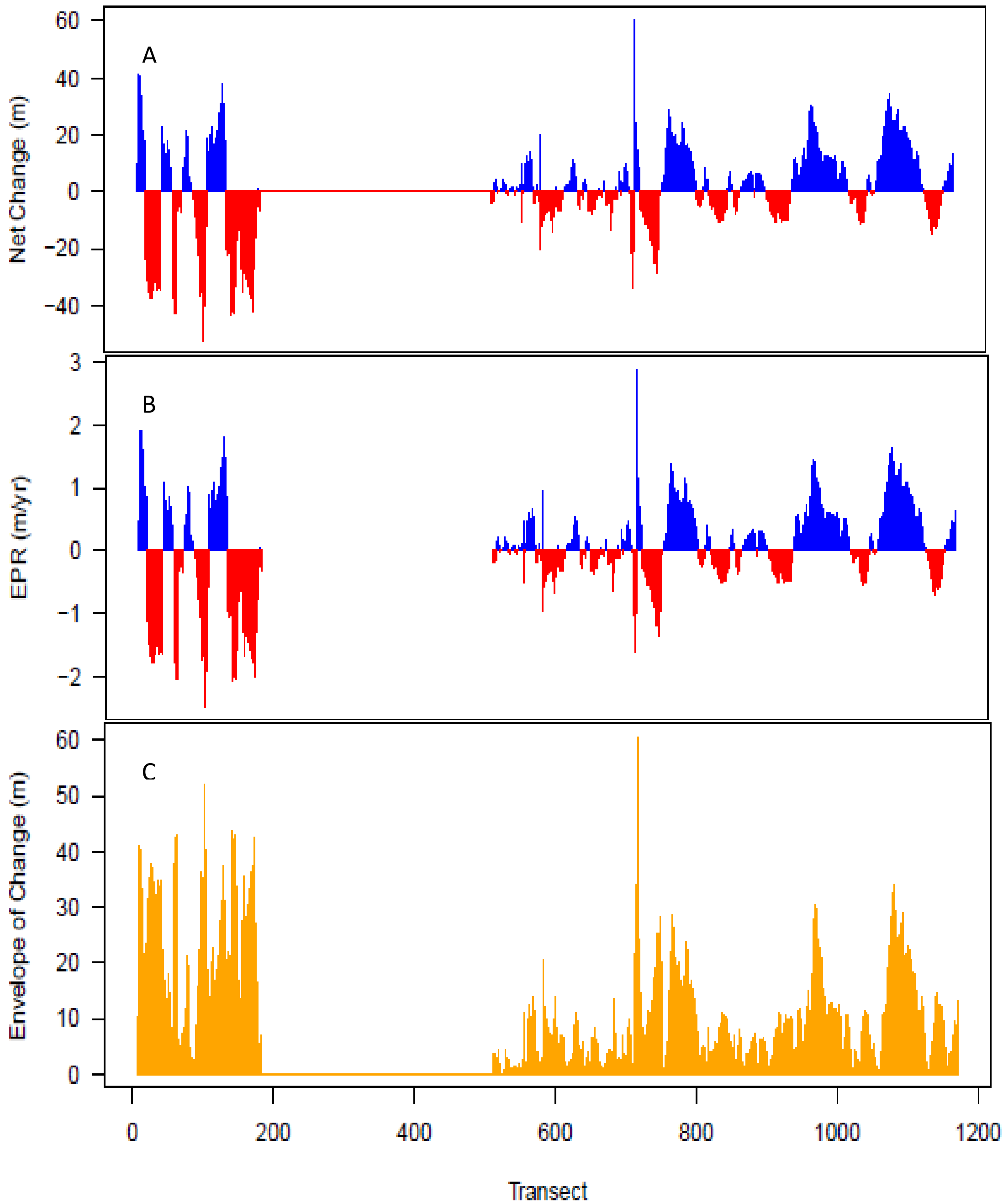

Figure 18: Decadal Shoreline Change 1977-1998. A. Net shoreline change in meters. B. End point rate in meters per year. C. Shoreline envelope of change in meters.

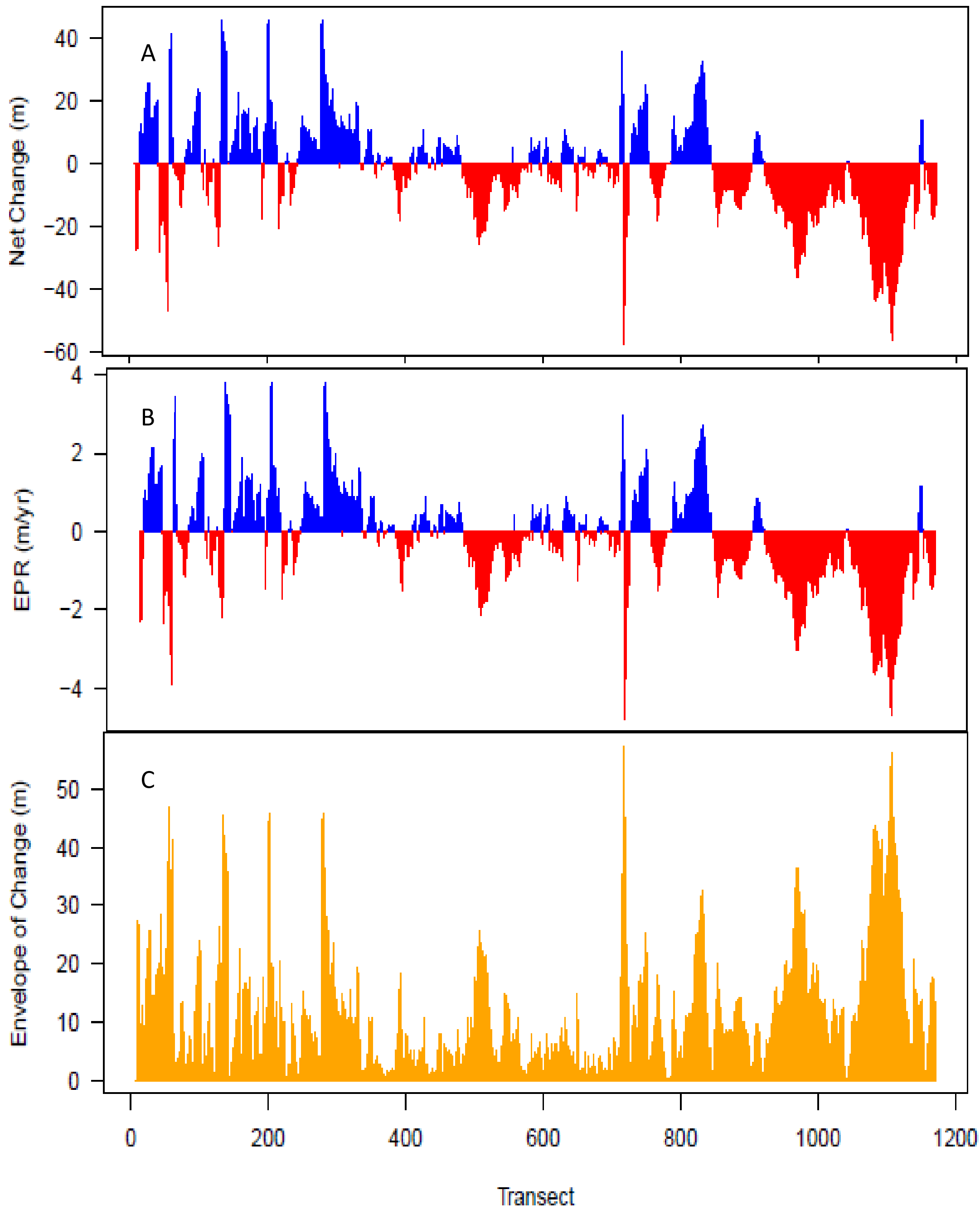

Figure 19: Decadal Shoreline Change 1998-2010. A. Net shoreline change in meters. B. End point rate in meters per year. C. Shoreline envelope of change in meters.

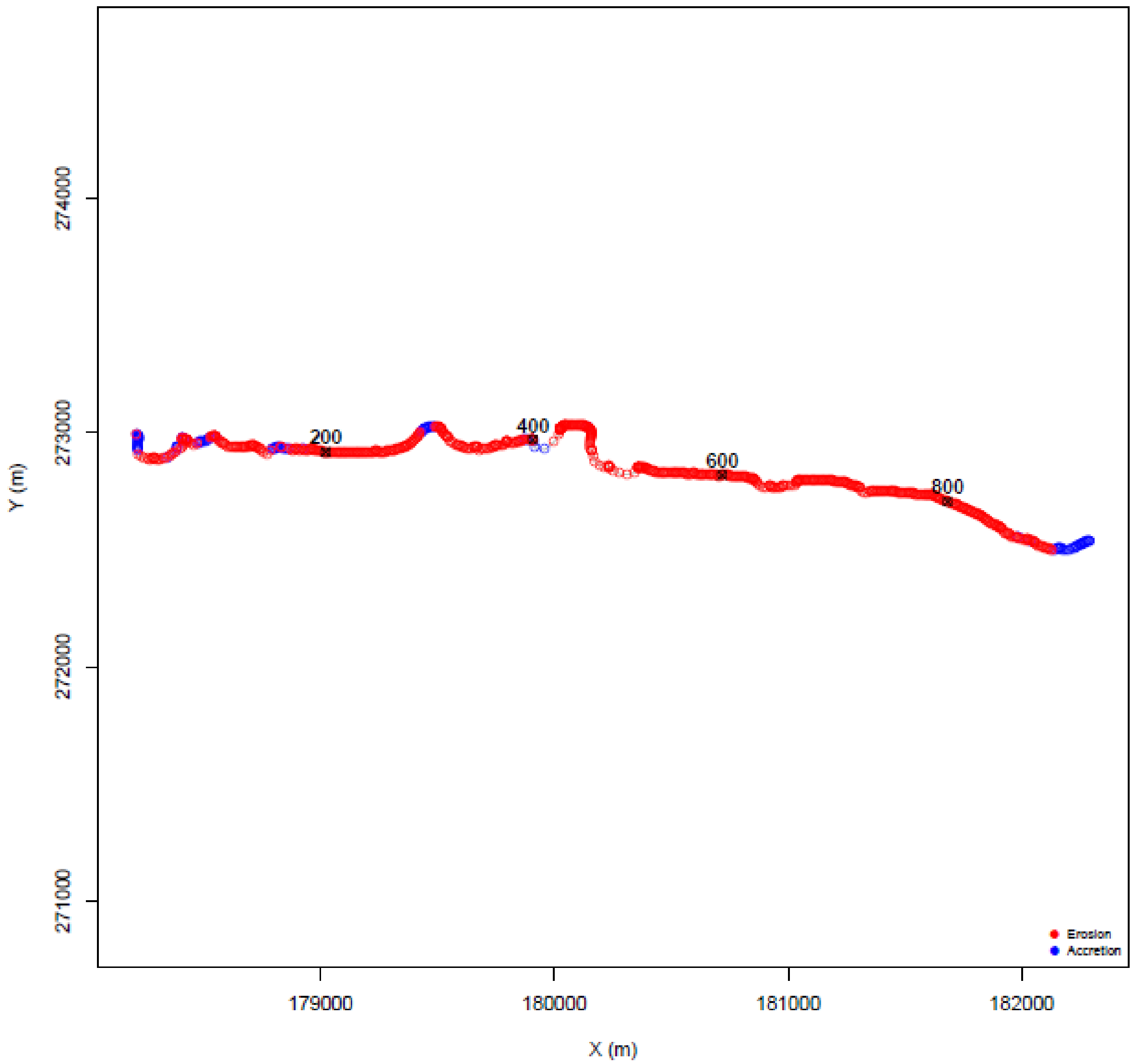

Figure 20: Map of net dune foot changes from all samples 1950-2010.

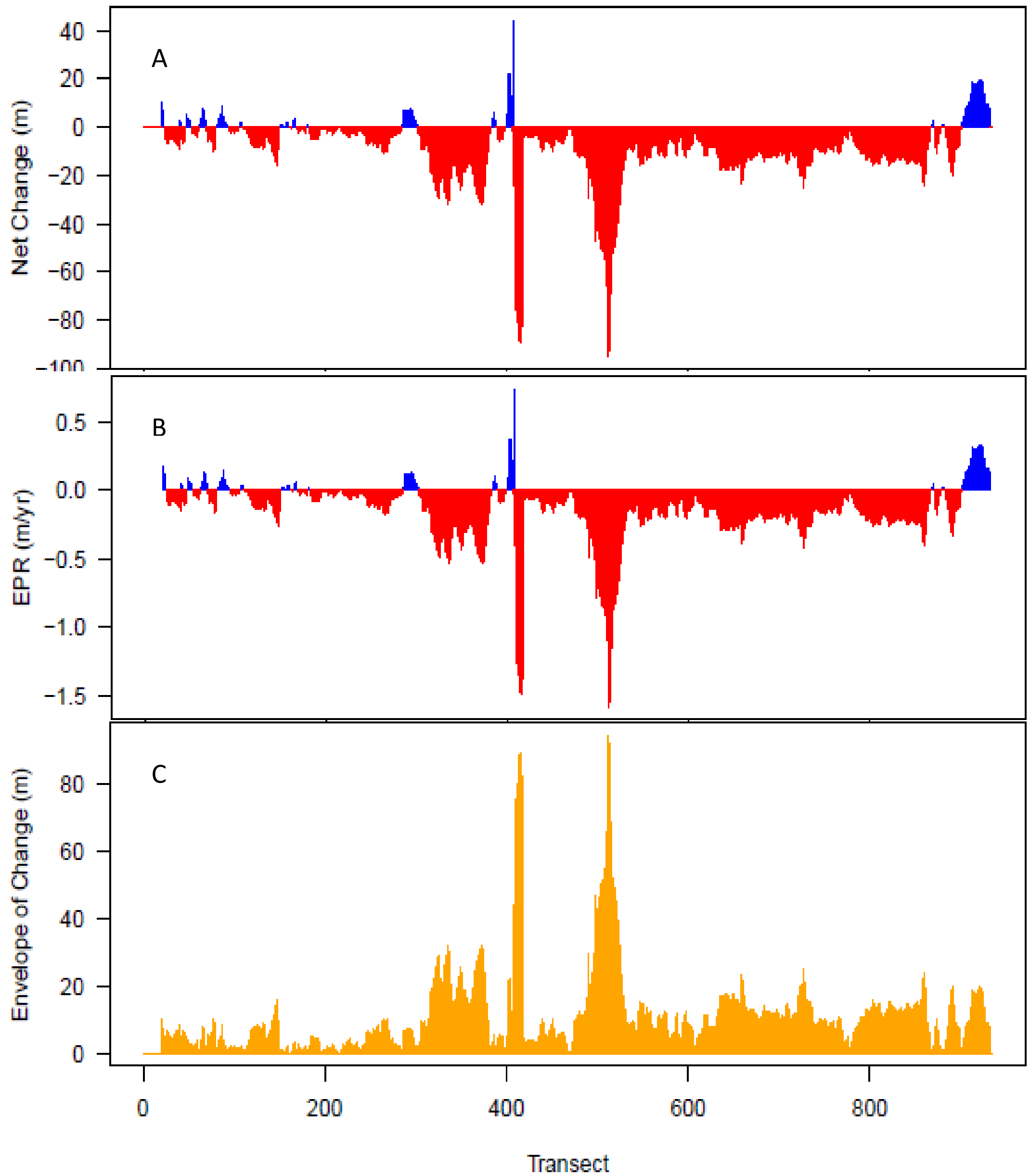

Figure 21: Dune foot change statistics from 1950-2010. A. Graph displaying the net dune foot changes in meters. B. Graph displaying the end point rate in meters per year. C. Graph displaying the dune foot change envelope in meters.

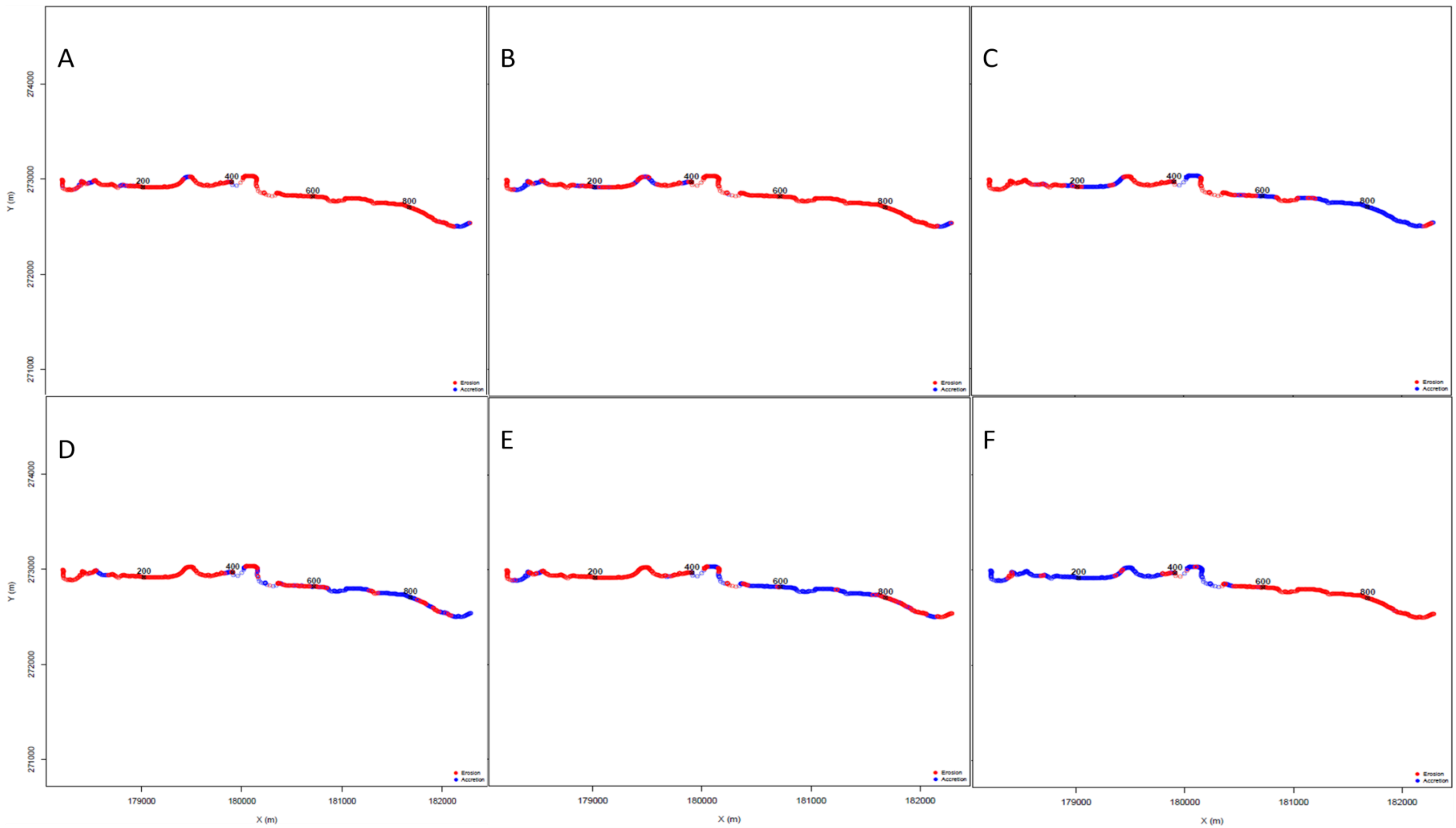

Figure 22: Net dune foot changes through AMBUR by decade. A. Net dune foot changes from 1950 to 2010. B. Net dune foot changes from 1950 to 1963. C. Net dune foot changes from 1963 to 1971. D. Net dune foot changes from 1971 to 1977. E. Net dune foot changes from 1977 to 1998. F. Net dune foot changes from 1998 to 2010.

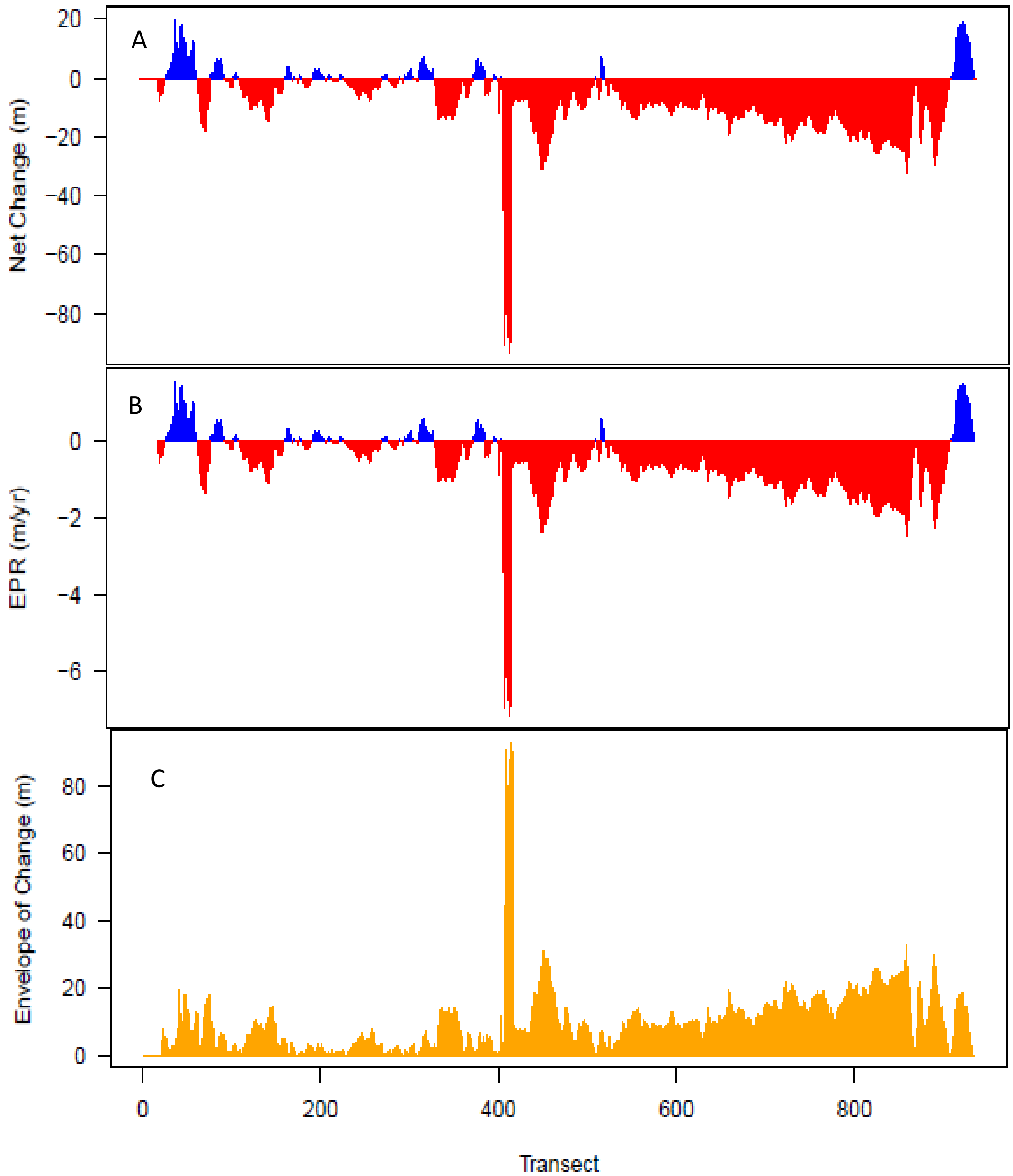

Figure 23: Decadal dune foot change 1950-1963. A. Net shoreline change in meters. B. End point rate in meters per year. C. Shoreline envelope of change in meters.

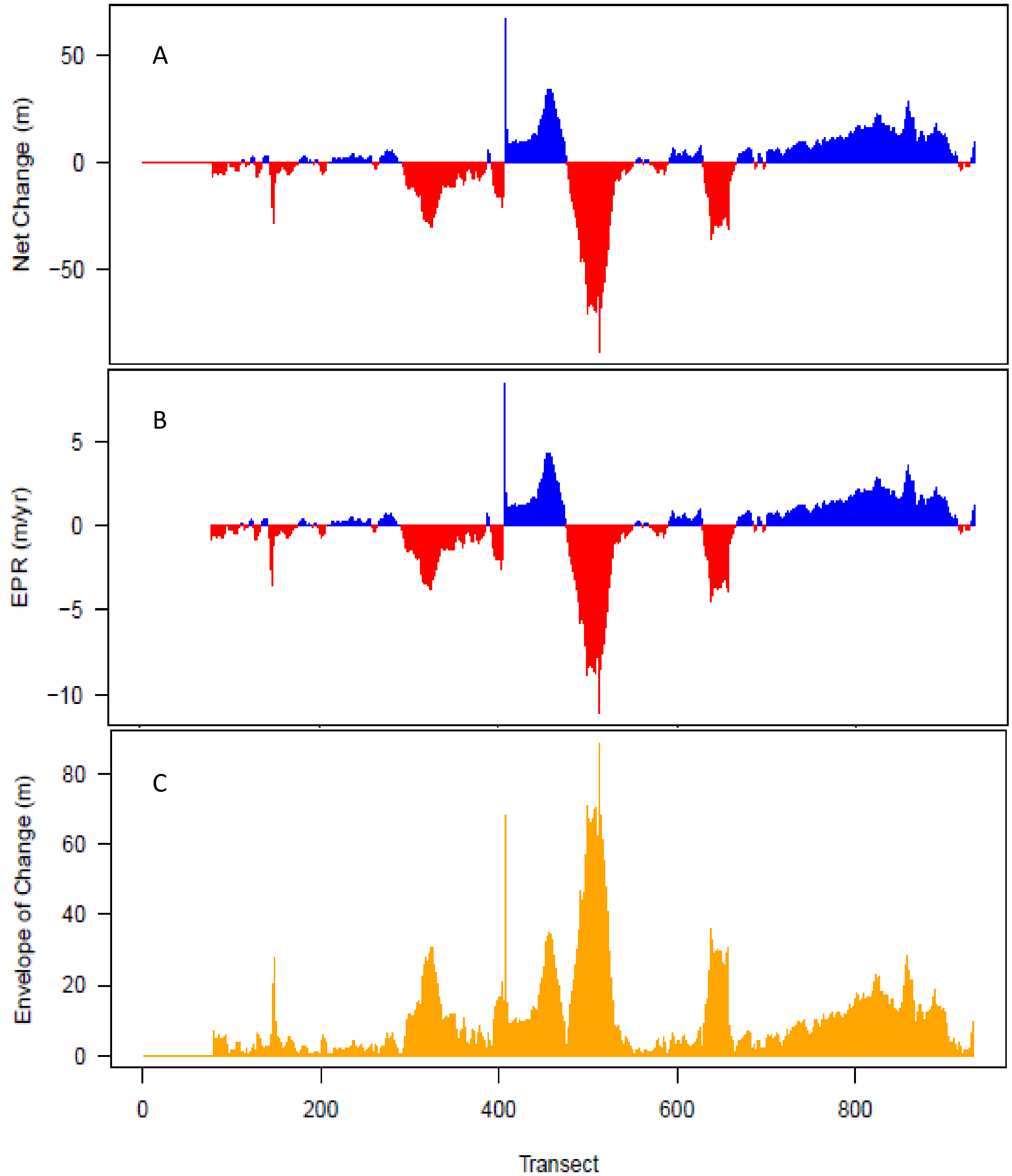

Figure 24: Decadal dune foot change 1963-1971. A. Net shoreline change in meters. B. End point rate in meters per year. C. Shoreline envelope of change in meters.

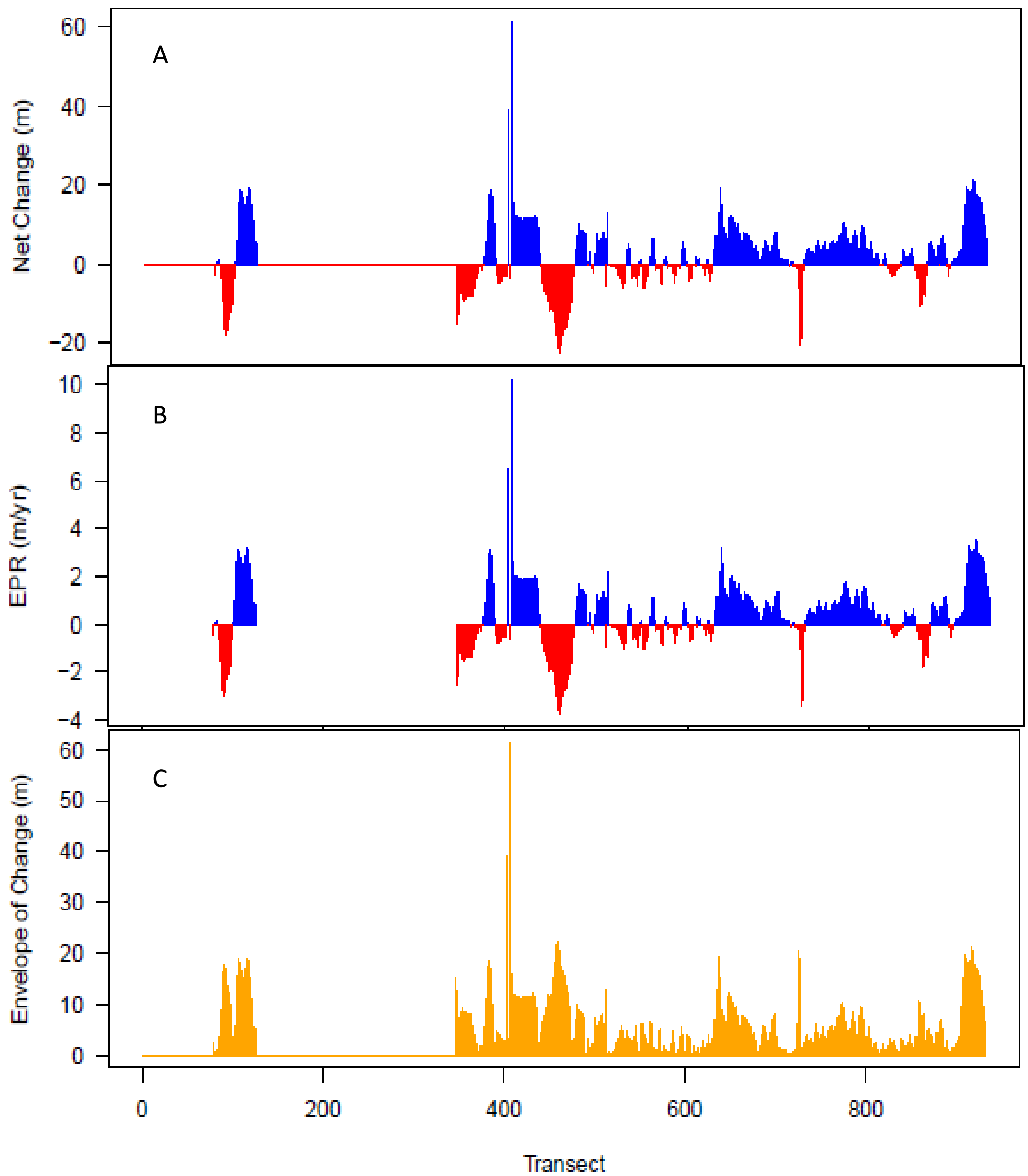

Figure 23: Decadal dune foot change 1971-1977. A. Net shoreline change in meters. B. End point rate in meters per year. C. Shoreline envelope of change in meters.

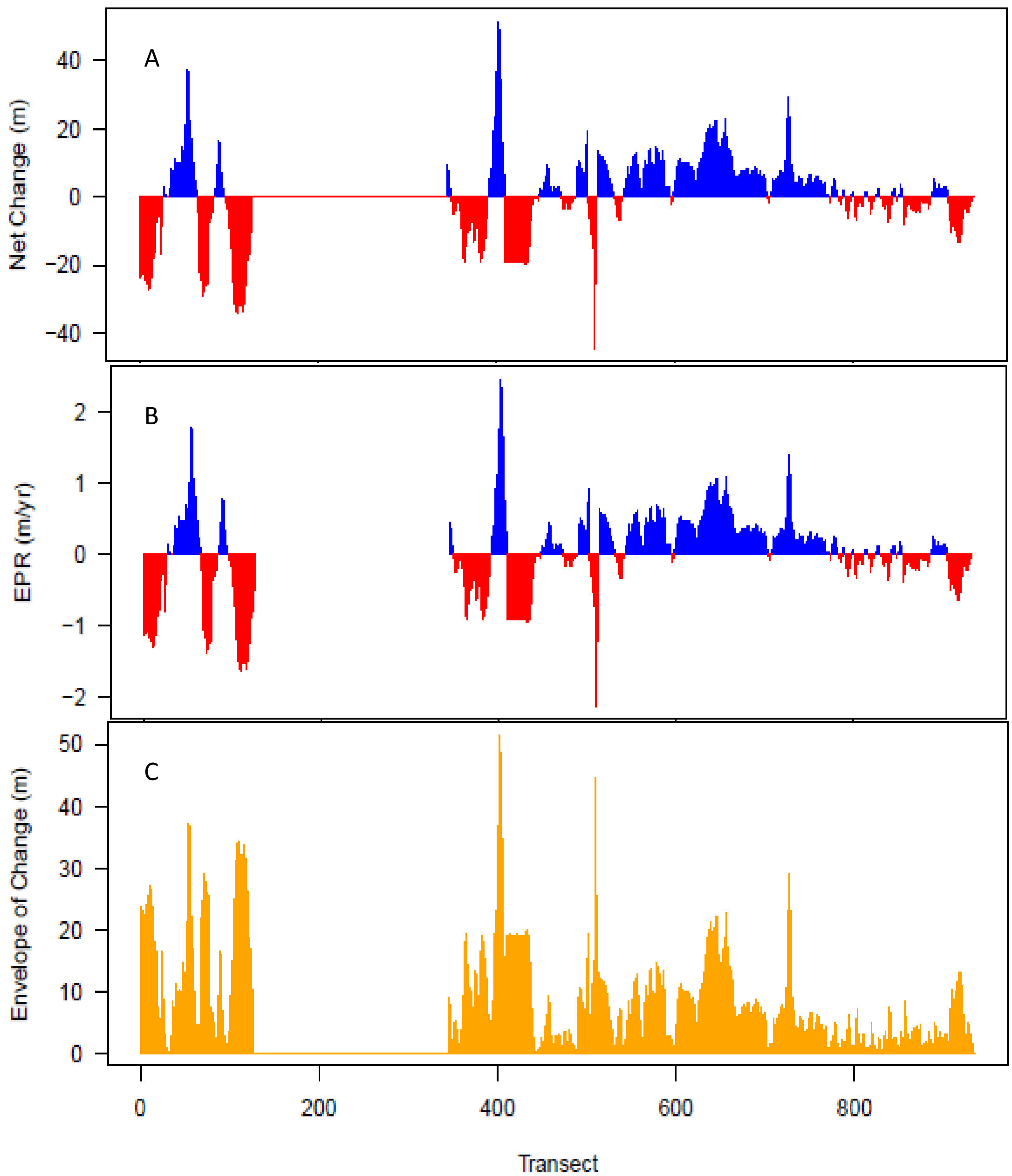

Figure 26: Decadal dune foot change 1977-1998. A. Net shoreline change in meters. B. End point rate in meters per year. C. Shoreline envelope of change in meters.

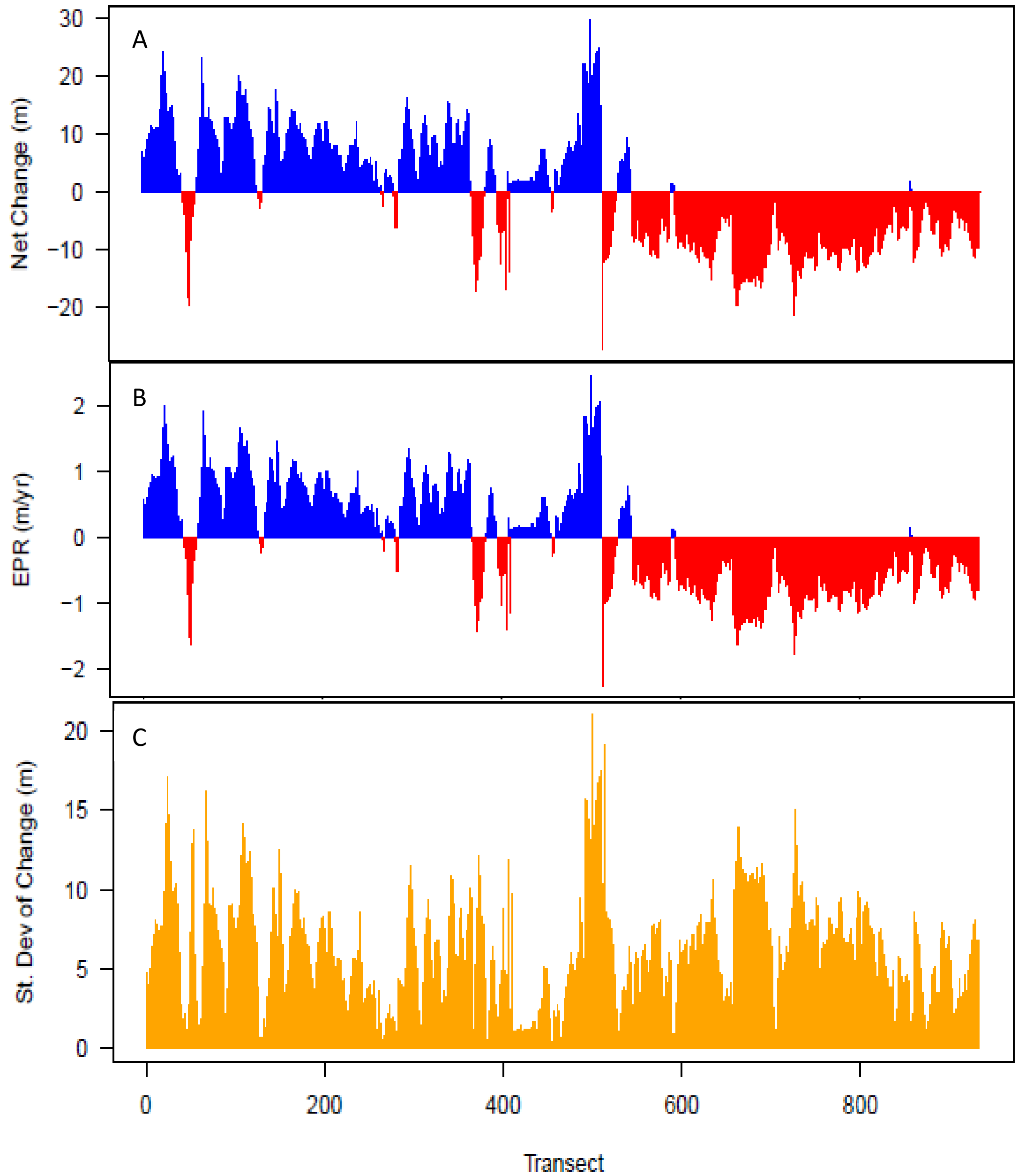

Figure 27: Decadal dune foot change 1998-2010. A. Net shoreline change in meters. B. End point rate in meters per year. C. Shoreline envelope of change in meters.

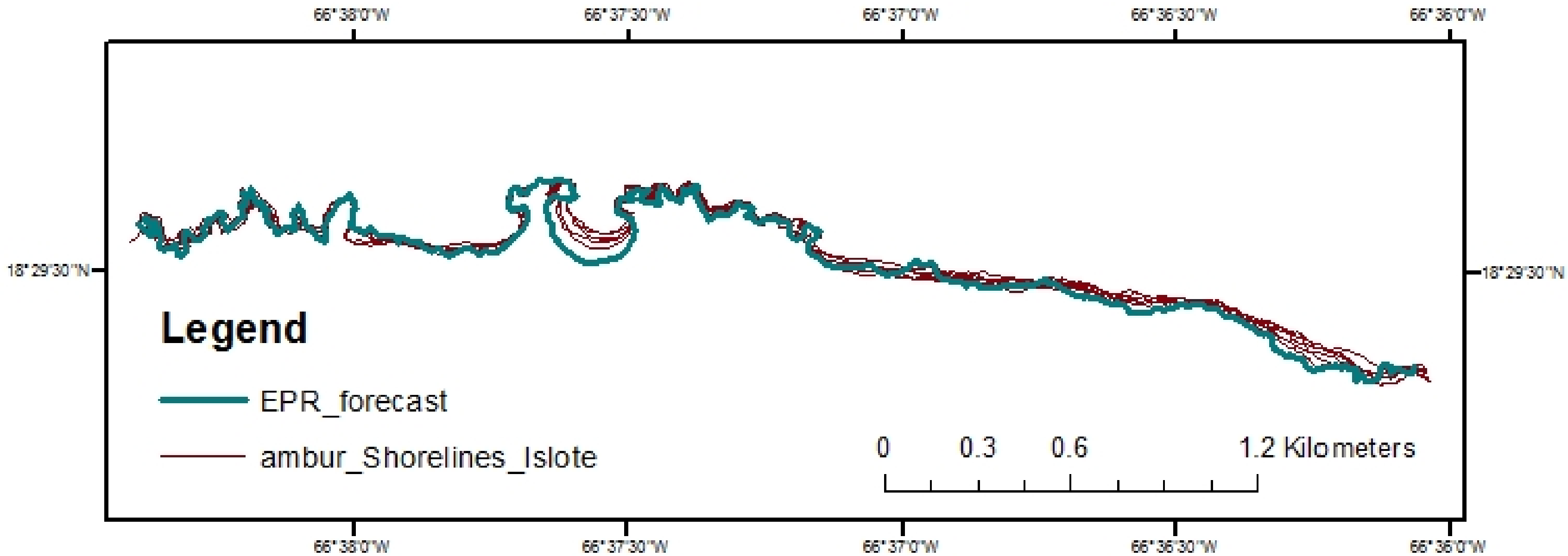

Figure 28: Map displaying a 50 year forecast from the 2010 shoreline. The teal line shows the shoreline of 2060.

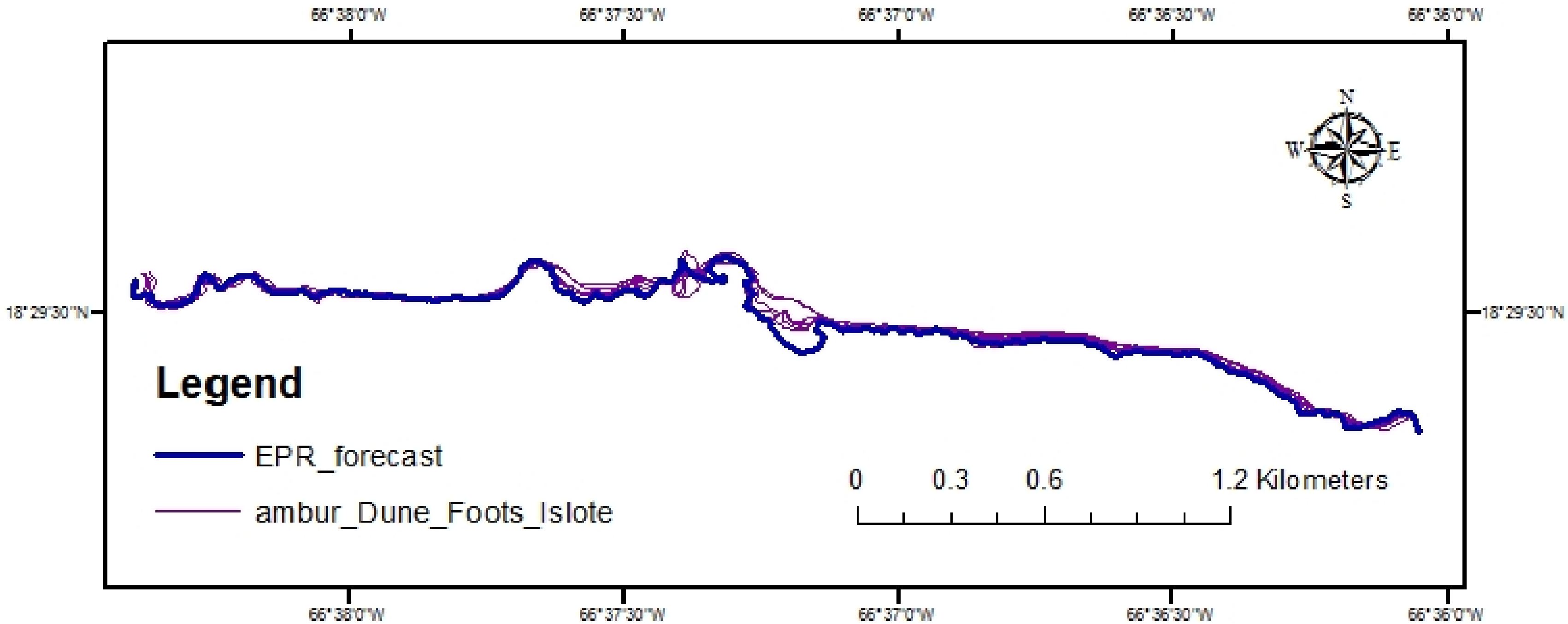

Figure 29: Map displaying a 50 year forecast from the 2010 dune foot. The teal line shows the dune foot of 2060.

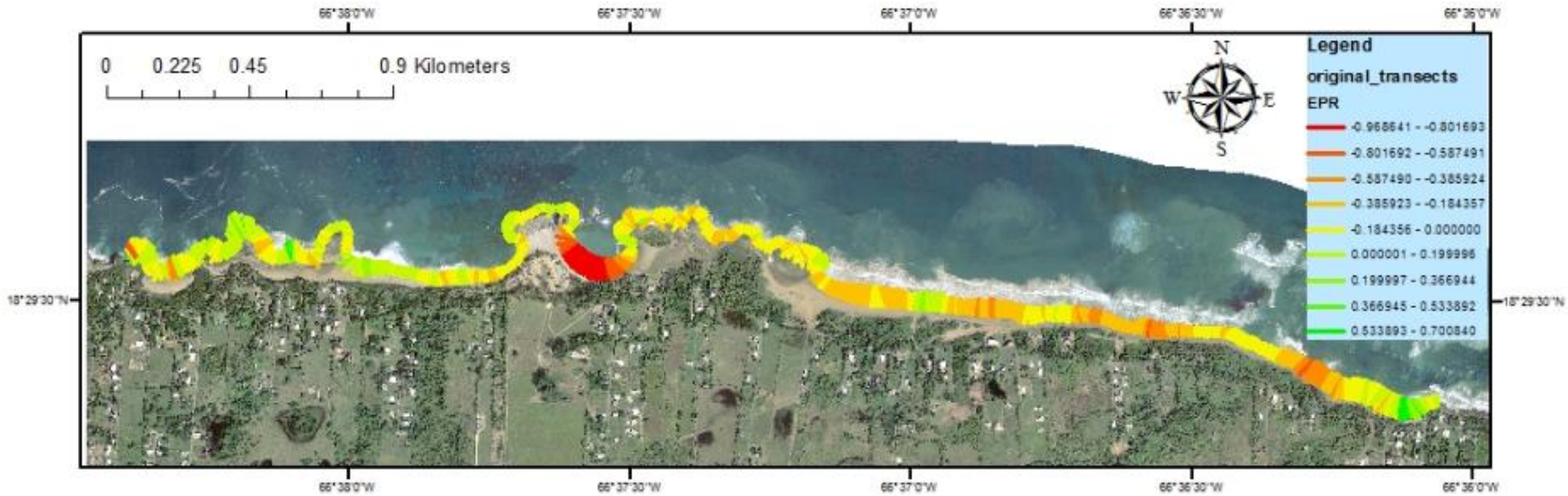

Figure 30: Shoreline spatial analysis with the EPR parameter. Greenish colors indicate accretion and reddish colors indicate erosion.

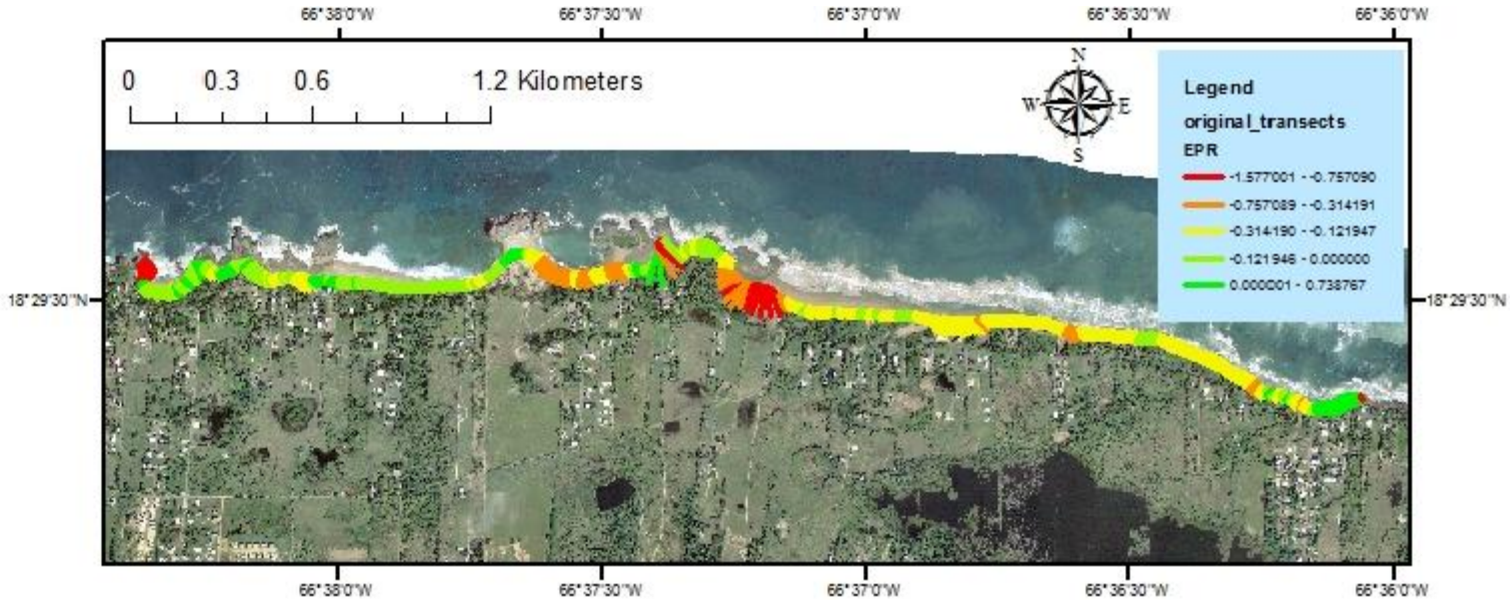

Figure 31: Dune foot spatial analysis with the EPR parameter. Greenish colors indicate accretion and reddish colors indicate erosion.

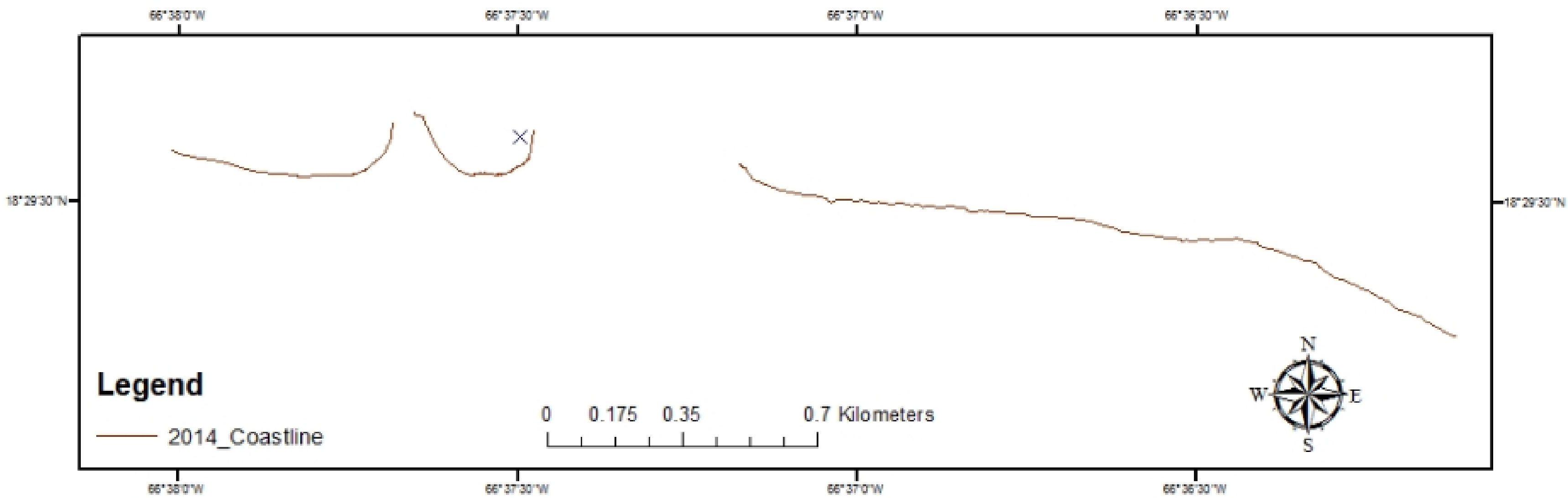

Figure 32: Map displaying the 2014 shoreline. Missing areas were rocky areas not studied because they were not safe to pass through.

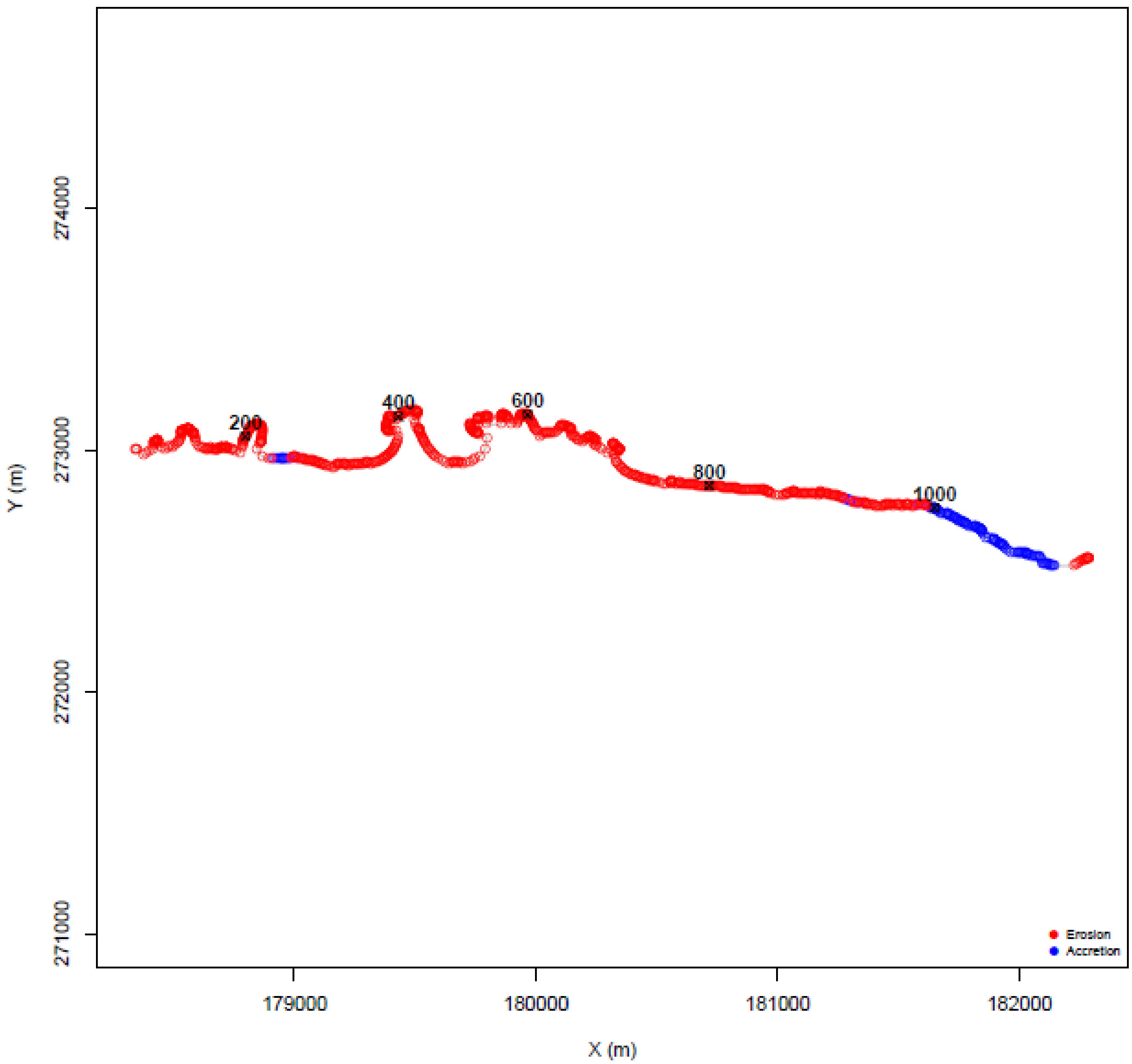

Figure 33: Map displaying the shoreline net change from 1950 to 2014.

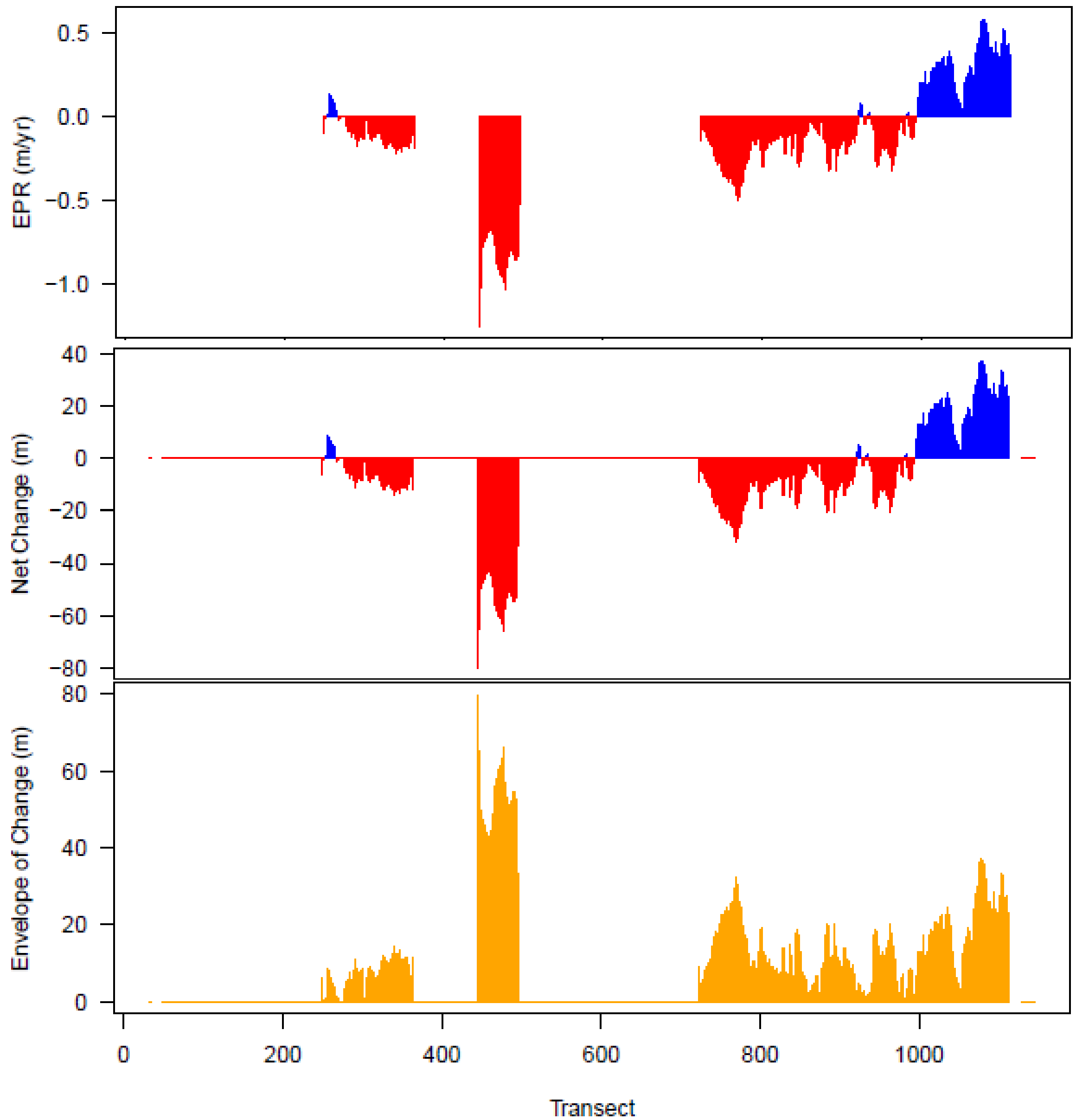

Figure 34: Shoreline change statistics from 1950-2014. A. Graph displaying the net shoreline changes in meters. B. Graph displaying the end point rate in meters per year. C. Graph displaying the shoreline change envelope in meters.

Tables

Table 1: Statistics of shoreline change between the AMBUR and DSAS extension tools.

Comparison of Shoreline Change with AMBUR and DSAS			
	EPR	NSM	SCE
DSAS Mean	-0.10 m/yr	-6.2 m	27.2 m
DSAS St. Dev.	0.28 m/yr	15.6 m	13.4 m
AMBUR Mean	-0.11 m/yr	-6.5 m	37.1 m
AMBUR St. Dev	0.21 m/yr	12.9 m	14.3 m

Table 2: Statistics of eolian deposits change between the AMBUR and DSAS extension tools.

Comparison of Eolian Deposits Change with AMBUR and DSAS			
	EPR	NSM	SCE
DSAS Mean	-0.21 m/yr	-12.6 m	17.3 m
DSAS St. Dev.	0.29 m/yr	27.2 m	21.1 m
AMBUR Mean	-0.15 m/yr	-9.1 m	33.0 m
AMBUR St. Dev	0.24 m/yr	14.3 m	15.0 m