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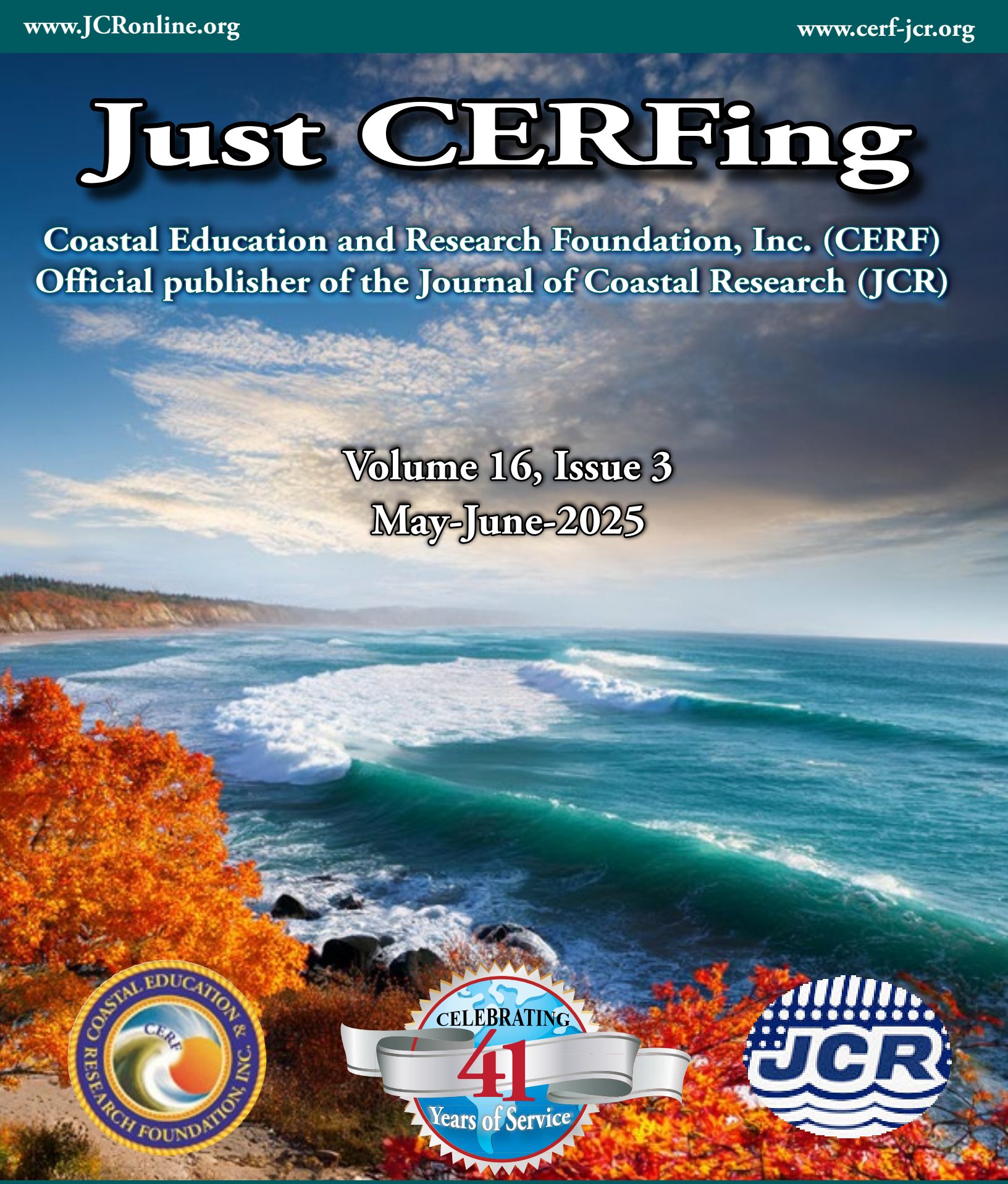

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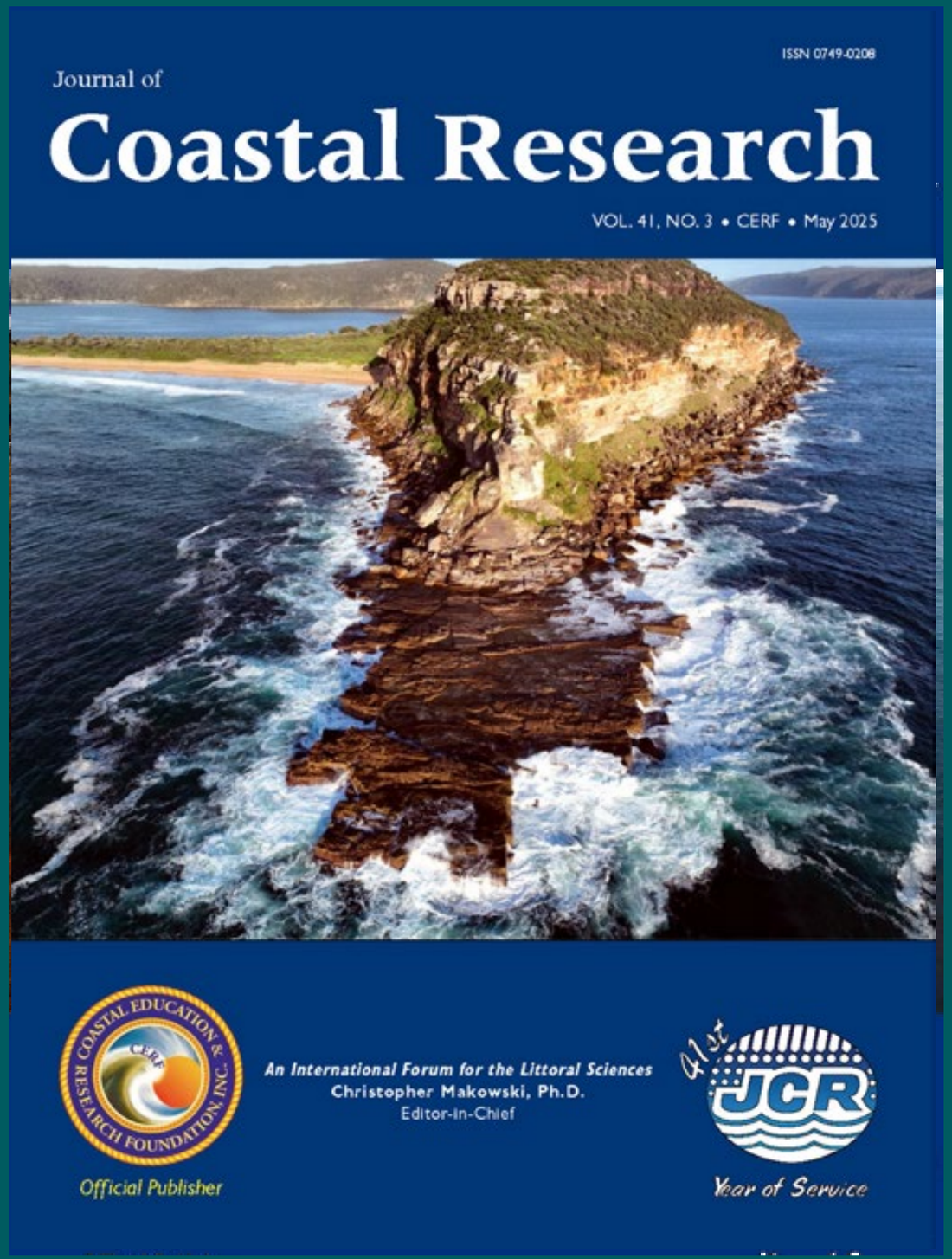

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COVER PHOTO

Barrenjoey Head, Broken Bay, NSW, Australia. Barrenjoey Head is a prominent headland located at the northern tip of Sydney (Latitude 33.5° S). The 104 m high headland forms the southern entrance to Broken Bay, a large drowned valley named by Captain James Cook the day after he departed Botany Bay. On 7 March 1770, as Cook sailed past the 3.5 km bay entrance, he sighted the numerous 'broken' headlands including Barrenjoey, Lion Island, and the First, Second and Third heads. His journal reports: "… some broken land that appear'd to form a bay … I named Broken Bay." Along the northern headland, Cook described: "Some pretty high land which projected out in 3 bluff Points, and occasioned my calling it Cape 3 Points." The southern headland was named Barrenjuee by Governor Phillip, the first governor of the new penal settlement of New South Wales, when he sailed as part of the first Europeans to enter the bay in 1788. The name refers to the aboriginal name for a small wallaby.

The Nepean-Hawkesbury river system which enters the bay began being settled soon after, with fishermen occupying the coastal areas and farmers (and escaped convicts) spreading up the Hawkesbury and its tributaries in search of fertile floodplains. While much development has taken place along the coastal strip, much of the shoreline and surrounding sandstone plateaus remain undeveloped and part of Bouddi, Brisbane Water and Ku-ring-gai national parks. Barrenjoey is connected to the mainland by a 1.3 km long beach (Palm Beach) and Holocene barrier, the initial 300 m wide regressive barrier now capped by stabilized transgressive dunes along its northern third, with a golf course, park and surf lifesaving club along its southern part. An arm of the bay called Pittwater lies behind the barrier.

The headland is composed of horizontally bedded Triassic sedimentary rocks. Hawkesbury Sandstone caps the upper third of the headland. It is a massive well-cemented quartz sandstone exhibiting distinctive inclined laminated cross-bedding. The lower two-thirds of headland consist of coarse-grained iron-stained sandstones interbedded with shale and siltstone of the Newport Formation. Both units display strong rectangular jointing which produces large joint blocks which fall from the cliff and collect along the landward margin of the rock platform. It is well exposed to an energetic wave climate with the predominately south swell averaging 1.6 m, and cyclonic wave commonly reaching several meters. The headland is surrounded by a well-developed supratidal rock platform which is widest at its eastern end, while considerable boulder debris covers the platform on its northern and southern side. The entire base is however accessible on foot. While the wave attack expends most of its energy breaking over the edge of the platform and remove debris from the platform, the sheltered cliff itself is retreating more rapidly. This is owing to the impact of subaerial weathering coupled with salt water and spray, which leads to an accelerated decomposition and failure of the cliff face, with gravity and wave constantly removing the smaller debris.

A temporary beacon was established on the headland in 1855, with a light tower constructed in 1865 and the present day sandstone lighthouse and keeper cottages in 1881. The headland, which is accessible on foot, is now part of Ku-ring-gai Chase National Park and offers guided tour of the lighthouse. (Photograph taken 5 March 2024 by John Hudson, Bawley Point, NSW, Australia.)

Segmentation and Classification of Pleiades Satellite Imagery for Complex Shoreline Proxy Delineation in the Western Canadian Arctic

Segmentation and Classification of Pleiades Satellite Imagery for Complex Shoreline Proxy Delineation in the Western Canadian Arctic

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ABSTRACT

Permafrost coasts are vulnerable to the effects of climate change, including above average warming in the Arctic, sealevel rise, and changes to sea-ice extent and duration. As a result, coastal erosion represents a prominent hazard that impacts communities and habitats locally, but it also potentially releases significant amounts of organic carbon that are consequential to understanding global greenhouse gas emissions, which requires appropriate quantification and monitoring. The extent and complexity of Arctic coasts represent a challenge for effective broad-scale monitoring using traditional methods of manual coastline delineation. In this study, an alternative to manual coastline delineation is presented using object-based image analysis to classify very high resolution Pleiades satellite imagery (0.5 m/pixel) scenes and subsequently extract two common coastline proxies, the tundra line and waterline.This study focused on three large, varied, coastal stretches in the Western Canadian Arctic: the Yukon North Slope, Tuktoyaktuk Peninsula, and Darnley Bay coasts. Twenty-five (25) images were classified with high accuracy (92% average), while the majority of extracted coastline proxies were within 3.0 m of the reference features and in many scenarios had accuracies better than 1.5 m, which is comparable to expected digitizing error, or loss of accuracy, associated with the variance of repeated shoreline digitization of the same coastal extent. This work presents an important step towards broadscale Arctic coastal change monitoring and quantification through semi-automated classification and feature extraction techniques, which will also enhance contextual information useful in conducting richer Arctic coastal erosion studies.

ADDITIONAL INDEX WORDS: *Arctic coastal erosion, object-based image analysis, coastal monitoring, remote sensing.*

INTRODUCTION

Of the more than 45,000 km of Arctic coasts, many segments are particularly vulnerable to the effects of climate warming and have seen an increase in retreat rates in recent decades (Gunther *et al.*, 2015; Irrgang *et al.*, 2018; Jones *et al.*, 2009, 2018). Arctic coastal erosion results from the combined effects of thermal and mechanical drivers where amplified surface air temperatures and solar radiation (Cohen *et al.*, 2014; Serreze *et al.*, 2009) lead to slumping through permafrost thaw and ground-ice melt (Nielsen *et al.*, 2020), while changes in the Arctic sea-ice regime mean coasts are exposed to longer periods of open water and greater fetch, contributing to increased storm frequency and intensity (Barnhart *et al.*, 2014; Casas- Prat and Wang, 2020; Nielsen *et al.*, 2020). Accelerating coastal erosion threatens infrastructure, coastal communities,and archaeological and coastal sites, and it creates risks for subsistence- based lifestyles (Couture *et al.*, 2018; Fritz, Vonk, and Lantuit, 2017; Obu *et al.*, 2017). Further, the erosion of permafrost coasts releases high volumes of organic carbon (OC) (Tanski *et al.*, 2019), which increases atmospheric and oceanic greenhouse gas concentrations, contributing to further warming (Schaefer *et al.*, 2014; Schuur *et al.*, 2015; Tanski *et al.*, 2019; Vonk *et al.*, 2012). Abrupt permafrost thaw due to coastal erosion is a relevant

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component of the Arctic carbon cycle, which is not included in the current generation of Earth system models (Nielsen *et al.*, 2022), potentially resulting in underestimated projections of OC losses (Martin *et al.*, 2021; Turetsky *et al.*, 2020). Therefore, this work advances broad-scale Arctic coastline delineation through a semi-automated object-based approach to aid in the monitoring of erosion using very high resolution (VHR; 50 cm/pixel) satellite imagery.

Arctic coasts represent 30%–34% of Earth's coastline (Lantuit *et al.*, 2012; Walker, 2005) and are characterized by high geomorphic variability (Irrgang *et al.*, 2022). Approximately 65% of Arctic coasts are unlithified and erosive, characterized by ice-rich permafrost bluffs, lagoon–barrier island systems, beach ridge complexes, spits, and deltas, and they are found primarily in Alaska, Canada, and Siberia (Farquharson *et al.*, 2018; Gunther *et al.*, 2013; Irrgang *et al.*, 2018; Jones *et al.*, 2018; Lantuit *et al.*, 2011; Lim *et al.*, 2020; Novikova *et al.*, 2018). Most current coastal change observations are derived from historical and research biases towards discrete sections of unlithified coasts near settlements or military infrastructure (Cunliffe *et al.*, 2019; Gunther *et al.*, 2013; Jones *et al.*, 2018; Lantuit and Pollard, 2008; Obu *et al.*, 2017; Radosavljevic *et al.*, 2016). Fortunately, developments in remote-sensing technologies have led to increasing high-spatiotemporal-resolution data sets allowing for investigation of remote areas and more comprehensive analysis of coastal dynamics (Cunliffe *et al.*, 2019; Jones *et al.*, 2018). In this study, three coastal stretches in the Western Canadian Arctic, each exceeding 100 km in length and representing three distinct coastal environments, were investigated using the latest high-resolution satellite imagery (50 cm/ pixel). The study sites included the rocky coasts of Darnley Bay in the Northwest Territories, the low-plain, ice-rich coasts of the Tuktoyaktuk Peninsula in the Northwest Territories, and the unconsolidated cliff- and bluff-dominated coasts of the Yukon. Because these study sites provide a representative coverage of Arctic coastal geomorphic variability, the semi-automated approach presented here can be extended to the entire Arctic, which is otherwise prohibitive using the traditional manual approaches.

Measurements of coastal changes are typically derived from the distances between multiple temporal shoreline positions and reported as an annual average in meters per year. Shoreline positions are often generated through manual interpretation and delineation of a shoreline proxy, which is dictated by the application, data availability, and data quality (Boak and Turner, 2005). More recently, efforts have been made to develop automated coastline delineation approaches (Bengoufa *et al.*, 2021; Goldstein, Coco, and Plant, 2019; Hoonhout *et al.*, 2015; Pardo-Pascual *et al.*, 2012; Philipp *et al.*, 2022); however, many of these studies focused on lower latitude coasts utilizing lower resolution (10–30+ m/pixel) satellite imagery, which limits delineation accuracy and subsequent quantification accuracy. Other studies (Aryal *et al.*, 2021; Kaiser *et al.*, 2021) have used VHR imagery (<1 m/ pixel), like that used in this study, to detect automated shoreline change of Arctic lakes. Differences in shoreline proxy, observation period, data resolution, and coastal extent have been shown to be highly spatially and temporally variable (Gunther *et al.*, 2013; Irrgang *et al.*, 2018; Jones *et al.*, 2018; Obu *et al.*, 2016; Solomon, 2005) and make cross-study comparisons challenging (Irrgang *et al.*, 2022). To assist future studies of Arctic coastal erosion monitoring, particularly to enhance current understanding of coastal dynamics over large scales, environmental drivers, shoreline change rates, and the role of Arctic coasts in the global climate system, this paper introduces and validates an object-based approach for coastal classification and proxy extraction for improved accuracy, frequency, and extent along varied Arctic coastal types. Specifically, VHR satellite imagery (0.5 m/pixel) and objectbased image classification approaches are leveraged to create broad-scale coastal classifications of varying coastal types and identify multiple, site-specific, coastal proxies. The goals were to understand how different Arctic coastal environments affect classification accuracy and resulting feature extraction using validation points to assess classification accuracy and shore-perpendicular measurements, or transects, to assess the accuracy of the extracted features (waterline and tundra line) relative to manually identified reference features. If the coastal proxies generated through these methods are within the generally accepted delineation tolerances seen in the literature (Cunliffe *et al.*, 2019; Del Río and Gracia, 2013; Irrgang *et al.*, 2018; Radosavljevic *et al.*, 2016) for manually delineated coastal proxies, then this approach can be considered to be an accurate alternative to manual coastline digitization of Arctic coasts.

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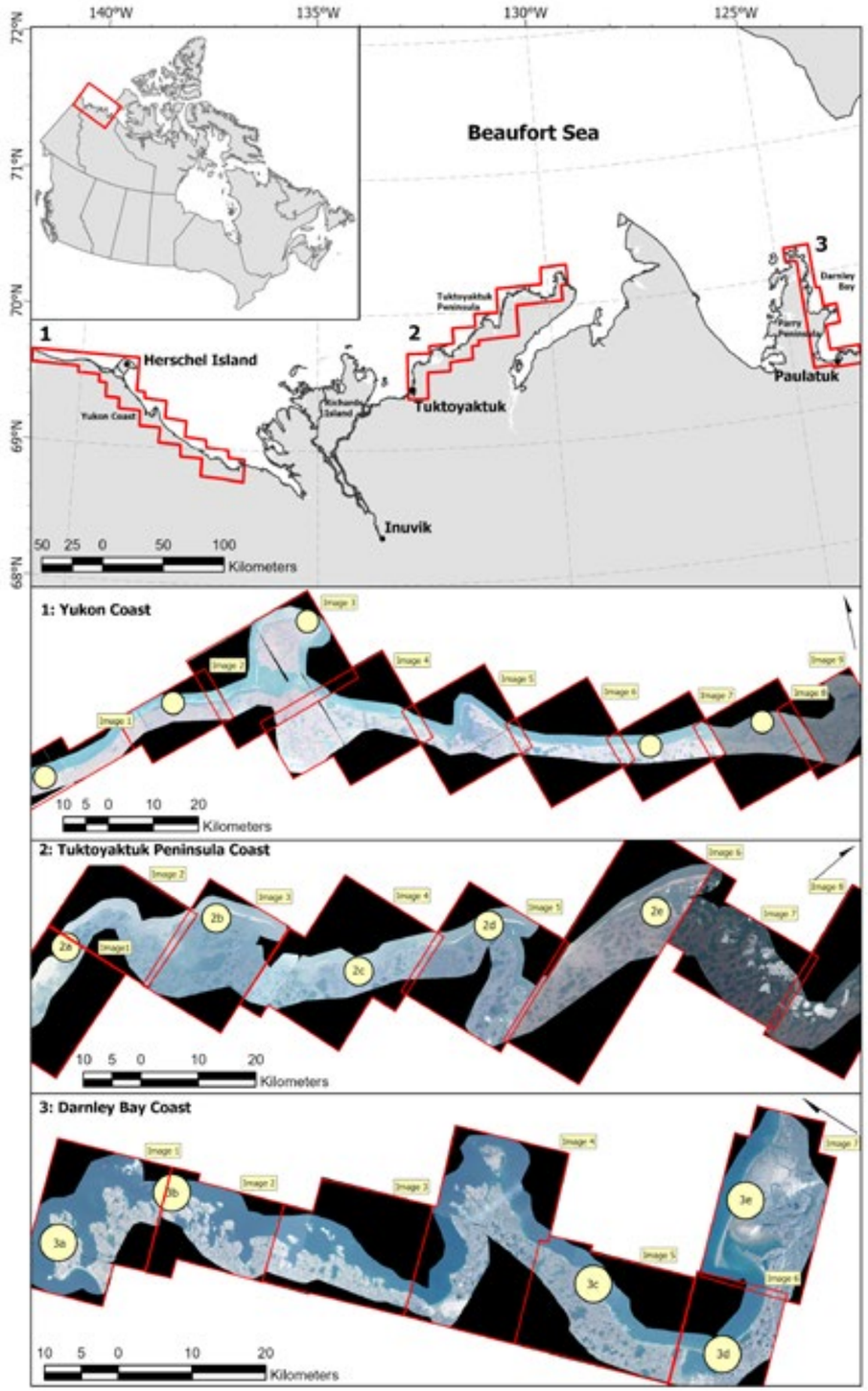

Figure 1. Coastal study areas of interest found in the Western Canadian Arctic. Study area 1 covers the Yukon coast and includes Herschel Island. Study area 2 covers the Tuktoyaktuk Peninsula in the Northwest Territories and includes the hamlet of Tuktoyaktuk near the western extent of the study area. Study area 3 covers the western coast of Darnley Bay and includes the hamlet of Paulatuk at the southernmost extent of the study area. Yellow circles (sections 1a–1d, 2a–2d, and 3a–3d) denote the location and extent of the validation sites along each coastal site, where the numerical value identifies the coastal area of interest (i.e. 1 = Yukon coast), while the accompanying alphanumerical value denotes the specific site identifier, which are referenced throughout the text. Image labels indicate the extent of individual image analysis. Labelled images are mosaicked images from pansharpened image tiles.

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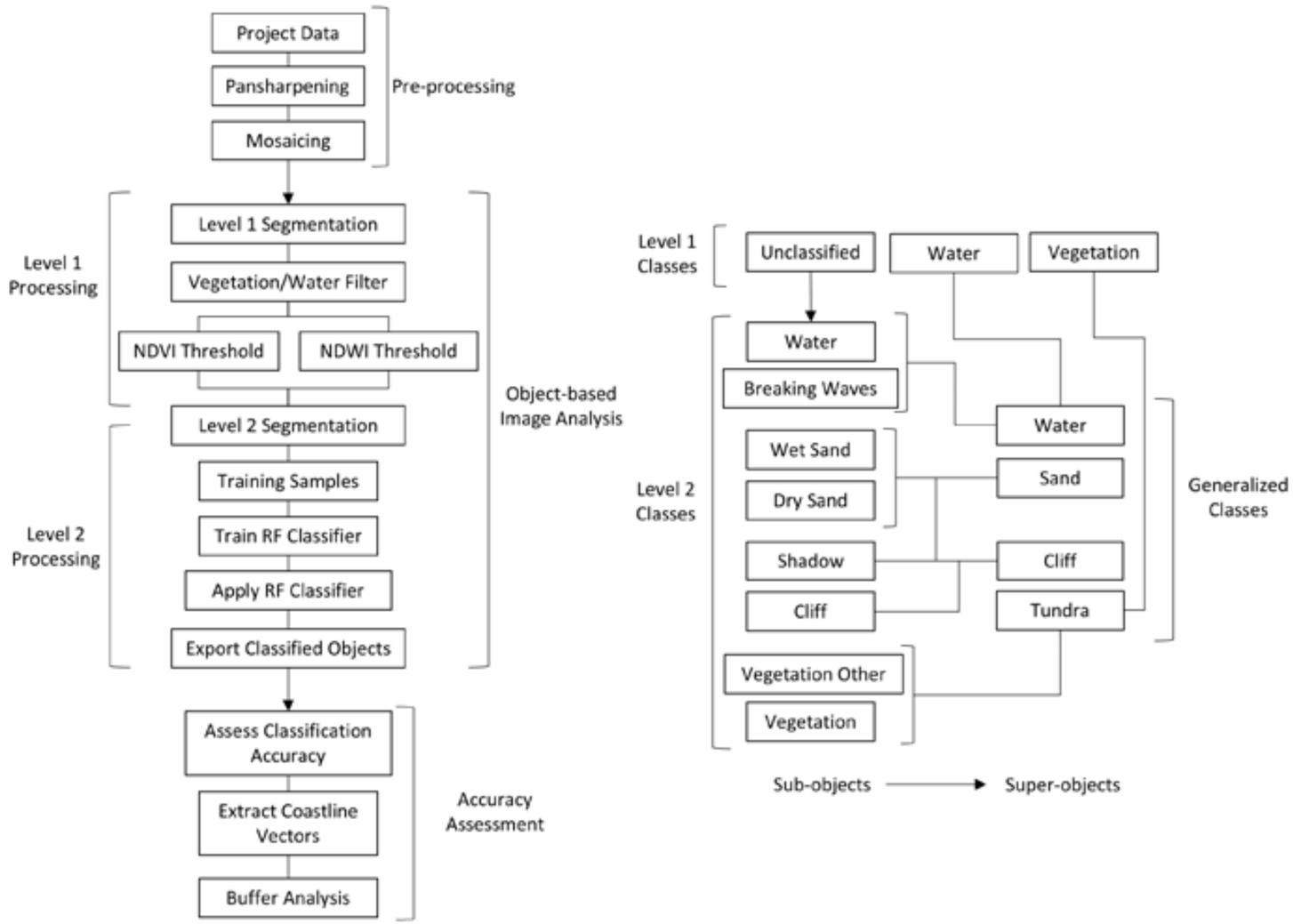

Figure 2. Data processing, analysis, and accuracy assessment and classification scheme. Data processing involved projecting the source imagery to a geographic coordinate system and subsequently pansharpening to 0.5 m/pixel. Images were mosaicked to preserve spectral uniformity and create functional subregions of analysis. Two segmentation levels were used during object-based image analysis, where a larger segmentation scale (first level) was used to filter out vegetation and water, while the second level focused on the coastal boundary area by creating a smaller segmentation scale, allowing for further discrimination between classes. The classification scheme (right) shows the relation between processing levels and class similarities used to generalize the classifications.

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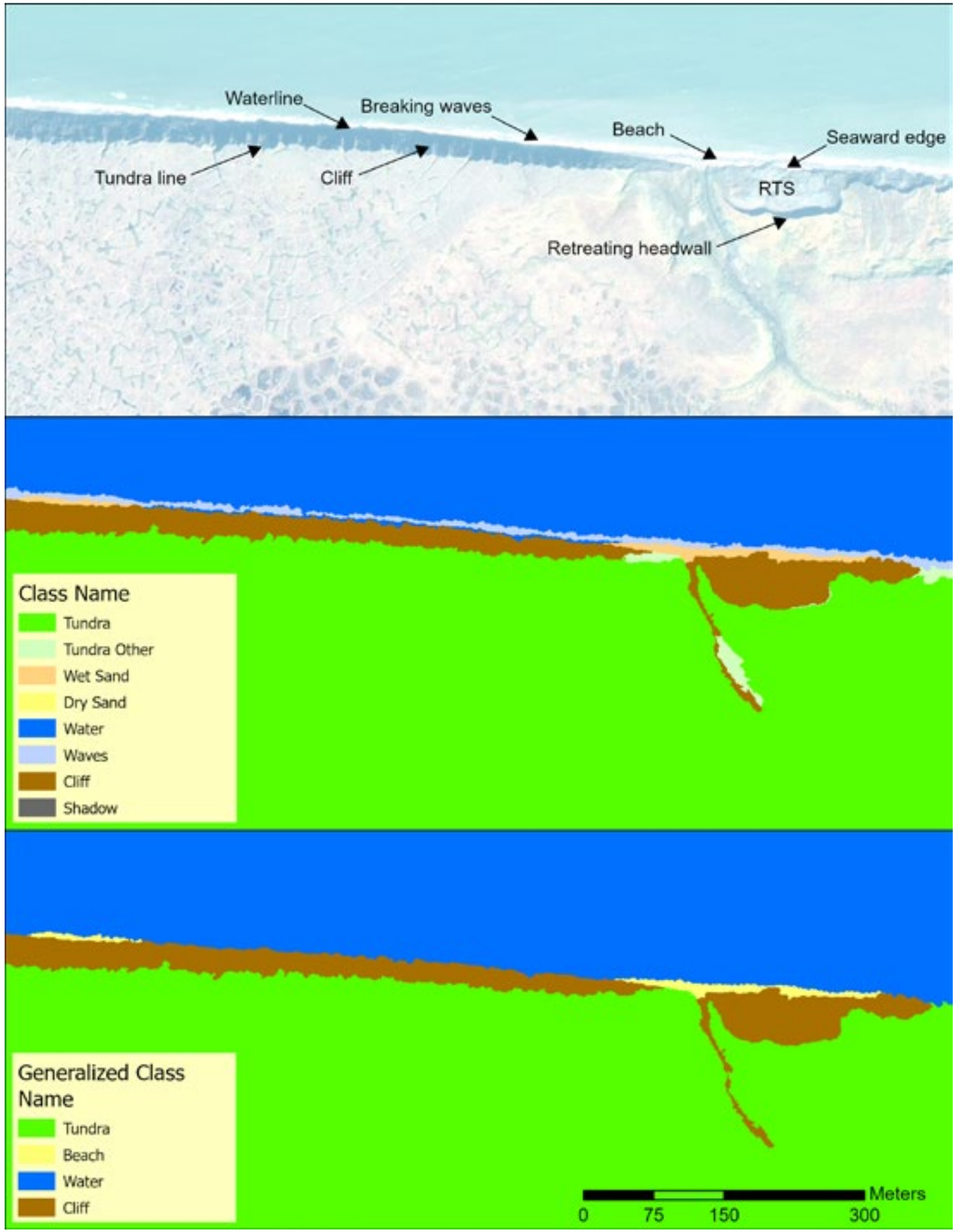

Figure 3. Classified objects to generalized objects along a section of the Yukon coast. The top panel is the true-color image for the classified area. To the left, there is a retrogressive thaw slump that is classified between the Cliff class and Tundra Other class, which becomes part of the Tundra class. The Waves class is captured by the Water class in the generalized classification. Dry Sand and Wet Sand are combined to make a Beach class in the generalized classification.

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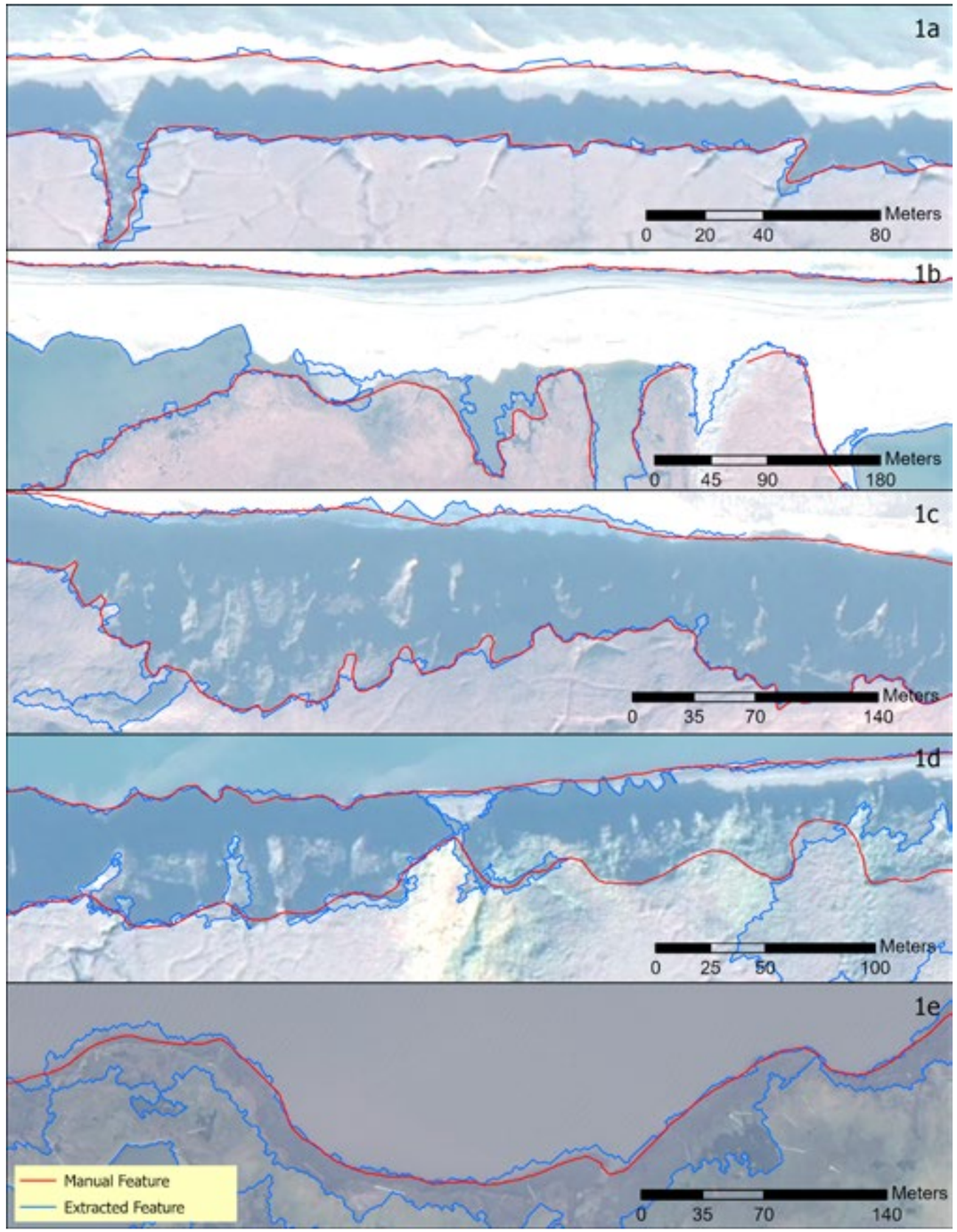

Figure 4. Sample areas of the validation regions along the Yukon coast. Panel labels correspond to validation regions denoted by yellow circle labels in Figure 1. Blue lines are the extracted features (waterline and tundra line), while the red lines are the manually delineated features. Coastal settings are described in Table 4.

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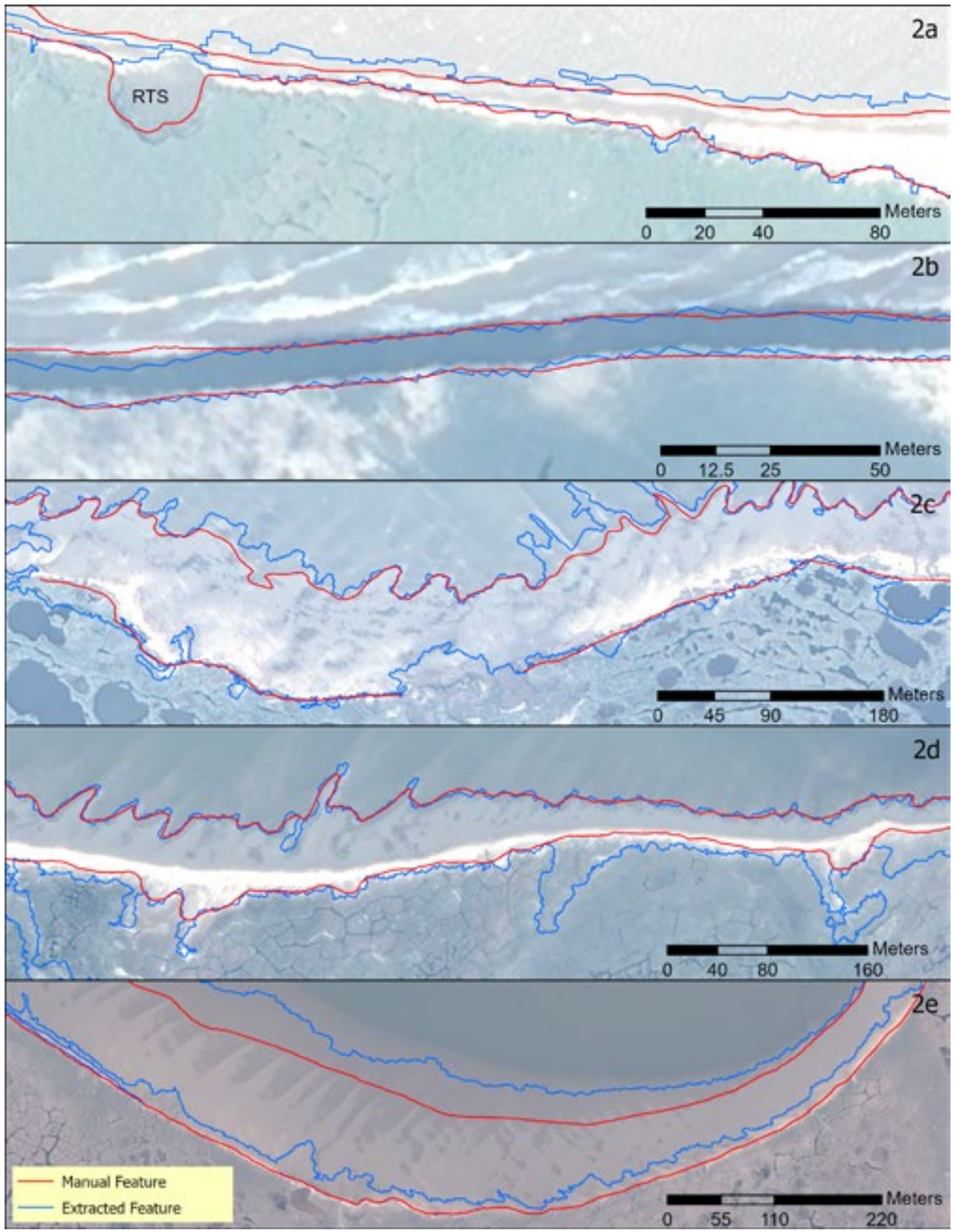

Figure 5. Sample areas of the validation regions along the Tuktoyaktuk Peninsula coast. Panel labels correspond to validation regions denoted by yellow circle labels in Figure 1. Blue lines are the extracted features (waterline and tundra line), while the red lines are the manually delineated features. Coastal settings are described in Table 5.

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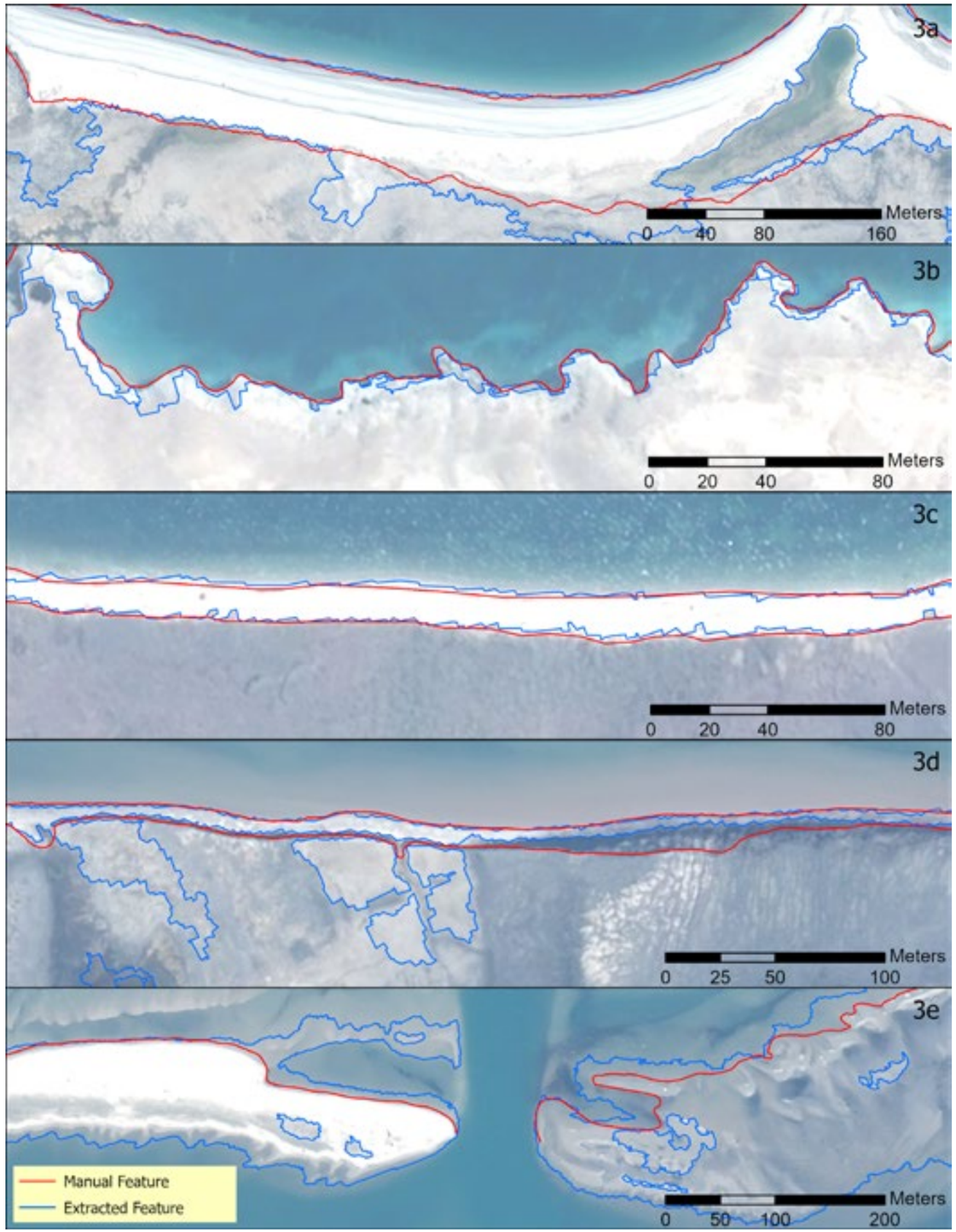

Figure 6. Sample areas of the validation regions along the Darnley Bay coast. Panel labels correspond to validation regions denoted by yellow circle labels in Figure 1. Blue lines are the extracted features (waterline and tundra line), while the red lines are the manually delineated features. Coastal settings are described in Table 6.

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Newly Announced:
SEA BEYOND OCEAN LITERACY CENTRE OPENS IN VENICE

https://www.pradagroup.com/en.html

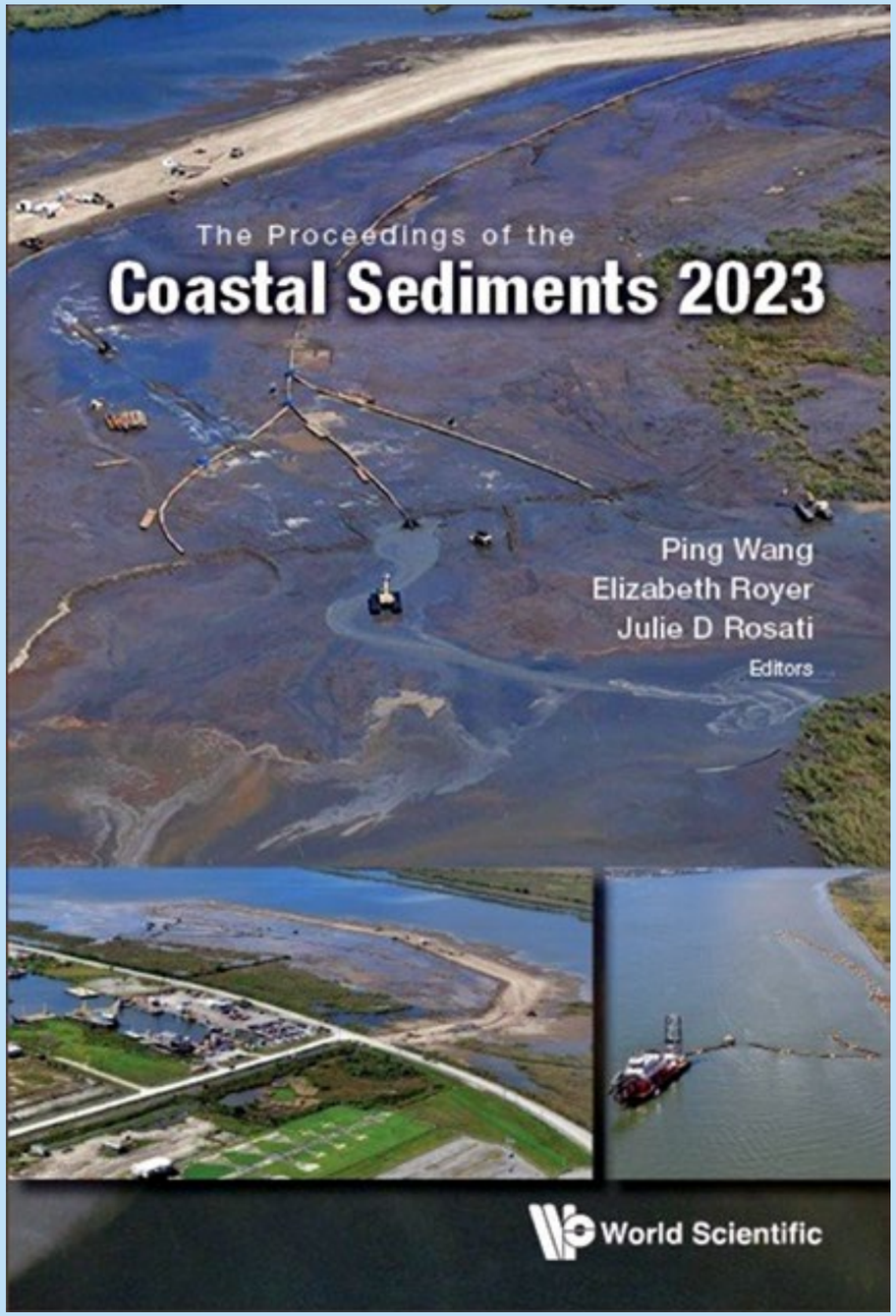
The Prada Group and UNESCO-IOC announce the opening of the first Italian centre dedicated entirely to ocean literacy, co-designed by CRA-Carlo Ratti Associati, located on the island of San Servolo in the Venetian Lagoon.

The ocean, human beings, and how each influences the other. The first and only Italian Centre dedicated to ocean literacy, which opens today, aims to encourage a wide and diverse audience to engage with this vital topic. The initiative is promoted by Prada Group and the Intergovernmental Oceanographic Commission of UNESCO (UNESCO-IOC), and forms part of the SEA BEYOND project, which has been working since 2019 to increase awareness among the younger generations of issues surrounding sustainability and ocean preservation. The SEA BEYOND Ocean Literacy Centre, co-designed by CRA-Carlo Ratti Associati and UNESCO-IOC, is located on the island of San Servolo, a cultural hub in the Venetian Lagoon that is already home to various major institutions. The choice of site is both tangibly and symbolically significant, as the area is a unique example of a 'transition ecosystem' shaped by continuous interactions between land, sea and humankind.

It was for this reason that Venice was selected for the first Ocean Literacy World Conference in June 2024, a two-day event that ended with 131 delegates representing UNESCO member states signing the Venice Declaration for Ocean Literacy in Action, a ten-point manifesto designed to restore society's relationship with the ocean.

The Centre's activities – designed to foster dialogue and employing an accessible, inclusive and multi-sensory approach – have been developed for students of all ages, local communities, researchers, residents, and tourists from both Italy and overseas. These diverse audiences will be addressed in a similarly broad language that compares ideas and perspectives from different disciplines. The aim is to encourage visitors to think critically about their relationship with the ocean, and the lagoon, and to adopt positive.

NEWLY PUBLISHED: PROCEEDINGS ANNOUNCEMENT



https://www.worldscientific.com/doi/epdf/10.1142/13358

This proceedings collection contains approximately 270 papers on a wide range of research topics related to coastal sediment processes, including nearshore sediment transport and modeling, beach processes, shore protection and coastal managements, and coastal resilience building.

This unique book provides a comprehensive documentation of cutting-edge research on coastal sediment process and morphodynamics from eminent researchers worldwide. Readers can learn from the most current coastal research studies and expand their knowledge on a numerous selection of topics related to coastal sediment processes and shore protection.

Edited by:

Ping Wang (University of South Florida, USA), Elizabeth Royer (University of South Florida, USA), and Julie D. Rosati (US Army Corps of Engineers, USA)

NEW BOOK ANNOUNCEMENT

https://www.cambridge.org/gb/academic/subjects/earth-and-environmental-science/sedimentology-and-stratigraphy/beach-inlet-interaction-and-sediment-management?format=HB

Beaches, barrier islands and tidal inlets are valuable coastal resources and provide desirable environments that are often densely populated. They are dynamic landforms that change constantly, driven by both normal processes and energetic storms. They behave as one interconnected system and must be understood and managed as such. This book discusses their various morphologic features, as well as the processes that shape them and future challenges due to environmental change. A major focus is placed on the interaction between sandy beaches and tidal inlets, and the sediment exchange among various morphologic features. Balancing these valuable sediment resources while maintaining the natural sediment exchange constitutes a major goal of modern shore protection and coastal management. Illustrated with numerous aerial photographs to demonstrate how beaches and tidal inlets interact, this book provides a valuable reference for graduate students, researchers and professionals working in coastal management and geomorphology.

- Presents an in-depth overview of beaches, barrier islands and tidal inlets, which is essential to shore protection and coastal management.
- Includes a discussion of multiple-scale beach and inlet processes and their interactions, making it a complete go-to reference on beach-inlet interaction and sediment management.
- Explains how beaches, barrier islands and tidal inlets are an interconnected system and how by treating them as such, management strategies can address both the protection of sandy beaches and inlet navigation safety.
- Discusses coastal sediment management which represents a major future direction in shore protection

Author Profiles

Ping Wang, University of South Florida
Dr Ping Wang is a Professor of Geology at the University of South Florida. He has been teaching and conducting research on barrier-inlet systems for over twenty years. He has over 100 publications in peer-reviewed journals, edited books and conference proceedings. The practical aspect of his research focuses on shore protection and coastal management.

Tanya M. Beck, US Army Engineer Research and Development Center
Dr Tanya M. Beck is the Program Manager for the Coastal Inlets Research Program, in the Coastal and Hydraulics Laboratory (CHL) at the US Army Engineer Research and Development Center (ERDC). She obtained her PhD in Geology from the University of South Florida and has published numerous technical reports and peer-reviewed articles. Her research focuses on the coastal environment related to geomorphic long-term evolution, erosion and sedimentation, and regional management of coastlines.

Longshore Sediment Transport and Sediment Budgets, Southeast Florida Coast, U.S.A.

Longshore Sediment Transport and Sediment Budgets, Southeast Florida Coast, U.S.A.

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ABSTRACT

Longshore sand transport (LST) along the SE coast of Florida was studied based on measured and modeled data of waves and currents (tide and wave driven), including the effect of the Florida Current. Much of the white sands on Florida beaches comprises a mixture of quartz crystals, coral fossil fragments, and mollusk shell fragments. The median grain size varies from about 0.3 mm at Palm Beaches to about 0.4 mm at Miami-Dade Beaches. Coastal reef systems are especially typical phenomena in the SE Florida region. Beach erosion is a major problem along the SE Florida coast because of (1) presence of rather steep seabed slopes in the surf zone and nearshore zone, (2) absence of natural and protective dunes with sufficient sand, and (3) presence of many inlets with jetties and insufficient bypassing of sediment. Beach erosion is strongly related to the variation of LST. Three approaches have been used to determine the input data and boundary conditions for computation of LST using an empirical LST equation: (1) measured nearshore wave data, (2) modeled nearshore wave data by the SWAN model, and (3) modeled nearshore waves and currents by the Delft-SWAN model system. A reliable indication of the net LST values was also obtained from the annual inlet bypass volumes of sand at various inlets. The modeled results show that the LST along the coastal section between Lake Worth Inlet and Miami from north to south with net LST values decreasing from 150,000 m^3/y (±30%) at Lake Worth Inlet to about 50,000 m^3/y (±30%) at Miami. The decreasing trend is caused by a milder wave climate and slightly coarser sediments in the southern direction. The LST results, in combination with available data of beach nourishments, were used to determine the overall sand budget of the SE Florida coast.

ADDITIONAL INDEX WORDS: *Longshore sand transport modeling, sand budget SE Florida coast, hydrodynamic field data SE Florida coast, SEFMOD study SE Florida*.

INTRODUCTION

The coastal system of SE Florida extends over approximately 180 km (100 mi) south of Lake Worth (LW) Inlet and comprises an interconnected chain of straight beach sections and barrier islands, dissected by smallscale tidal inlets, through which sediment is exchanged with the littoral zone of the open coast and back-barrier basin (Figure 1). Some of the tidal inlets at the Florida coast serve as navigation (shipping) channels for commercial and recreational vessels. Safe navigation often requires the presence of hard jetties for inlet stability and maintenance dredging activities of channel deposits for optimum navigability.

The beaches of the SE Atlantic Coast Region of Florida comprise sand and coral sediments in the range of 0.2 to 0.8 mm and are widely used by residents and tourists because of proximity to urban areas and easy access by vehicular

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traffic (Benedet, Finkl, and Klein, 2004). High ecological values are present in the form of ancient reef tracts covered with corals and biological communities that extend from the Florida Keys to St. Lucie County and includes the study area.

Unfortunately, many of the beaches in the SE Florida region are in poor condition, typified by narrow dunes and beaches (<30 m), steep beach profiles, absences of pronounced breaker bars, and shortage of sand due to severe erosion. Some beaches are armored with seawalls, bulkheads, revetments, straight and T-head groins of rocks, timber, piles, and reef-type breakwaters. Beaches in the north near LW Inlet and Port Everglades (PE) Inlet are extremely narrow and steep, whereas beaches north of Miami Harbor (MH) Inlet (Government Cut) are flatter and wider. Many eroded beaches are intensively nourished with sand from borrow sites on land or at sea, requiring regular maintenance (replenishment) of sand (FDEP, 2018b).

Earlier research work on the SE Florida coast was completed by Benedet, Finkl, and Klien (2004). They classified the beach state of the coastal segments using a beach state indicator defined as $\Omega = H_s/(w_s T)$, with Hs being the yearly average value of the significant wave height at the breaker line, T is the wave period, and w_s is the fall velocity of beach sediment.

The beaches between Palm Beach and southern Miami-Dade were classified as intermediate beaches ($\Omega \approx 5$) near Palm Beach to dissipative beaches ($\approx$ 1) near Miami. Intermediate beaches typically comprise medium to coarse sand with one breaker bar (plunging to spilling breakers), whereas dissipative beaches comprise fine-grained sediments with multiple low-relief breaker bars. More reflective beaches ($\Omega > 5$) with steeper slopes can be found north of Palm Beach. Finkl and Hobbs (2009) state that repetitive beach nourishments are necessary along the erosive beaches of the SE Florida coast because the nourishments reduce the strong vulnerability of the coast against storm effects. Finkl and Hobbs (2009) also discussed the need and consequences of mining of sand on the Continental Shelf as more nearshore sources of sand are exhausted. In line with this, Ousley, Kromhout, and Schrader (2012) and USACE (2014b) performed the Sediment Assessment and Needs Determination study. They quantified the beach nourishment needs (about 175 million cubic yd; 135 million cubic m) and available domestic sand resources (about

Figure 1. Plan view of inlets Lake Worth (LW) Inlet, Port Everglades (PE) Inlet, and Miami Harbor (MH) Inlet, Florida.

are necessary along the erosive beaches of the SE Florida coast because the nourishments reduce the strong vulnerability of the coast against storm effects. Finkl and Hobbs (2009) also discussed the need and consequences of mining of sand on the Continental Shelf as more nearshore sources of sand are exhausted. In line with this, Ousley, Kromhout, and Schrader (2012) and USACE (2014b) performed the Sediment Assessment and Needs Determination study. They quantified the beach nourishment needs (about 175 million cubic yd; 135 million cubic m) and available domestic sand resources (about are necessary along the erosive beaches of the SE Florida coast because the nourishments reduce the strong vulnerability of the coast against storm effects. Finkl and Hobbs (2009) also discussed the need and consequences of mining of sand on the Continental Shelf as more nearshore sources of sand are exhausted. In line with this, Ousley, Kromhout, and Schrader (2012) and USACE (2014b) performed the Sediment Assessment and Needs Determination study. They quantified the beach nourishment needs (about 175 million cubic yd; 135 million cubic m) and available domestic sand resources (about 285 million cubic yd of sediment; 220 million cubic m) within the limits of dredging technology to support the placement of beach nourishments along the SE Florida coast for the next 50 years.

Throughout the past three decades, the U.S. Army Corps of Engineers (USACE) and other federal, state, and local agencies have provided several investments (around tens of millions each year) to improve engineering

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practices at barrier-inlet systems. These investments were made in the pursuit of more sustainable regional sediment management of coastal sediment resources. Regional sediment management studies include regional-scale, offshore-sediment resource identification, as well as studies related to maintenance dredging and beach nourishment along adjacent shorelines. These types of plans are extensively discussed by Beck and Wang (2019) for inlet systems present along the SE Florida Coast.

In 2019, the USACE, Jacksonville District, Florida, embarked on a multiyear, multimillion dollar, and multiproject study called the Southeast Florida Sediment Morphodynamics (SEFMOD) study. The study team included USACE, Environmental Tracing (United Kingdom; Environmental Tracing, 2022a, b, c), Water-Proof Marine Consultancy (The Netherlands; WaterProof, 2022a–j), and Leo van Rijn-Consultancy (The Netherlands; van Rijn, 2022). All technical reports are publicly available from USACE, Jacksonville, Florida.

The study focused on improving sediment management at Palm Beach Harbor, PE Harbor, Miami-Dade County, and adjacent SE Florida beaches. The study implemented a large-scale field data collection campaign that included baseline acoustic Doppler current profiler (ADCP) velocity data acquisition to map the overall circulation as well as sediment (sand and silt) tracers released in a variety of ways and locations to identify sediment pathways. The study included detailed modeling of hydrodynamics and sediment dynamics for the entire study area between LW Inlet and Miami harbor Inlet.

Study Sites and Field Data

Brief descriptions of the three primary focus areas and surroundings (LW Inlet, PE Inlet, and Miami-Dade coastal area) in the SE Florida area are provided. Figure 1 provides a plan view of SE Florida with the study areas highlighted.

The LW Inlet and LW Lagoon are located in Palm Beach County along the SE coast of Florida. The LW Lagoon is a shallow water body typically ranging in depth from 0.3 to 3 m (1 to 10 ft). A barrier island separates the lagoon from the Atlantic Ocean. The Atlantic Intracoastal Waterway runs along the entire length of this estuary. Currently, the LW Lagoon receives drainage from approximately 1170 km^2 (450 mi^2). Excessive freshwater inflows over a short period of time cause a sudden drop in salinity. A major threat to LW Lagoon is excess suspended sediment loading. Suspended sediments increase turbidity and find their way into estuaries *via* fresh-water tributaries, canals, and upland run-off. As sediments fall out of suspension, they accumulate on the bottom, sometimes forming a silty layer over previously natural sediment. Three inlets are situated between LW Inlet and PE Inlet (from north to south): Boynton Inlet, Boca Raton Inlet, and Hillsboro Inlet (Figure 1).

Port Everglades is located in the Ft. Lauderdale area on the SE coastline of Florida between Hillsboro Inlet at 18 km in the north and Baker's Haulover (BH) Inlet at 22 km in the south. The PE Shipping Channel serves as the entrance to PE Harbor; the channel is about 240 m wide and has a maximum depth of 13.7 m mean lower low water. Inside the PE basin, waters from inland canals and surface runoff merge with oceanic waters. In the early 1970s, the Federal Harbor Deepening Project was initiated, focusing on widening and deepening of the entrance channel to 140 m (450 ft) and 13.7 m (45 ft), respectively. In 2005/2006, two boulder mound T-groins and one jetty spur groin were constructed immediately south of the south jetty for 210 m (700 ft). The federal navigation channel was maintenance dredged, and the dredged material was placed on the south State Park Beach (USACE, 2015).

In 2013, another navigation channel maintenance project placed additional beach-quality sand on the State Park Beach. In 2017, the PE Sand Bypassing Project was authorized (FDEP, 2018a). The project comprises a sediment impoundment basin (sand trap). The landward end of the rubble spoil shoal (approximately 340 m [1130 ft] in length from the 1962 port improvement project, will be excavated to remove non-beach compatible material and to re-expose a portion of a buried hard bottom. To date, this project has not been constructed.

The Miami-Dade study area includes the urbanized Miami-Dade County coast, including Golden Beach, Sunny Isles (SI) Beach, Haulover Park, BH Inlet, Bal Harbour, Surfside (SS) Beach, Miami Beach, Miami Harbor Inlet (Government Cut), Virginia Key, and Key Biscayne. Miami Harbor Inlet (Government Cut) is the main shipping channel located between Miami Beach and Fisher Island, which allows better access to the Port of Miami in Miami, Florida. The back-basin area of Miami Inlet is about 30 km^2. Another smaller inlet is BH Inlet between Haulover Park and Bal Harbour (between PE and Miami; Figure 1).

Biscayne Bay is SW of the City of Miami Beach and is divided from the

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Atlantic Ocean by many low-lying barrier isles (keys) along the coast. Biscayne Bay is a long, narrow water body with an average depth of 2 to 3 m (6 to 10 ft). The low elevations and connections to the Biscayne Bay place a significant percentage of the Miami-Dade area at risk of coastal and tidal flooding from high tides, hurricanes, and tropical storms.

Figure 2 depicts typical offshore profiles at each of the three study sites. At both PE Inlet and LW Inlet, the offshore profile is steep with slope values in the range of 1 to 10 and 1 to 20 and rapidly drops off with distance from shore. In the southern portion of Miami Beach, just north of Government Cut, a wide, shallow region extends 3 to 4 km offshore before a rapid drop off to depth.

Coral Reefs

Coastal reef systems are especially typical phenomena in the SE Florida region. The shoreface, beaches, dunes, and inland marsh areas are accumulated on top of landward extensions of bedrock highs. The rocky nature of the shore is visible at many places with exposed rock outcrops, and bedrock faces are present in the nearshore. Basically, the SE Florida coasts are sand-starved and must be periodically renourished so that the underlying bedrock is not exposed.

Three coral reef lines separated by sand–gravel–shell deposits (flats) run approximately parallel to the shore in water depths ranging between 5 m and 30 m. A series of ridges and colonized pavements exists in the nearshore landward of the inner reef (Figure 2).

Walker *et al*. (2012) and Walker and Klug (2014) have completed habitat mapping and coral reef community characterization in shallow waters (2 to 10 m). Of the 170 km^2 (65 mi2) seafloor mapped, the polygon totals indicated that about 40%was sand, 47% was coral reef and colonized pavement, 10%was seagrass, and 3% was other delineations.

Sediments at Beaches

Much of the white sands on Florida beaches comprises a mixture of quartz crystals, coral fossil fragments, and mollusk shell fragments. Grain size information is provided by Benedet, Finkl, and Klein (2004). Samples were collected on the beach and in shallow water. The calcium carbonate content of the beaches ranged up to 55%, with many beaches containing .40% carbonate. The mean grain sizes of nearshore sediments increase from north to south as the content of siliciclastic materials decreases and the calcium carbonate content increases. The median-grain size varies from about 0.3 mm at the Palm Beaches to about 0.4 mm at Miami-Dade Beaches, but coarser values in the southern part may reach 0.7 to 0.9 mm because of shell fragmentation (additional information provided by FDEP [2018a,b]). Various vibrocores were collected in 2006 and 2008 in the BH Inlet channel.

Based on this, the sediment within the channel was found to comprise poorly sorted, fine-grained sand with composite mean value of 0.26 mm. The average carbonate content was 48%; the average visual shell content was about 13%. A total of 15 samples were collected from Bal Harbour Beach in January 2009. These beach samples were poorly sorted, fine- to medium-grained sand with composite mean value of 0.57 mm, carbonate content of about 70%, and average visual shell content of 45%. Various samples from the beaches along the SE coast of Florida were collected and analyzed in 2022 (Water-Proof, 2022i). Characteristics of the samples are provided in Table 1. Typical results are (1) median particle size between 0.15 and 0.85 mm; (2) dry beach samples finer than samples from the low waterline; (3) coarser beach sediments in the south, with a relatively large percentage of carbonate materials (shell and coral fragments) south of Palm Beach; and (4) somewhat finer sand fraction (20%) than carbonate fraction, with particle-size distributions slightly bimodal.

Hydrodynamics

The morphology of inlets and adjacent beaches is mainly influenced by a combination of waves and tide-, wind- and wave-induced currents in the shallow nearshore zone and by the Florida Current (FC). The deformation of the tidal wave in the shallow nearshore area around the inlets affects the peak flood and ebb velocities in the inlet channel and the associated sediment transport rates. Generally, the flood period of the tidal cycle in the inlet channel is characterized by a relatively high-current velocity of short duration, whereas the ebb period has a relatively low velocity of longer duration. Thus, the inlet channel is mostly flood-dominated (peak flood velocity greater than peak ebb velocity). Residual currents are key for net sand-transport directions, particularly for fine sediments. Wave penetration through the inlet depends on the inlet geometry and the strength of the tidal currents. Most major inlets have hard jetties to stabilize local morphology and to prevent the deposition of longshore sand moving into the inlet channel. Jet flow around the jetty tips

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can modify the natural sediment bypassing patterns.

The FC is an ocean current through the Straits of Florida between the Florida Keys and Cuba and northward around the Florida peninsula. The FC is driven by water level and density gradients related to temperature gradients, atmospheric pressure gradients, wind forces, and Coriolis effects and generates strong flows over a rapidly changing three-dimensional topography of the Florida Strait. The FC involves a great variety of motions (e.g., meandering, eddies, energetic internal tides, up- and downwelling) spanning a large range of spatial scales on seasonal and interannual time scales. Soloviev *et al.* (2017) studied the FC along the SE Florida coast based on measured velocity data of ship-mounted ADCP, long-term moorings at depths of 11 m and 244 m, and ship transects (at latitude 26.28, about 60 km north of Miami) from offshore to the coast. Based on analysis of data over 13 years, Soloviev *et al.* (2017) have identified some typical phenomena: (1) strong variability on time scales of weeks, (2) northward-directed flow over most of the depth in deep water during most of the time, (3) southward countercurrent (occasional) in the nearshore coastal region during occasional events, and (4) southward undercurrents (occasional) in the shelf region and on the Miami Terrace shelf region.

The FC meanders in the Straits of Florida over days to weeks while undergoing distinct seasonal changes in vertical structure (Vassiliki, Kourafalou, and Kang, 2012). The velocities in the upper half of the flow can be as high as 2.5 m/s, whereas those at mid-depth are in the range of 0.5 to 1 m/s. The maximum current velocity mostly occurs in the deep offshore areas (350 to 700 m) of the Florida Strait, but occasionally the high-velocity zone shifts to the coastal zone with smaller depths (100 to 300 m) because of meandering and advection effects.

The SEFMOD study has produced an extensive database of Acoustic Doppler Current Profiler velocity data at many coastal locations from December 2019 to September 2020 (Environmental Tracing, 2022a,b,c). Figure 3 shows the frequency of occurrence of north- and south-going longshore currents at LW Inlet and PE Inlet, which occur most frequently (approximately 80% to 90% of the time). West- and east-going currents occur much less frequently (,10% to 20%). The highest current velocities do occur in the deepwater zone (.50 m), where the FC is dominant with north-going velocities up to 1.3 m/s at a depth of 70 m for 80% of the time. High velocities up to 0.9 m/s in the nearshore zone occur during storm events. Velocity data of ADCP-tracks near LW Inlet in the aftermath of Hurricane Dorian (8–15 September 2019) also show relatively high values up to 0.7 m/s in shallow nearshore water (10 to 15 m).

The strength of the current velocities gradually decreases toward the coast because of bottom friction; the frequency of south-going currents gradually increases from 20% in deep water to 30% to 40% in shallow nearshore water. South-going longshore currents are dominant (.70%) in the surf zone with breaking waves landward of the 7.5 m depth contour. Wave-induced longshore currents during daily conditions and minor storm events with waves up to 2 m are most intense in the inner surf zone landward of the 4.5 m depth contour.

Figure 4 shows similar frequency distributions for the near-shore moorings in the Miami-Dade area (data for December 2019 to July 2020, with only one month for August–September 2020 for BH 18 m [60 ft]). Most of the current velocities are in the range of 0.1 to 0.3 m/s. North-going currents dominate south-going currents at all locations. The highest currents are 0.6 to 0.7 m/s near BH Inlet. The goal of the modeling was to establish nearshore wave and sediment transport conditions that produced sediment transport rates and patterns consistent with generally accepted, average annual sediment transport rates along the county shoreline. Model results of net LST values for representative beach sand are as follows: 90,000 m^3/y at Hillsboro Inlet; 55,000 m^3/y at Northern Fort Lauderdale; 40,000 m^3/y at South Fort Lauderdale; and 40,000 m3/y at the southern Broward County line (Olsen Associates, 2020). These values have been used as validation data in the present paper.

The decrease in the net sand transport rate along the Broward County shoreline is principally due to the effect of variations in the width, depth, and configuration of the nearshore reef and hard-bottom features on the incident wave field along the county shoreline. The nearshore features offshore of the most northern Broward County shoreline are much narrower in the cross-shore direction and are deeper than the same features at the southern Broward County line. As such, more wave energy reaches the northern shoreline areas than the southern shoreline areas. This causes a gradual north to south reduction in the overall sand transport rates along the county shoreline.

A reliable indication of the net LST values can be obtained from the annual inlet bypass volumes of sand at various inlets (validation data). These latter

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volumes are provided in the 2021 report from the Florida Department of Environmental Protection (FDEP, 2021). The annual inlet report high-lights the surplus and deficit of material that is being bypassed on an annual basis to each side of an inlet that is actively managed. The bypass volumes annualized over approximately 20 years are shown in Table 2. The bypass volume varies between approximately 185,000 m^3/y at LW Inlet and about 30,000 m^3/y at BH Inlet. The most recent bypass volume at LW Inlet is about 115,000 m3/y. The bypass volume at PE Inlet is exceptionally small.

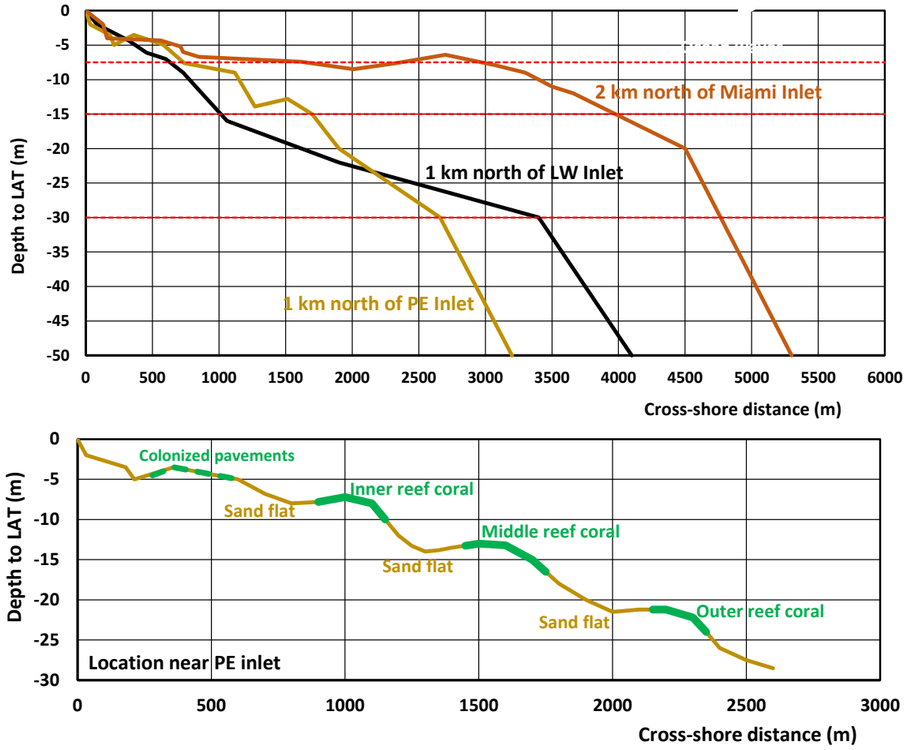
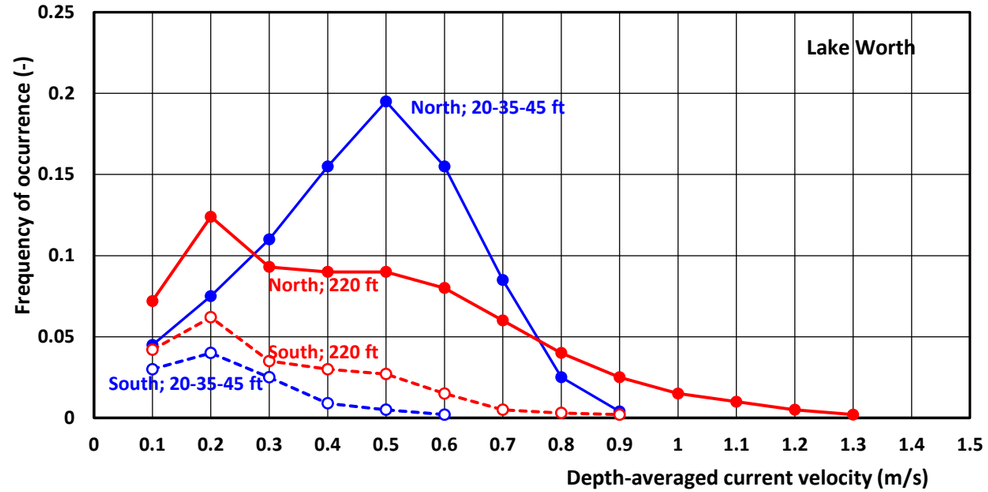


Figure 2. Typical cross-shore bed profiles at Lake Worth (LW), Port Everglades (PE), and Miami Harbor (MH), Florida.



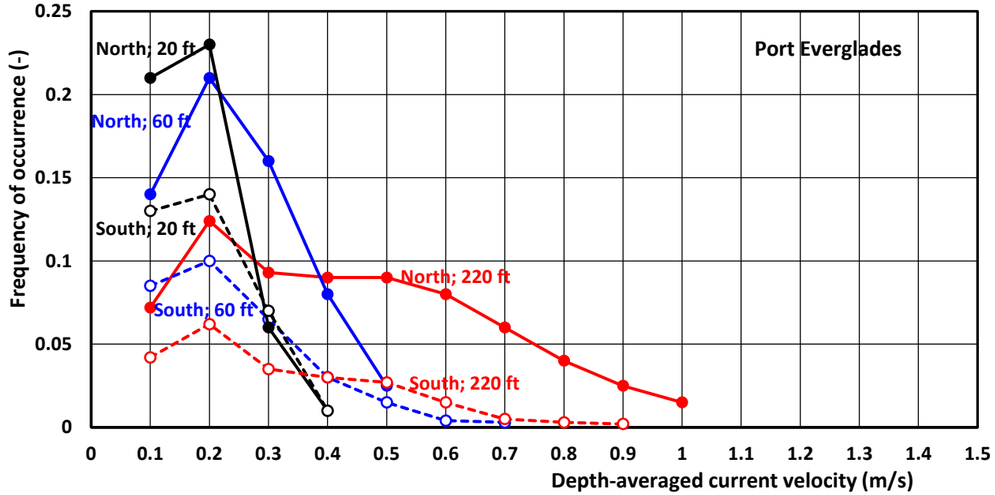


Figure 3. Frequency distributions of measured north- and south-going currents at depth of 6 to 67 m (20 to 220 ft) at Lake Worth Inlet and Port Everglades.

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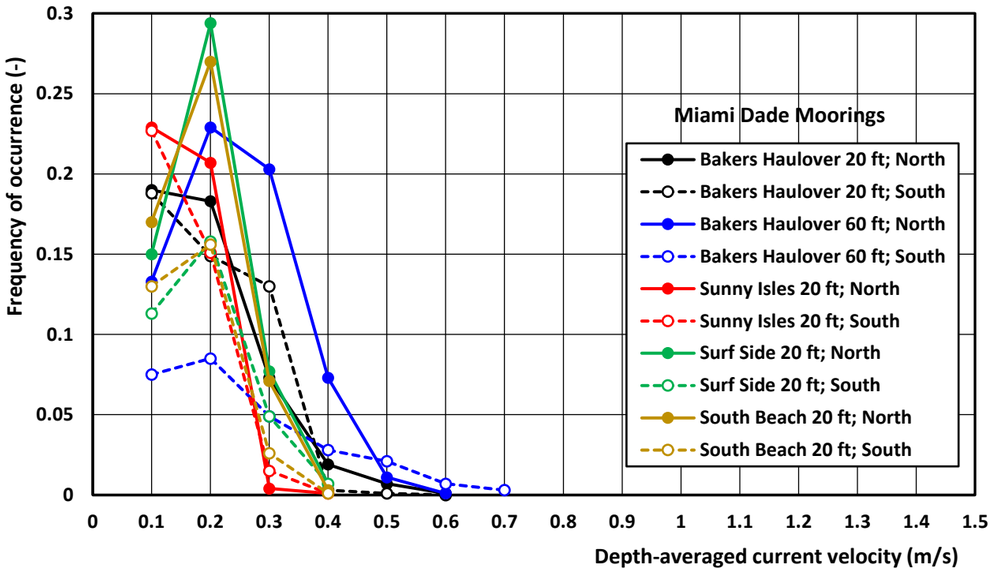

Figure 4. Frequency distributions of measured north- and south-going currents at depth of 6 to 18 m (20 and 60 ft) at Baker's Haulover, Sunny Isles, Surfside, and South Beach.

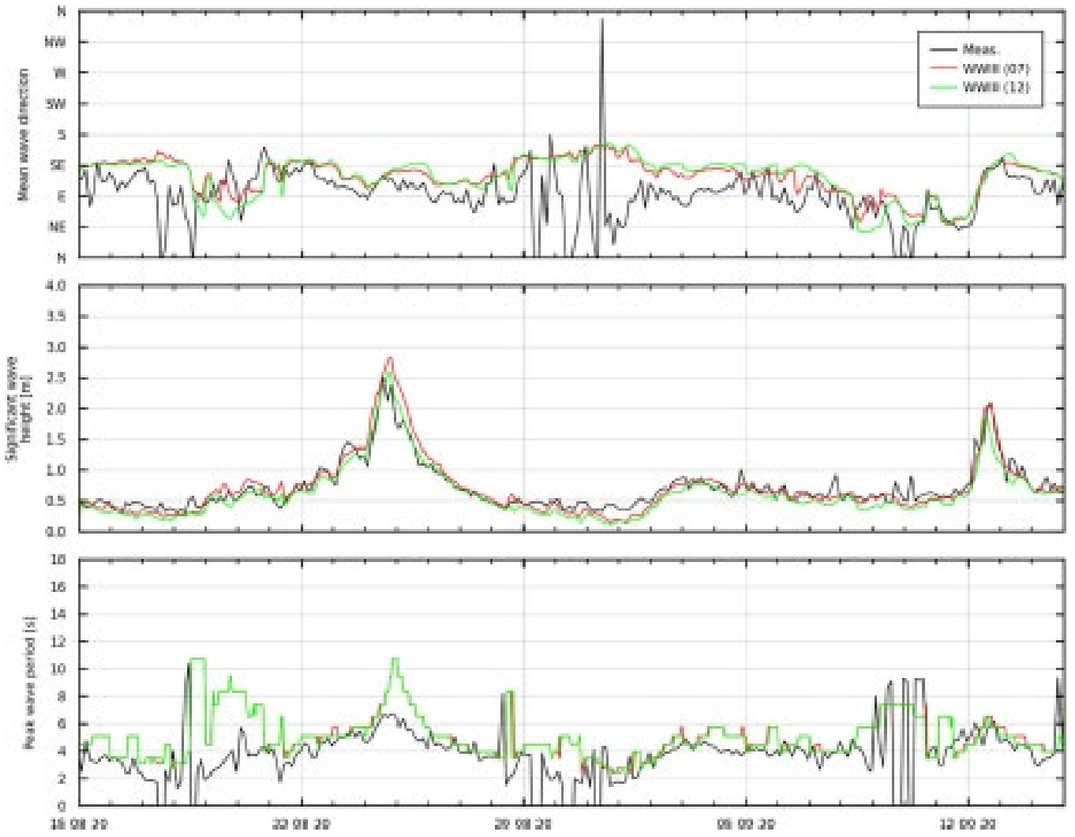

Figure 5. Example of a comparison between the measured and computed wave direction (upper panel), height (middle panel), and period (lower panel) at a mooring offshore Miami-Dade County–Baker's Haulover, with water depth of approximately 17 m (55 ft). The red and green lines represent the Delft-SWAN model results, including (run 7) and excluding wind forces (run 12). Including wind forces lead to slightly higher wave heights (middle panel).

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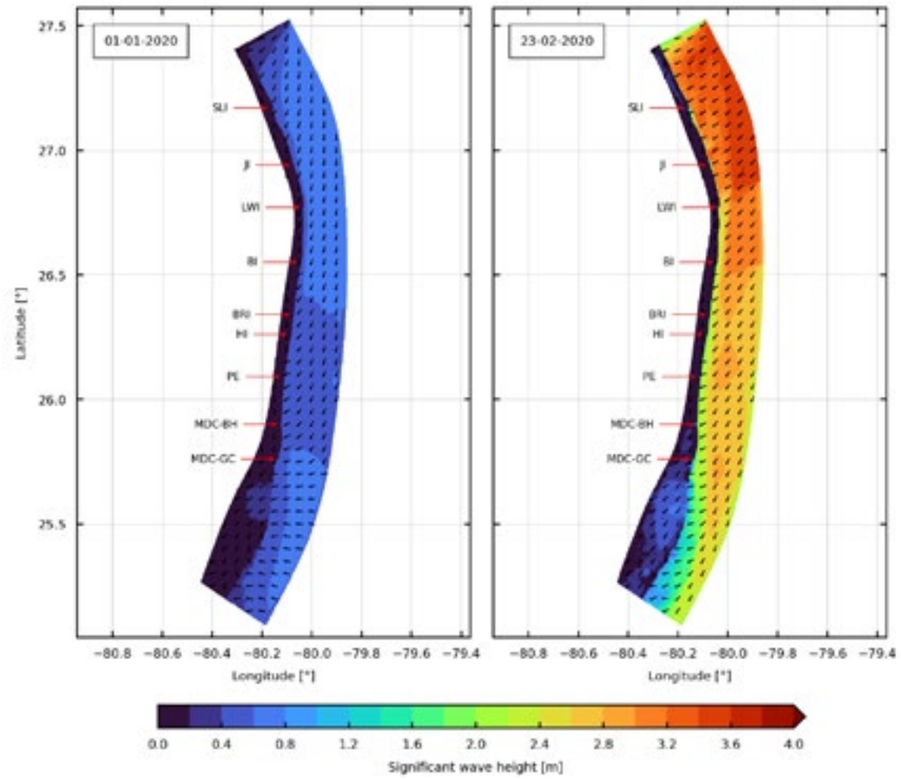

Figure 6. Computed significant wave height (color) and mean wave direction (black arrows) on 1 January 2020 (relatively mild conditions; left) and 23 February 2020 (stormy conditions; right). In addition to LW Inlet, PE, MDC-BH, and MDC-GC, five other inlets are highlighted: BI = Boynton Inlet; BRI = Boca Raton Inlet; HI = Hillsboro Inlet; JI = Jupiter Inlet; SLI = St. Lucie Inlet.

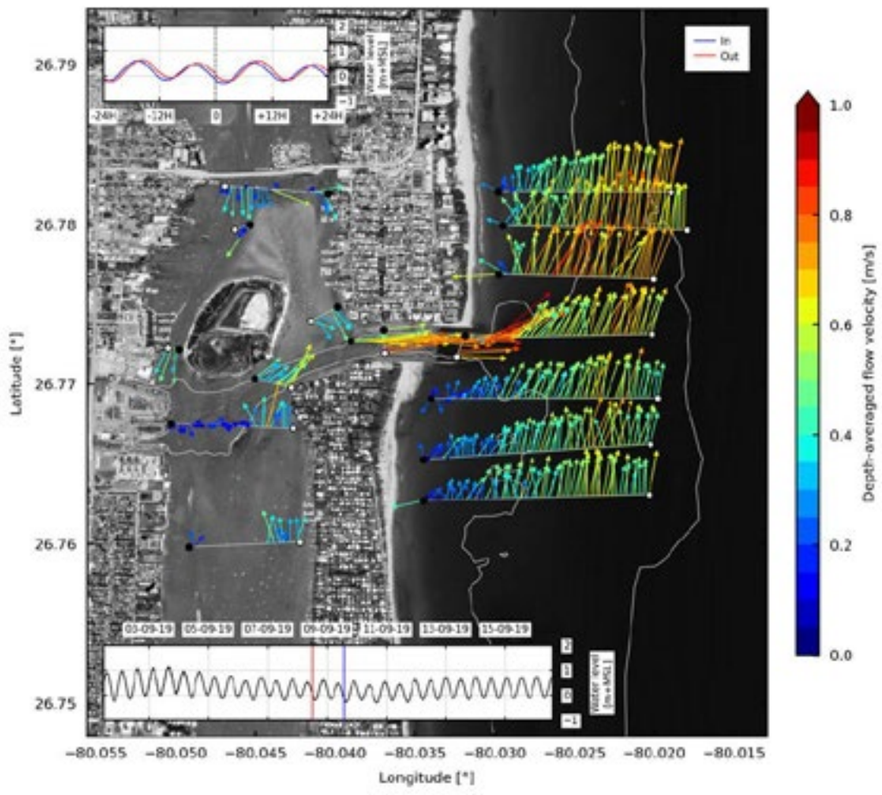

Figure 7. Measured depth-averaged current velocity vectors during the maximum ebb phase derived from ship-mounted ADCP data at Palm Beach (September 2019; two ebb tidal phases during neap tide).

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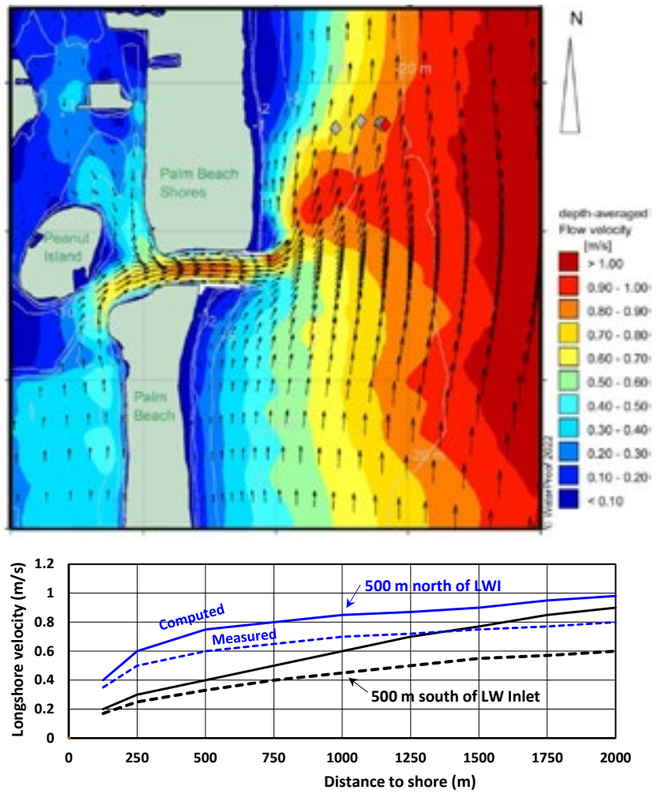
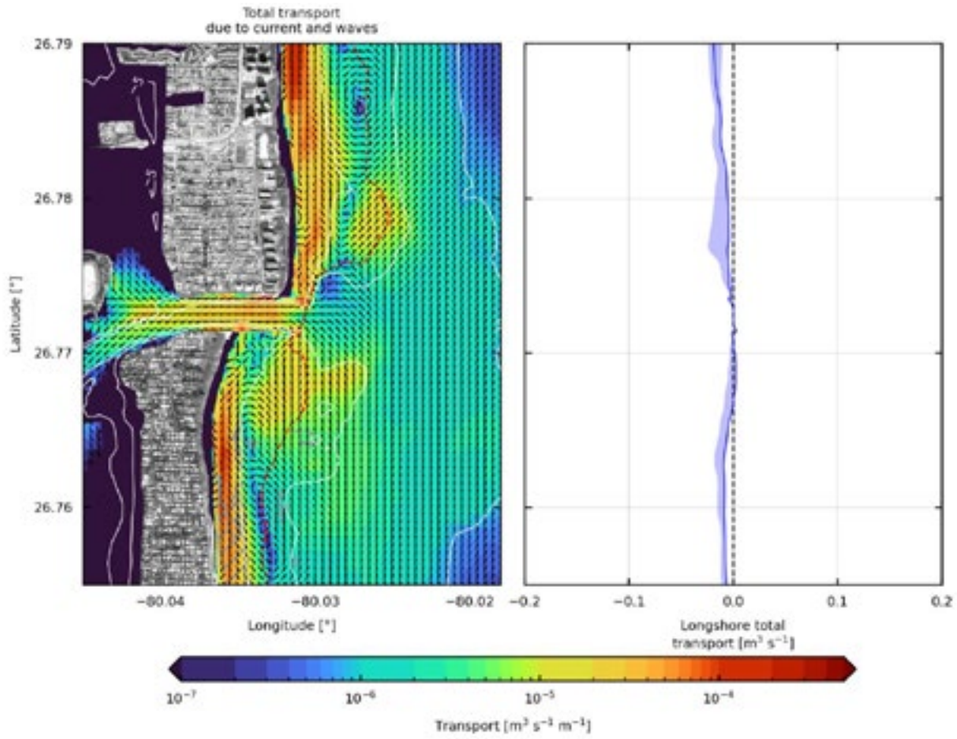


Figure 8. Plan view of computed (Delft3D), depth-averaged current field during the ebb phase at Palm Beach, driven by a combination of tidal flow, Florida Current, and bathymetric effects (upper); measured and computed depth-averaged velocities in two cross-sections (lower).



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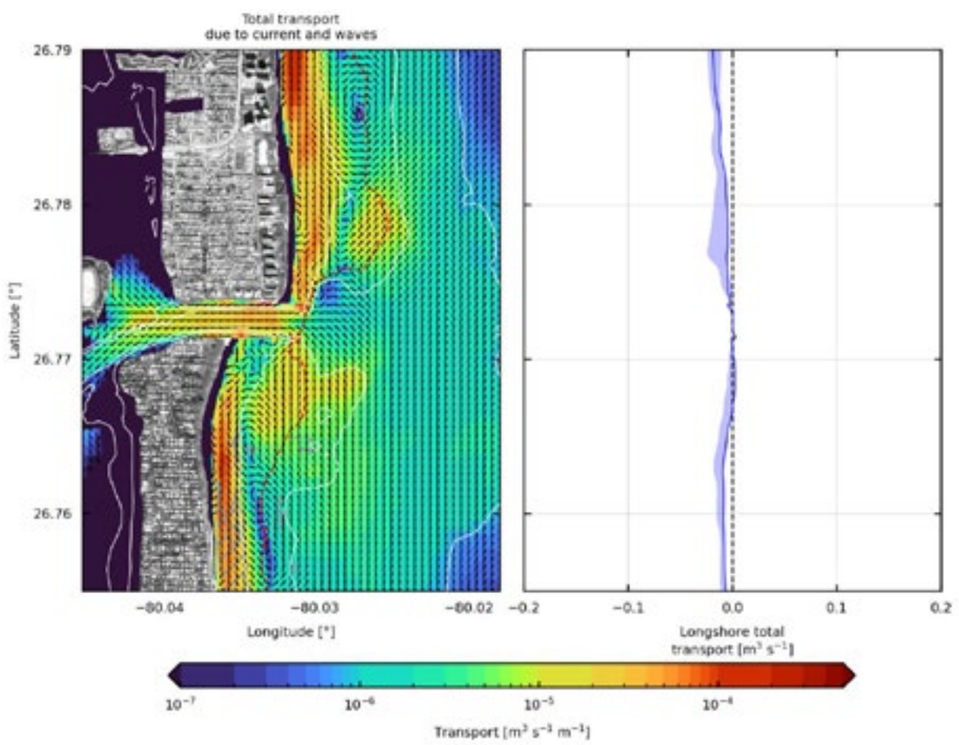

Figure 9. (Left panel) Computed sediment transport patterns for Palm Beach during flood tide for case of waves of 2.0 m from 60°N and a Florida Current of 0.4 m/s to the north in a water depth of 15 m. (Right panel) Total longshore sediment transport, summed over the cross-shore zone up to MSL -7.5 m (negative values to the south).

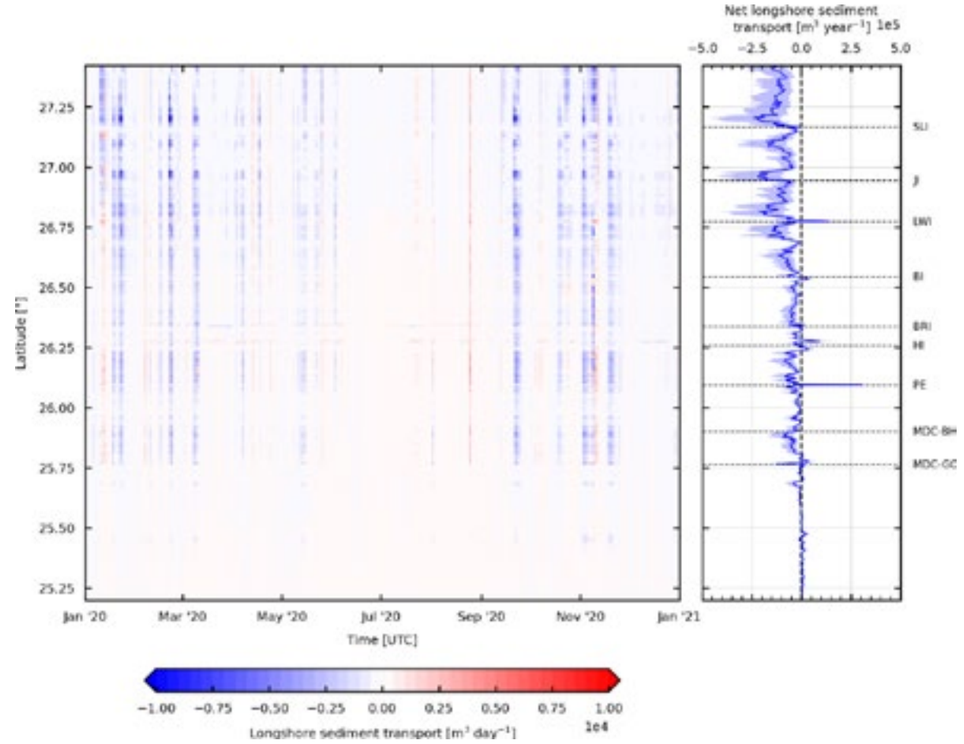

Figure 10. Computed annual net longshore sediment transport based on the Continental Shelf wave-current model of the SE Florida coast, excluding Florida Current. (Left) Longshore sediment transport as a function of time and latitude (m^3/day); (right) yearly longshore sediment transport as a function of latitude (m^3; negative values to south). BI = Boynton Inlet; BRI =Boca Raton Inlet; HI = Hillsboro Inlet; JI = Jupiter Inlet; SLI = St. Lucie Inlet.

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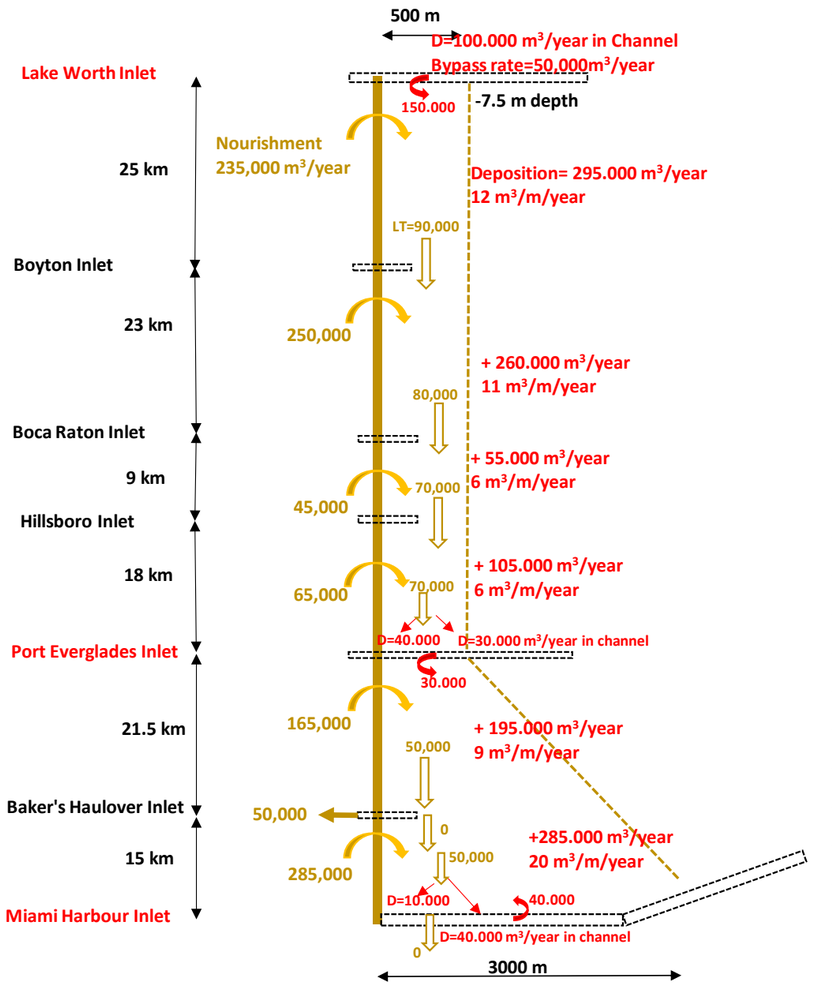

Figure 11. Sand budget of the SE Florida coast between Lake Worth Inlet and Miami Inlet (yellow: nourishment and longshore sand transport LT; red: deposition [values in m³/y]; net sand transport across -7.5 m depth contour is assumed to be zero).

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Benthic Foraminifera as Useful Bioindicators of Heavy Metal and Organic Enrichment in Northern Temperate Coastal Zones: A Comprehensive Review

Benthic Foraminifera as Useful Bioindicators of Heavy Metal and Organic Enrichment in Northern Temperate Coastal Zones: A Comprehensive Review

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ABATRACT

Benthic foraminifera are known to respond to naturally occurring and anthropogenically induced stresses. A considerable body of literature exists describing the effects that contamination by heavy metal and organic enrichment has on these organisms in coastal environments. This review of the literature on the subject since 1980 shows that these types of contamination are reflected through changes in the physiology, abundance, and community structure of foraminifera, confirming them as useful bioindicators of environmental quality in the geographical context of the north temperate zone. Based on this analysis of the literature, results show that metal enrichment leads to deformations and altered foraminiferal test chemistry, whereas organic enrichment tends to mostly affect foraminiferal abundance and community structure, with little evidence for morphological effects. Additionally, anthropogenic activities can degrade and even destroy the ecological niches occupied by foraminifera, as evidenced by the disappearance of symbiont-bearing taxa with increasing organic contamination. This review highlights the usefulness of the ecological responses of foraminifera in assessing the current and long-term state of ecosystems in temperate benthic coastal environments, especially in the context of increased heavy metal and organic contamination by anthropogenic activities.

ADDITIONAL INDEX WORDS: *Test deformation, community structure, species assemblage, ecosystem conditions, anthropogenic pressure.*

INTRODUCTION

Most of the world's coastal regions are heavily affected by human pressures (Williams *et al.*, 2022). Coastal ecosystems are experiencing rapid physicochemical alterations due to enhanced anthropogenic activities such as unregulated and improper disposal of sewage and solid waste (including heavy metals) (Yang *et al.*, 2007), overuse of fertilizers (Bailey *et al.*, 2020), and emission of toxic and nontoxic gases into the atmosphere (Allegra *et al.*, 2018). These activities contribute to the deterioration of coastal ecosystem health and the loss of marine life, especially in areas where human settlements are dense and widespread. Urbanization, increased land use, and industrialization can lead to severe alteration of the physical and chemical properties of marine environments (Tanaka, Minggat, and Roseli, 2021), thus impacting the persistence of benthic organisms, especially calcifiers like corals and foraminifera (Ciais *et al.*, 2014; Doney *et al.*, 2012; Hoegh-Guldberg *et al.*, 2007; Orr *et al.*, 2005).

Layers of coastal sediments act as a repository for contaminants entering coastal marine systems and can preserve a reliable record of contamination sources (Sawe, Shilla, and Machiwa 2022). This contamination is not always directly evident but can make the sediments toxic for the benthic and epibenthic organisms that spend a large part of their life cycle in or on the sediment. It can lead to toxicity, bioaccumulation, and biological disruptions within the benthic and epibenthic communities (Billah *et al.*, 2022). These

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effects can manifest as reduced biodiversity, altered community structure, impaired reproduction and development, and even population decline (Billah *et al.*, 2022). Several studies have attempted to evaluate the anthropogenic contribution towards the degradation of the health of the coastal benthic environment through various techniques, by documenting (1) geochemical proxies (e.g., isotopic studies) (Barik *et al.*, 2022; Dasgupta *et al.*, 2018), (2) geophysical properties (e.g., magnetic susceptibility and saturation isothermal remanent magnetization) (Yang *et al.*, 2007), and (3) biomarkers (Vilela *et al.*, 2004). Benthic foraminifera are one such group of organisms that rapidly and faithfully record variations in their surroundings and, as such, can be considered useful bioindicators of anthropogenically induced environmental change. For example, traces of anthropogenic CO2 and heavy metal concentrations in seawater and sediment can be integrated and preserved in their mineralized tests (Weber and Casazza, 2006). They are useful for monitoring environmental changes, including contamination, biodiversity, climate, and various physicochemical parameters that directly or indirectly affect the state of the marine ecosystem (Boltovskoy, Scott, and Medioli, 1991).

Foraminifera are marine protists that are abundant world-wide (Frontalini and Coccioni, 2011). They have survived multiple mass extinction events since emerging during the Cambrian explosion, around 500 Ma (Culver and Buzas, 1995). Extant species are estimated to number around 10,000 (Pawlowski, Holzmann, and Tyszka, 2013; Vickerman, 1992). They are classified into four subclasses based on the composition of their tests: (1) allogromid (test made of organic materials) (Pawlowski *et al.*, 2002), (2) agglutinated (particles from the surrounding environment agglutinate to form the test)(Bender *et al.*, 1995), (3) siliceous (test composed of silica)(Gupta, 1999), and (4) calcareous (calcium carbonate test)(Gupta, 1999). Calcareous foraminifera are further subdivided into hyaline (porous CaCO3 test with interlocking microcrystals) and porcelaneous (nonporous CaCO3 test with randomly arranged rods) forms. According to the World Modern Foraminifera Database (Hayward *et al.*, 2024), the Foraminifera Phylum contains four extant classes: Globothalamea, Monothalamea, Nodosariata, and Tubothalamea.

Foraminiferal tests can be well preserved in sedimentary archives for millions of years (Holbourn *et al.*, 2013) and thus provide an archive that can be used to reconstruct past environmental changes at different timescales. For the recent past, they can be useful to assess the impact of anthropogenic activities, like the emergence of industries on estuarine environments (Cearreta etal., 2000, 2002; Ruiz *et al.*, 2004). They were used for the first time as proxies for contamination in the early 1960s (Alve and Murray, 1995; Boltovskoy, Scott, and Medioli, 1991), and since then, publications focusing on foraminifera as a tool for monitoring coastal contamination have increased substantially (Scott *et al.*, 2005; Yanko, Arnold, and Parker, 1999). Different environmental settings have been the focus of the response of benthic foraminifera to various forms of contamination (Alve, 1995; Culver and Buzas, 1995; Martin, 2000; Murray, 2006; Murray and Alve, 2002; Scott, Medioli, and Schafer, 2007; Yanko, Ahmad, and Kaminski, 1998; Yanko, Kronfeld and Flexer, 1994). These include sewage outfalls (Schafer, 1973), oil spills (Lee *et al.*, 2014), heavy metal inputs (Youssef, 2015), inputs related to paper and pulp mills (Nagy and Alve, 1987), and thermal activities where water is used for cooling purposes in industries or power plants, where the water absorbs heat and is then released back into the environment at a higher temperature (Arieli *et al.*, 2011). This can disrupt the aquatic ecosystem in several ways, such as by reducing oxygen solubility and increasing the incidence of algal blooms (Schafer, 1970, 1973; Xu *et al.*, 2021).

Many characteristics of foraminifera make them powerful environmental bioindicators: a short lifespan and rapid growth, rich diversity and specific autecological preferences, and a small size (~0.1 mm to 20 mm). They also often have high population density, allowing for statistically significant sample sizes that can be collected quickly and inexpensively for either assemblage assessments or experimental studies, with minimal environmental impact (Desrosiers *et al.*, 2013). In unfavorable environmental conditions or in the context of a disturbance, foraminifera protect themselves through a biological defense mechanism that causes morphological changes, which translate as detectable evidence of stress (Ben-Eliahu *et al.*, 2020; Bergamin *et al.*, 2019; Frontalini and Coccioni, 2008). Living populations and surface sediment assemblages can therefore be used to assess the current state of the benthic ecosystem, while the foraminiferal content of stratified sedimentary accumulations can serve as archives of past environmental conditions. In the

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paleoenvironmental context, the study of benthic foraminifera morphology, such as pore patterns, test thickness, and proloculus size, offers critical insights into past environmental stressors and bottom water conditions. Recent findings, such as those by Ni *et al.*(2024), highlight how species like Elphidium clavatum adapted to varying salinity and oxygen levels during the Last Interglacial period. These adaptations, including increased porosity and reduced test thickness under stressful conditions, underscore the utility of foraminiferal morphological features as reliable proxies for reconstructing past environmental changes in brackish and hypoxic marine settings. Such studies enhance our understanding of foraminiferal responses to ecological shifts and contribute to broader paleoclimatic reconstructions.

The objective of this study was to analyze the scientific literature to assess the usefulness of benthic foraminifera as bioindicators of recent anthropogenic heavy metal and organic enrichment in coastal environments of the Northern Hemisphere. To do this, data available from the literature relating to human impacts were reviewed, and a list was compiled of potentially useful indicator species of these types of contamination in various regions that could help to track coastal change.

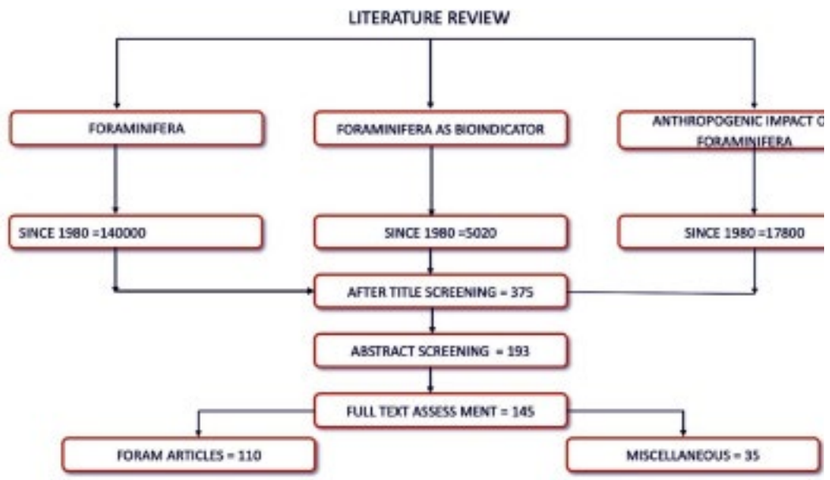

Figure 1. Flow chart of the methodology used in the literature review.

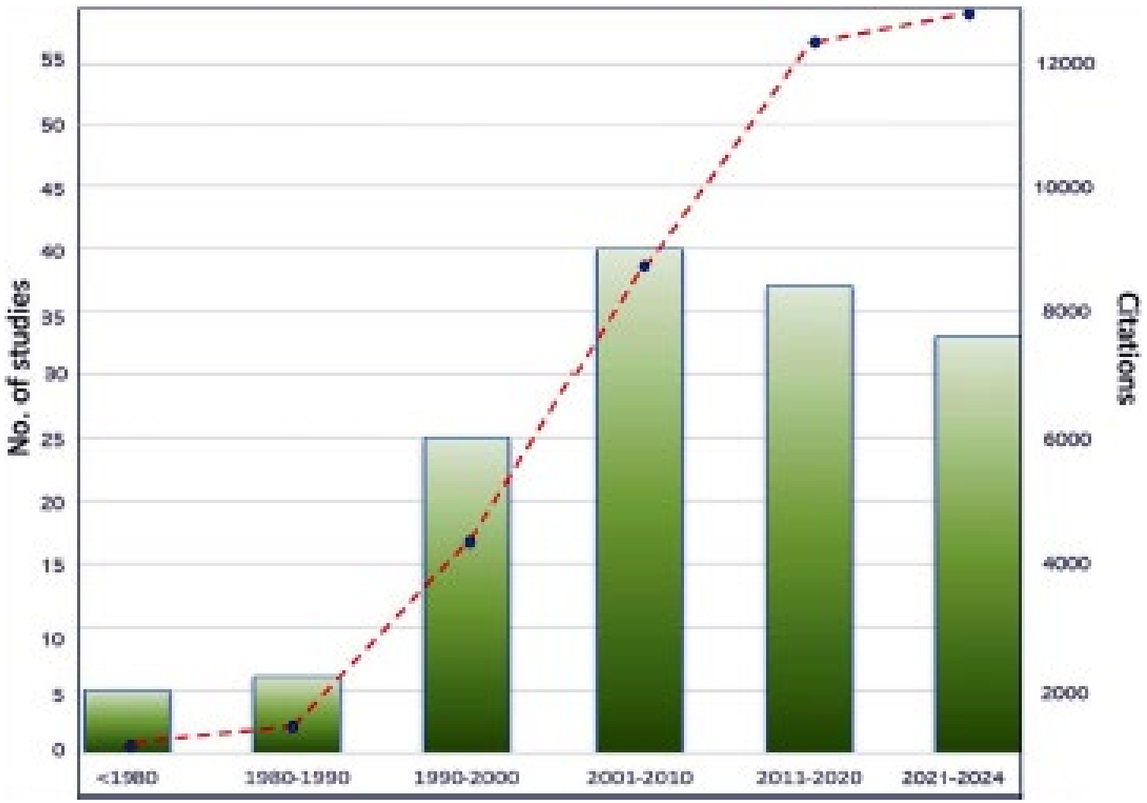

Figure 2. Distribution of the number of articles included in this study through time and their total citations (dashed line).

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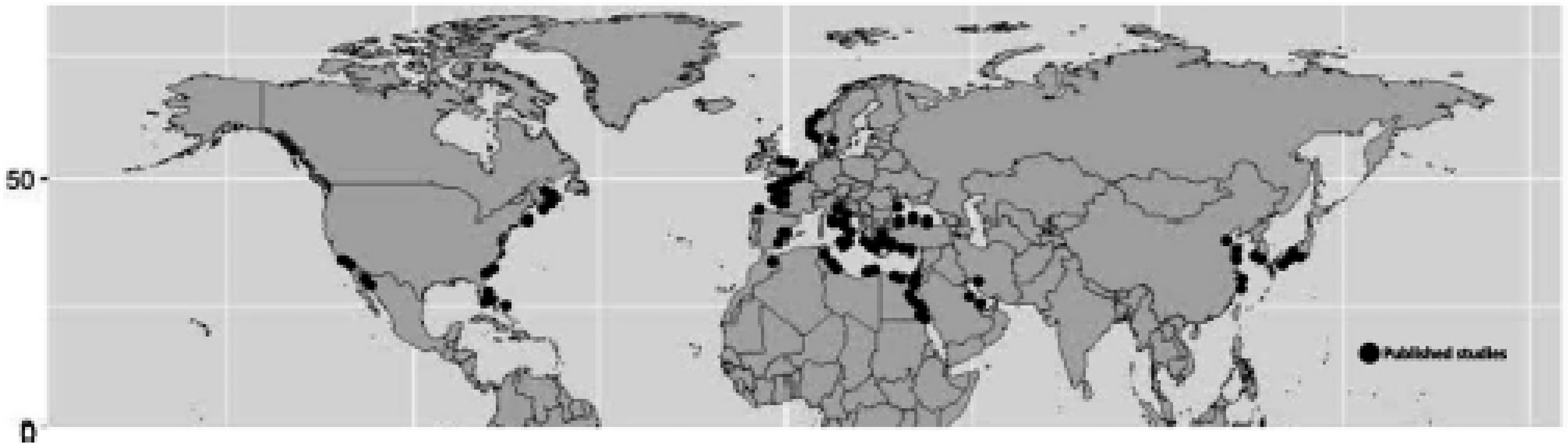

Figure 3. Map showing the location of the published studies used in this article on benthic foraminifera and metal ion/organic contaminants from the Northern Hemisphere.

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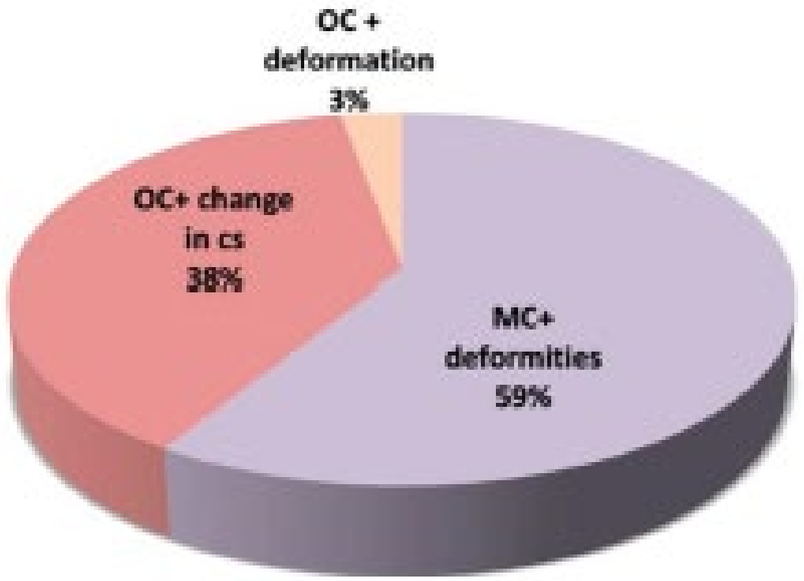

Figure 4. Chart showing various contaminants and their effect on foraminifera. OC = organic contamination; MC = heavy metal contamination; cs = community structure.

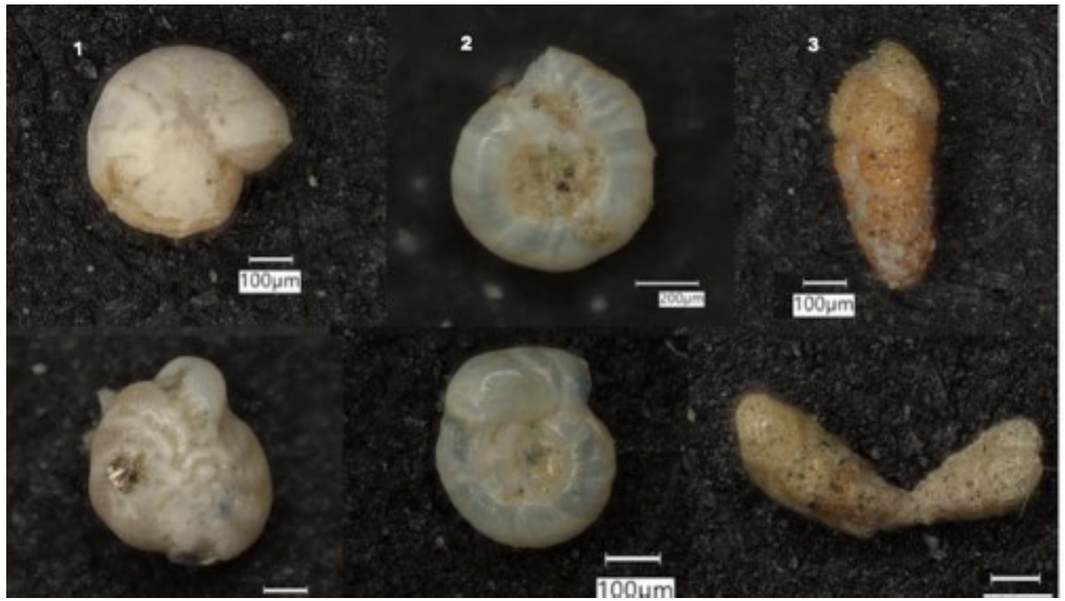

Figure 5. Benthic foraminifera showing normal (top images) and abnormal forms (bottom images) observed in samples from the Bay of Sept Îles, Québec, Canada (Joshi, personal observation). (1) Elphidium clavatum (protuberance in the shell), (2) Cornuspira planorbis (protuberance in the outermost chamber), (3) Eggerella advena (Siamese twins).

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Soil Microbial Community Diversty Varies by Coastal Dune Successional Stagefrom a High Spatiotemporal Resolution Dataset

Soil Microbial Community Diversity Varies by Coastal Dune Successional Stage

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ABSTRACT

Coastal sand dunes play a vital role in protecting inland ecosystems and urban areas against storm surges and sea-level rise, which will become increasingly important under human-induced climate change. While plant community dynamics have been found to benefit coastal dune resilience and resistance to disturbances, there has been relatively little investigation of soil microbial communities. Soil microorganisms play a vital role in coastal ecosystems by contributing to soil development, stabilization, and the mediation of plant productivity and diversity. In nutrient-poor environments like sand dunes, plant-microbe interactions are crucial due to their reliance on resource exchange. This study investigated soil microbial communities and whether they are primarily driven by abiotic or biotic conditions across successional habi-tats of a coastal dune system at St. George Island, Florida, southeastern United States, to help elucidate dune function and resilience. By assessing bacterial and fungal amplicon sequences across a disturbance gradient, it was found that different successional habitats harbored distinct soil communities, which varied in taxonomic diversity and microbial functional groups. Bacteria showed the greatest diversity in interdunes, whereas fungal diversity was greatest in the foredunes. Additionally, it was found that plant and soil characteristics were differentially associated with the soil microbial community based on habitat age, with pH and soil moisture as important compositional drivers. Overall, these findings highlight how coastal dune dynamics differentially influence above- and below-ground biotic communities.

ADDITIONAL INDEX WORDS: *Barrier island, bacteria, fungi, climate change, amplicon sequencing.*

INTRODUCTION

Coastal sand dunes play a crucial role in protecting inland ecosystems and urban areas against storm surges and sea level rise (Maun, 2009), which will become increasingly vital under human-induced climate change (Psuty and Silveira, 2010). The unique interplay between plant community dynamics and sand formation makes dunes particularly resilient to these forms of disturbance (Maun, 2009). Since dunes tend to undergo regular intervals of disturbance from wind and wave action (Silva *et al.*, 2008), and storm surges (Houser, Hobbs, and Saari, 2008), the areas closest to the ocean, termed fore-dunes, are frequently subject to perturbations and sediment deposition, causing regular sand movement and accumulation. Meanwhile, interdunes, which occur inland from foredunes, tend to be more protected from regular wind and wave action but occasionally experience both freshwater and saltwater flooding from heavy rainfall and overwash (Miller, Gornish, and Buckley, 2010). Coastal dune features furthest from the ocean, protected by the foredunes and interdunes, are the backdunes, which are the oldest, most intact, and most stable habitat within a dune system (Miller, Gornish, and Buckley, 2010). These physical processes shape dune formations, enabling the estab-

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lishment of distinct plant communities (Cowles, 1899), which in turn help to determine dune shape and stability (Dura´n and Moore, 2013; Hesp, 2002). While plant community composition is fairly well documented across sand dunes (Cowles, 1899; Isermann, 2011; Miller, Gornish, and Buckley, 2010), there has been relatively little investigation of corresponding soil microbial communities (however, see Lin *et al.*,2014; Nayak, Behera, and Dash, 2019; Yoshitake and Nakatsubo, 2008).

In nutrientpoor environments such as sand dunes, plantmicrobe interactions are thought to be especially important given their mutual dependence on resource exchange (Lambers *et al.*, 2008). Furthermore, soil microbial communities are integral for ecosystem function by contributing to biogeochemical processes (Falkowski, Fenchel, and Delong, 2008), soil development and stabilization (Coban, De Deyn, and van der Ploeg, 2022), and plant productivity and diversity (van der Heijden, Bardgett, and Van Straalen, 2008). They have even been found to tolerate the negative effects of climate change through their rapid eco-evolutionary processes (Chase, Weihe, and Martiny, 2021). Ecosystem processes like nutrient cycling, decomposition, and plant production are further enhanced under increasing levels of soil biodiversity (Delgado-Baquerizo *et al.*, 2020), thereby highlighting the importance of diverse soil microbial communities. Without the array of benefits offered from soil microorganisms, coastal sand dunes would be especially vulnerable to disturbances. Therefore, investigating soil microbial communities in coastal dune systems can help to elucidate dune function and resilience.

Previous studies have found evidence that abiotic factors such as pH (Fierer and Jackson, 2006), organic matter (Delgado-Baquerizo *et al.*, 2016), moisture availability (Angel *et al.*, 2010), and climate (Zhou *et al.*, 2016) act as primary drivers of soil microbial diversity and composition. Yet, there is growing evidence that community-level plant attributes such as plant diversity and cover also play important roles in regulating soil microbial community structure (Delgado-Baquerizo *et al.*, 2018). Identifying soil microbial community structure throughout a coastal dune system and understanding whether it is primarily driven by abiotic or biotic conditions are important factors to better clarify how these vital communities become established and persist.

Uniquely adapted plant species establish across the abiotic gradients of coastal dunes, with early, mid-, and late successional plant communities inhabiting foredunes, interdunes, and backdunes, respectively (Maun, 2009; Miller, Gornish, and Buckley, 2010). Increased plant cover and diversity are generally found across successional gradients (from early to late succession), as maturation of soils and prolonged stability support a growing number of species (Lalibert´e *et al.*,2013; Odum, 1969; Turner *et al.*, 2019). However, many studies have found that diversity tends to decrease in late successional habitats (Moi *et al.*, 2020), suggesting that local species diversity peaks when ecological disturbance is neither too rare nor too frequent (Connell, 1978; Grime, 1973). While there are relatively few studies investigating soil microbial communities across successional gradients, a metaanalysis found that bacteria follow similar successional patterns to plants, with increased taxonomic and functional diversity in late versus early successional habitats (Ortiz-Álvarez *et al.*, 2018). Other studies have found that bacteria dominate early successional habitats in the presence of fast-growing pioneering vegetation, while fungal communities are often more abundant in late successional habitats where established slow-growing woody species produce preferentially consumed lignin (Bokhorst *et al.*, 2017; Kardol, Martijn Bezemer, and van der Putten, 2006). For this reason, it is also important to distinguish community differences between bacteria and fungi, given the different roles they may play across successional gradients.

In this study, soil microbial communities were surveyed using high-throughput molecular methods across successional coastal dune habitats of a barrier island at St. George Island, Florida, southeastern United States. The aim of this study was to determine (1) the patterns of change in the composition and taxonomic diversity of soil bacterial, archaeal, and fungal communities across successional dune habitats (foredunes, interdunes, and backdunes); (2) whether there are consistent patterns in the coupling of plant and soil microbial communities; (3) if soil microbial community composition is related to soil physicochemical properties; and (4) if differences occur in the relative abundances of microbial functional groups across habitat types. This study tested the hypothesis (H1) that the successional characteristics of each habitat type would drive the composition and diversity of soil microbial communities (Connell, 1978; Grime, 1973). More specifically, it was expected that the foredunes would have the lowest bacterial and fungal diversity compared to

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interdunes and backdunes due to increased wind and wave disturbance. Given that interdunes occasionally undergo inundation periods following storm surges and rainfall events, this study tested the hypothesis that interdune soil microbial diversity would be greatest due to distinct abiotic conditions that support a greater soil microbial community. Meanwhile, it was expected that the low disturbance in backdunes would support a more diverse soil microbial community than the highly disturbed foredunes, but this community would be less diverse than that in the interdunes. Any difference in soil microbial community composition across each habitat type was assumed to be due to either differences in (H2) plant community composition or (H3) soil physicochemical properties. Furthermore, this study tested the hypothesis (H4) that distinct microbial functional groups would dominate different habitat types. More specifically, it was expected that functional groups related to plant symbiosis (i.e. nitrogen-fixing bacteria and mycorrhizal fungi) would be more abundant in early successional habitats (i.e. foredunes), while functional groups associated with decomposition (i.e. cellulolytic bacteria and fungal saprotrophs) would be more abundant in late successional habitats (i.e. backdunes). These trends were predicted based on the fact that plant-microbe interactions benefit from symbioses under increased stress in the foredunes and that decomposers would thrive from the accumulation of plant inputs (Lambers *et al.*, 2008).

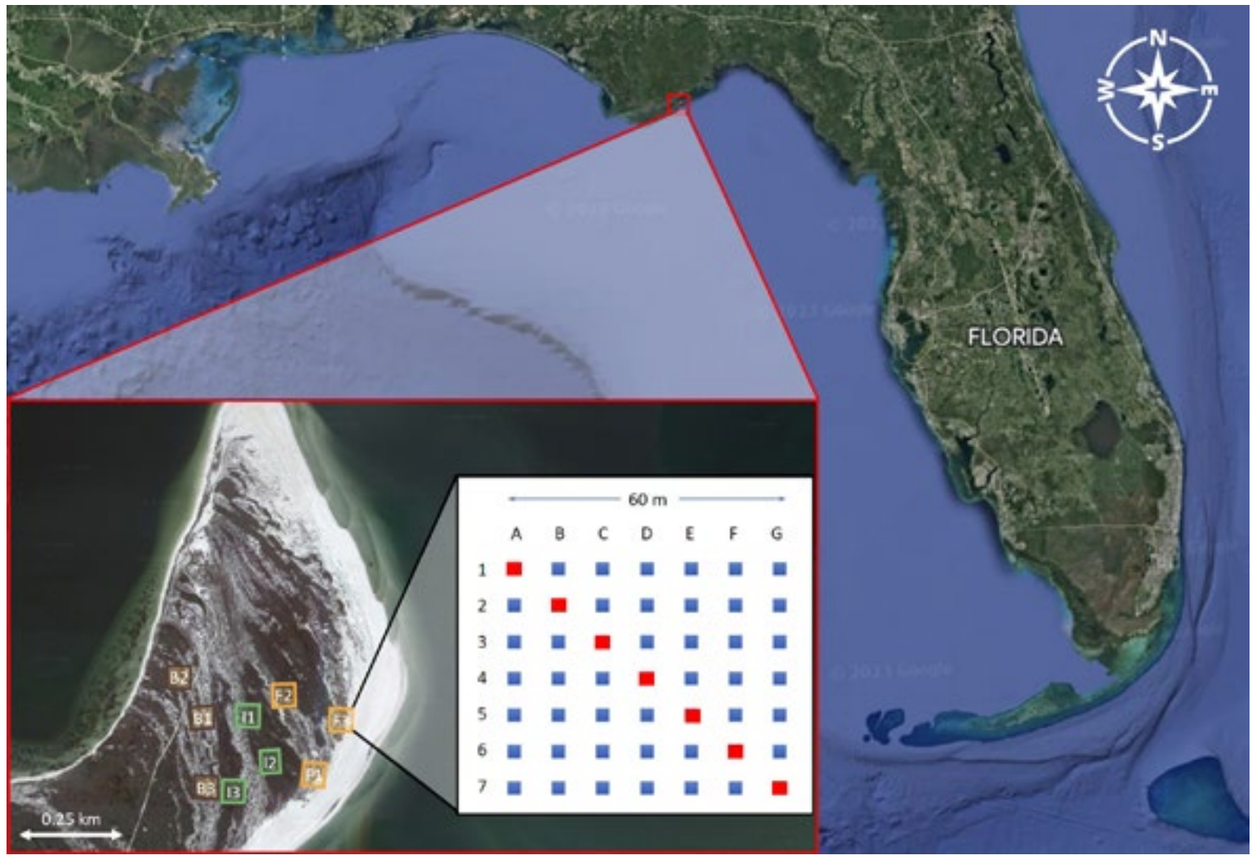

Figure 1. St. George Island study site (St. George Island State Park, Florida, U.S.A.). Blocks F1–F3 encompass foredunes, blocks I1–I3 encompass interdunes, and blocks B1–B3 encompass backdunes. Within each block, a 7 × 7 array of 1 m^2 plots, 10 m apart, were set up. For this study, plots in red (plots A1, B2, C3, D4, E5, F6, and G7) within each block were sampled, totaling 63 plots (21 per habitat type). Source imagery: Florida: Google Data Satellite Imagery Operations (SIO), National Oceanic and Atmospheric Administration (NOAA), United States Navy (U.S. Navy), National Geospatial-Intelligence Agency (NGA), General Bathymetric Chart of the Oceans (GEBCO), Landsat/Copernicus, Instituto Nacional de Estadística, Geografía e Informática (INEGI).; St. George Island: Google TerraMetrics, Imagery date: 4/28/2019.

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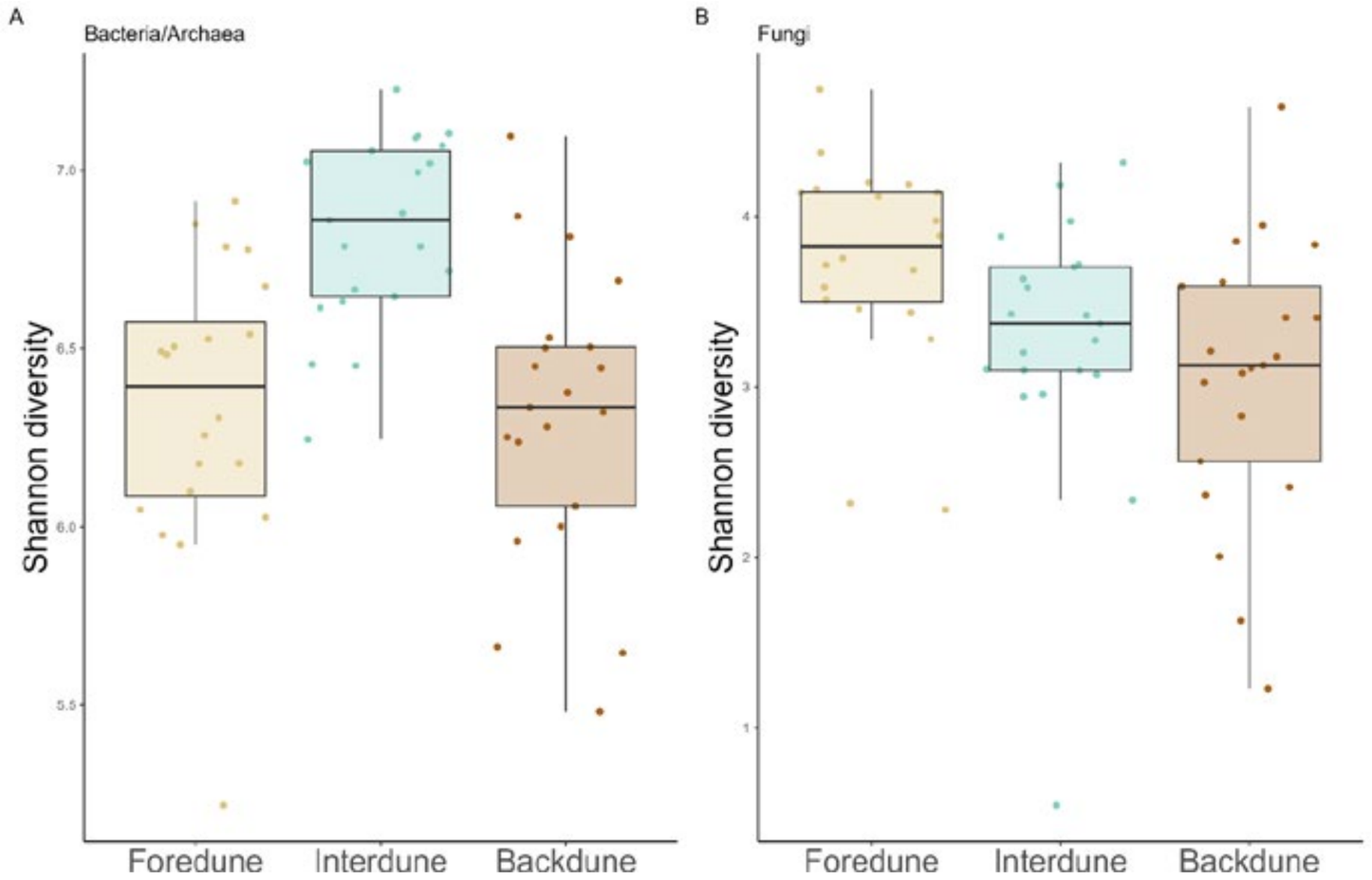

Figure 2. Soil microbial diversity (Shannon-Wiener index) for bacterial/archaeal (A) and fungal (B) communities based on habitat type.

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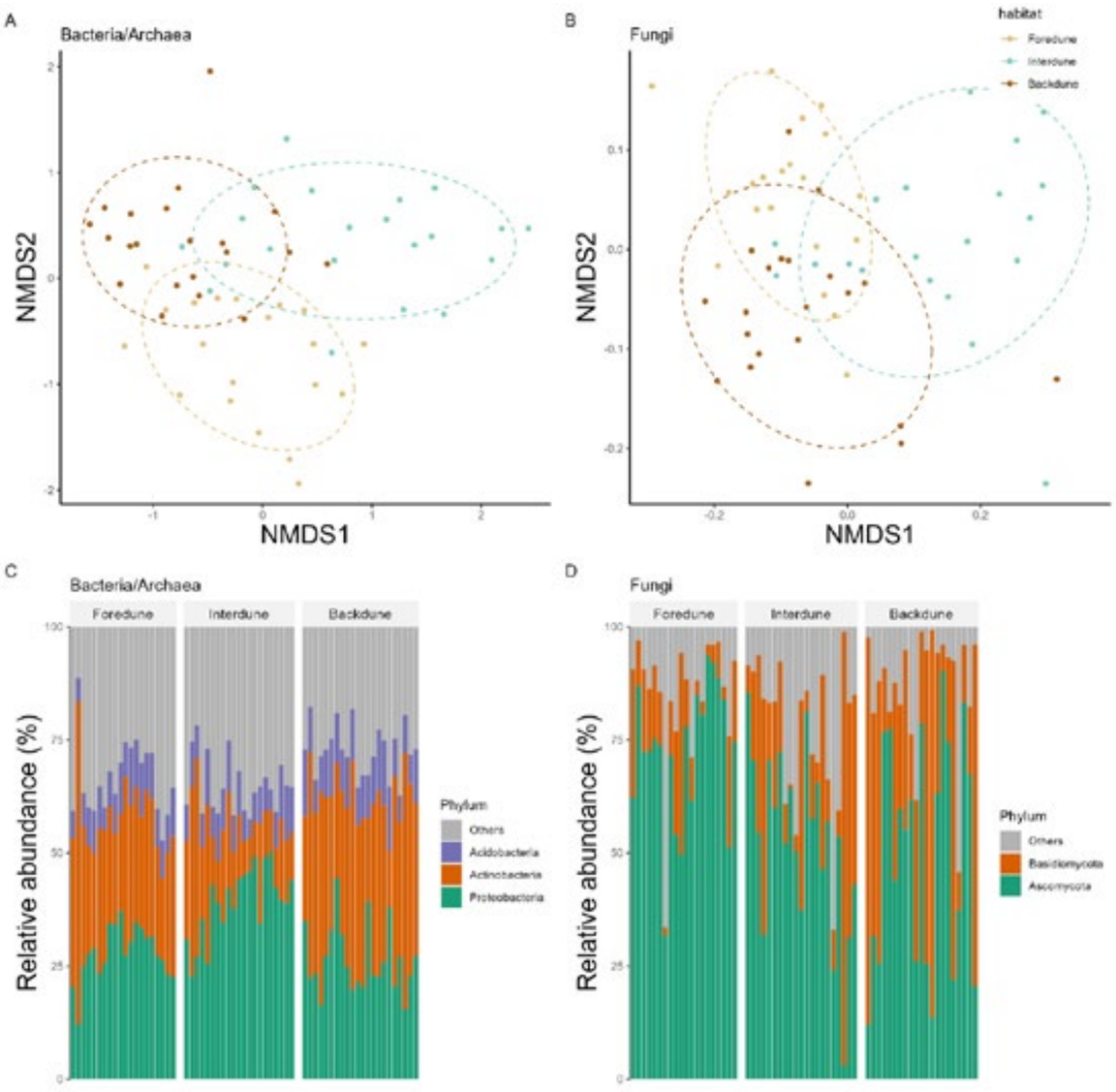

Figure 3. (A–B) Nonmetric multidimensional scaling (NMDS) ordination of bacterial/archaeal (A) and fungal (B) soil communities by habitat type. Ellipses represent a 95% confidence interval of a multivariate normal distribution. Stress = 0.0917 for bacteria/archaea; stress = 0.197 for fungi. (C–D) Dominant phyla by habitat type for bacteria/archaea (C) and fungi (D), with dominant phyla subset by plot to illustrate variability within habitat type. Relative abundances of phyla constituting <5% were combined into the Others category.

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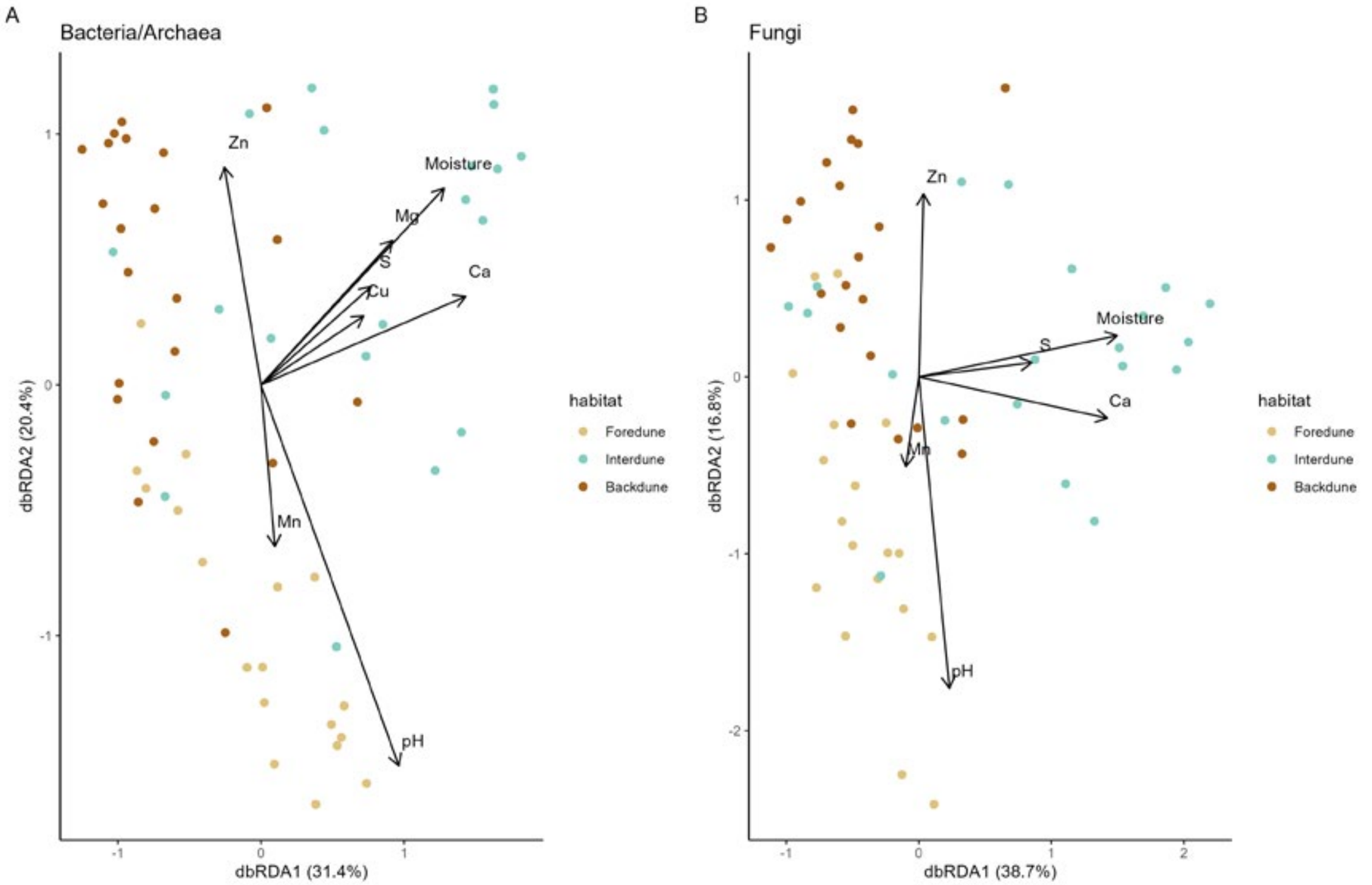

Figure 4. Distance-based redundancy analysis (dbRDA) biplot of bacterial/archaeal (A) and fungal (B) community composition in relation to environmental variables and habitat type. Statistically significant environmental variables (bacteria: Ca, Cu, Mg, Mn, S, Zn, pH, and soil moisture; fungi: Ca, Mn, S, Zn, pH, and soil moisture) are represented as vectors. The length and direction of the vectors indicate the strength and direction of the relationship between the environmental variables and microbial community composition. Community composition is represented by points, with the positioning reflecting their association with the environmental gradients.

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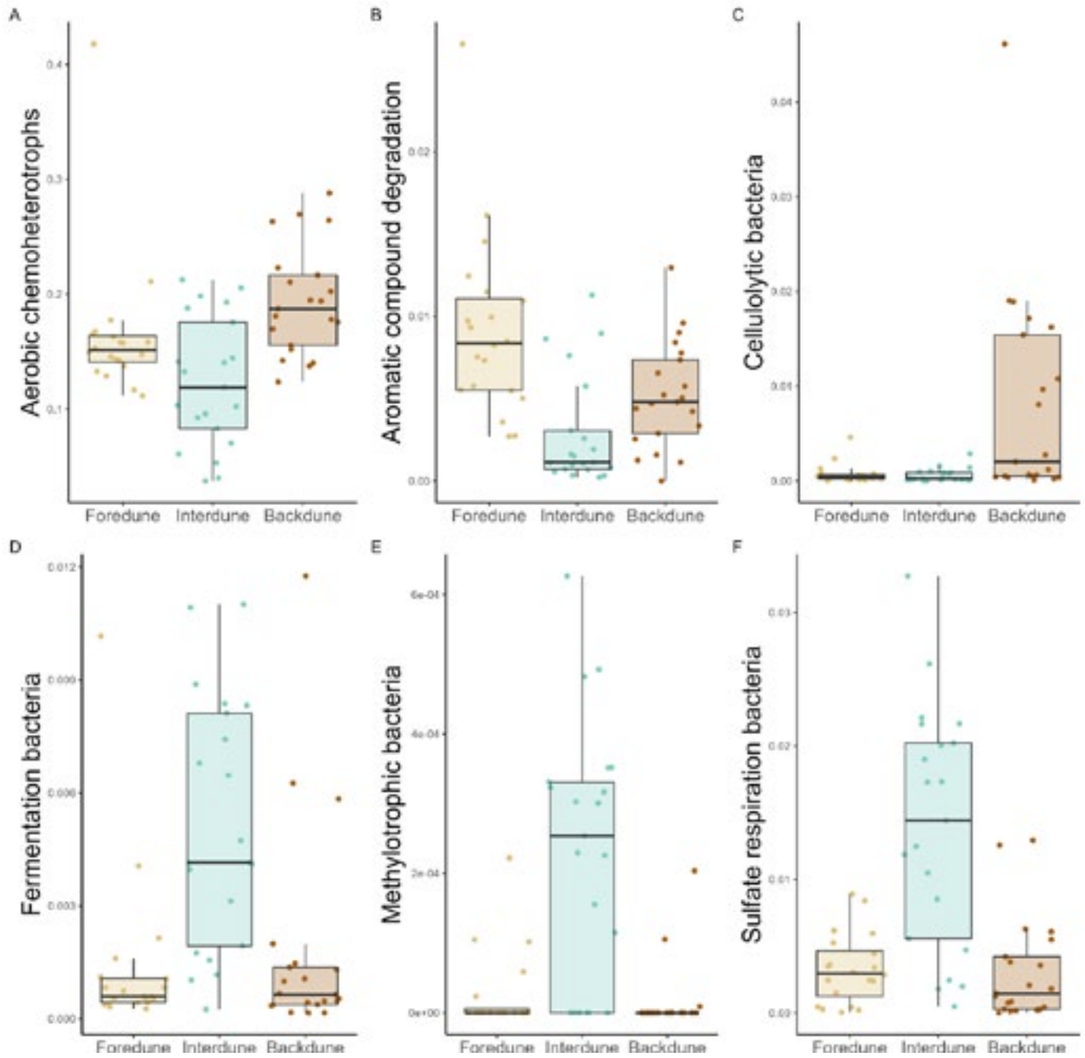

Figure 5. Inferred soil microbial functional groups by habitat type. Functional groups include aerobic chemoheterotrophic bacteria (A), aromatic compound degrading bacteria (B), cellulolytic bacteria (C), fermentation bacteria (D), methylotrophic bacteria (E), and sulfate respiration bacteria (F).

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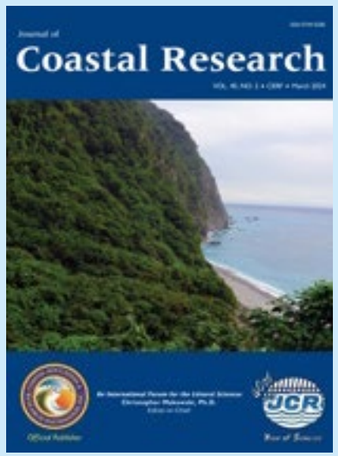

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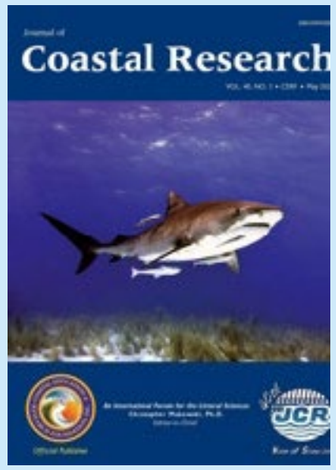

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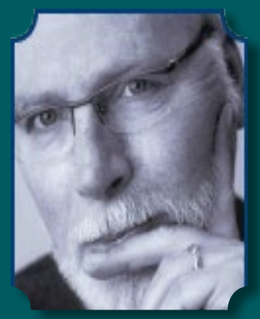

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If you have any news or announcements to feature in our newsletter, please send your request or inquiries directly to: cerf.jcr@gmail.com

CERF continues to provide our members with the most up-to-date, professional features of the society. We encourage you to please visit our Foundation's website at http://www.cerf-jcr.org to see all the new content that has been added.

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