Review Article

The application of satellite remote sensing to coastal dune environments: A systematic review

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Abstract

Sandy coasts are dynamic landscapes due to long-term processes and short-term events leading to changes at various temporal and spatial scales. Coastal dune environments are well studied at a 'micro' scale, both temporal and spatial, using detailed and costly in-situ surveys. However, understanding their dynamics at medium and large spatial scales is fundamental for coastal management and conservation. This review gathers recent progress on the use of satellite remote sensing to study coastal dune environments at medium and large spatial scales (from beach scale to coastal landscape scale). It is motivated by the increasing availability of satellite data at resolutions which, coupled with other coastal monitoring systems, can be applied to understanding coastal processes at medium and large spatial scales and by the need to investigate the most suitable satellite sensors and remote sensing methods for coastal studies, with a focus on dune detection, characterisation and monitoring. The reader will obtain a range of useful information from practical knowledge on landscape scale sandy coast mapping to discussions on linking plot and landform observations to landscape scale. The outcomes of this review show an increasing availability of suitable satellite data and methods that facilitate the exploration of coastal dune change at spatial and temporal resolutions that were not possible until recently. Some of the benefits and challenges of using a range of satellite products to map coastal dune landscape elements (e.g., vegetation cover, topography), and how this information can be used in coastal management in general, are discussed.

Keywords

coastal dunes, sandy coasts, remote sensing, satellite remote sensing, coastal environments

Introduction

Background

Coastal dunes form under various geological and climatic conditions (Farrell et al., 2024; Hesp and Walker, 2013). They are strongly controlled by sediment availability and vegetation (Martínez et al., 2013; Maun, 2009). Dunes reduce storm impact. They can be eroded by large waves and storm surges, and then recover by effective aeolian transport (Delgado-Fernandez and Davidson-Arnott, 2011). These sediment exchanges form the basis of our current understanding of short term beach-dune interaction and

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eco-morphodynamic adjustments of sandy shorelines to coastal processes (Hesp and Martínez, 2007; Jackson and Short, 2020; Sherman and Bauer, 1993). In the medium-long term, sandy beaches adapt to changes in sediment budgets and mean sea-level. Changes to the amount of sediment available to littoral processes affects the amount of sediment delivered, leading to different dune morphologies and dynamics (Bauer and Sherman, 1999; Psuty, 1988). The response of dunes on sandy beaches to rising sea levels is complex because of feedback mechanisms, sediment transport pathways, and interactions between hydro and aerodynamic processes and the ecosystem (Davidson-Arnott and Bauer, 2021). Given space landward, beaches and dunes can migrate with rising sea levels, although the rate and the mechanisms regulating this are still under investigation (Davidson-Arnott, 2005).

Climate change, sea-level rise, and the adaptation of coastal communities are global concerns. In Europe, up to 41% of people live in coastal regions (Collet and Engelbert, 2013), with coastal populations growing fast (European Environment Agency, 2006). Increasing human pressure has led to a loss of coastal environments (Williams et al., 2022). Coastal dunes are distributed along sandy shorelines (Doody, 2001) and they sustain important coastal habitats (Martínez and Psuty, 2004). Adequate monitoring of coastal dunes is key for management in the context of climate change and human impacts (Cooper et al., 2009; McLean et al., 2001). This requires the capacity to understand how coasts evolve at various interconnected temporal and spatial scales (Farrell et al., 2024; Sherman, 1995), including large, regional scales.

Scope and outline of this review

Coasts are dynamic and have been traditionally monitored using field methods, which are costly and spatially limited. Satellite remote sensing can complement these and monitor beaches at various spatiotemporal scales to understand coastal dynamics (Austrich et al., 2021; Castelle et al., 2021; Cenci et al., 2021; Munasinghe and Warnasuriya, 2023). Linking remote sensing and field information bridges process-response dynamics concepts and long-term, large-scale processes influencing landform evolution in sand dune systems (Walker et al., 2017; Zheng et al., 2022). It is also useful for coastal management and planning by providing large-scale, spatially explicit information (Al Ruheili and Boluwade, 2021; Vallarino Castillo et al., 2022).

Walker et al. (2017) proposed a 'scale aware' conceptual framework to structure beach dune dynamics research, identifying three scales of interest: (1) the 'plot' scale, at a scale of metres and over seconds to days, focused on sediment transport and erosion/deposition patterns at discrete locations; (2) the 'landform' scale, at a scale of hundreds of metres and over months to years, focusing on shoreline erosion/progradation, biogeography, foredune size and geometry, beach width and slope, surface characteristics, wind characteristics, human influence, sediment transport rate, and erosion/deposition patterns; and (3) the 'landscape' scale, across a kilometre scale and over decades to centuries, focusing on shoreline erosion/progradation, biogeography, foredune size and geometry, and beach width and slope.

The landform scale acts as a link between the plot and the landscape, requiring studies covering various years (Walker et al., 2017). Remote sensing is ideal for this purpose. This, together with the increasing availability of remote sensing data sources and constant development in computer science and image analysis (Zheng et al., 2022) has motivated this review. The main aim is to inform about the progress made in remote sensing for coastal dune environments over the last 15 years, assess the effectiveness of remote sensing methods and datasets for coastal dune research, and provide scientific guidelines regarding the use of these technologies. A similar approach has been followed for terrestrial inland dunefields by (Zheng et al., 2022), but beach-dune environments are fundamentally different from inland surfaces due to the nuances of sand transport in the presence of water, which creates heterogeneous conditions over the spatial extent of the beach (Walker et al., 2017).

This review is structured according to the framework by Walker et al. (2017) (Table 1). As most of the publications fall within the 'landscape' scale, this category has been divided into three sub-categories.

Literature selection

Peer-reviewed journal articles and reviews published between 2009 and 2024 were considered. A

title and abstract search using two keyword sets (Figure 1) was performed in Scopus. The first search returned 466 publications, which were reduced to 250 after reading their title, abstract and keywords. This first filter excluded articles that were not sufficiently related to coastal science or satellite remote sensing, or that were not peer-reviewed. The following criteria were applied to rule out 36% of the remaining publications after reading the full text: (1) focus was a social science problem; (2) about inland environments; (3) about rocky or gravel coasts; (4) satellite remote sensing was only ancillary; (5) not written in English or Spanish. Of the 160 articles remaining, 3 were literature reviews and 157 were experimental studies.

The increasing number of publications over the last 15 years (Figure 2) shows a growing interest in satellite remote sensing of coastal dune environments. Most publications were from journals on coastal and marine sciences, including relevant journals for coastal dune studies such as *Aeolian Research* (Figure 3). Journals on remote sensing and applied informatics and statistics, and on Earth system science, physical geography and geomorphology were also present. A few more publications are cited than those screened in the review, as they helped setting up the context or explain basic tools and data sources.

Satellite data sources for coastal dune environments

Landsat missions and Sentinel-2 were the most widely used data sources. These are freely available, medium resolution optical data. Very high resolution (VHR) imagery from online globes such as Google Earth is the third most used source. Its limited spectral information is compensated by its ease of use. Optical VHR data from satellite platforms such as QuickBird, Pléiades or RapidEye are also present. VHR data's high spatial resolution allows the detection of fine scale processes in coastal environments. Despite its advantages such as high atmospheric penetration (even through cloud) or ability to measure topographic changes (through interferometry), active synthetic aperture radar sensors (Radarsat, ALOS-PALSAR, Sentinel-1, TerraSAR-X) scarcely appear. A summary of all satellite data sources present in the review is in the supplementary material (Table A) (Alaska Satellite Facility, 2024; EO Portal, 2012; EO Portal, 2023; EO Portal, 2024a; EO Portal, 2024b; ESA, 2024a; ESA, 2024b; ESA, 2024c; ESA, 2024d; ESA, 2024e; ESA, 2024f; ESA, 2024g; ESA, 2024h; ESA, 2024i; ESA, 2024j; ESA, 2024k; ESA, 2024l; ESA, 2024m; ESA, 2024n; ESA, 2024o; ESA, 2024p; ESA, 2024q; ESA, 2024r; JPL, 2024; NASA, 2024; NIK, 2024; Satellite Imaging Corporation, 2022a; Satellite Imaging Corporation, 2022b; Satellite Imaging Corporation, 2022c; Satellite Imaging Corporation, 2022d; Krebs, 2023; Thome, 2024).

Remote sensing methods for coastal dune environments

Beach-dune variables

Since shoreline progradation/erosion is the dominant beach-dune variable in this review (Figure 4), most methods were related to the retrieval of shoreline positions. The most widely used tool is the Digital Shoreline Analysis System (DSAS) (Abd-Elhamid et al., 2023; Al Ruheili and Boluwade, 2021; Baral

Table 1. Organising framework of this literature review, adapted from the conceptual framework by Walker et al. (2017).

Scale of interest		Spatial scale of study
Plot		Microscale: m^2
Landform		Mesoscale: Tens of m to less than 1 km^2
Landscape	Sub-regional	1–10 km^2
	Regional	10–100 km^2
	Super-regional	Larger than 100 km^2

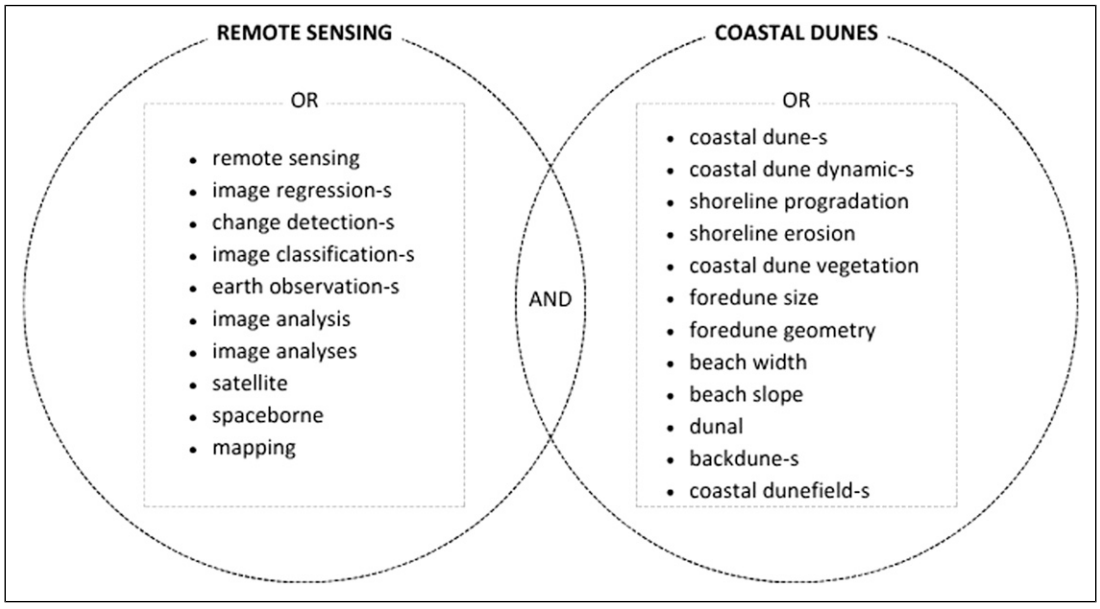

Figure 1. Keyword combinations used for the literature search.

et al., 2018; Cenci et al., 2021; Cohn et al., 2022; Dada et al., 2016; Dhanalakshmi et al., 2019; Duarte et al., 2018; Elfadaly et al., 2023; ElKotby et al., 2023; El-Zeiny et al., 2022; Emam et al., 2019; Flores et al., 2020; Gómez et al., 2017; Hoque et al., 2019; Hossain and Saha, 2024; Jolivet et al., 2019; Kaliraj et al., 2014; Liu et al., 2020; Mann and Westphal, 2014; Markose et al., 2016; Mbezi

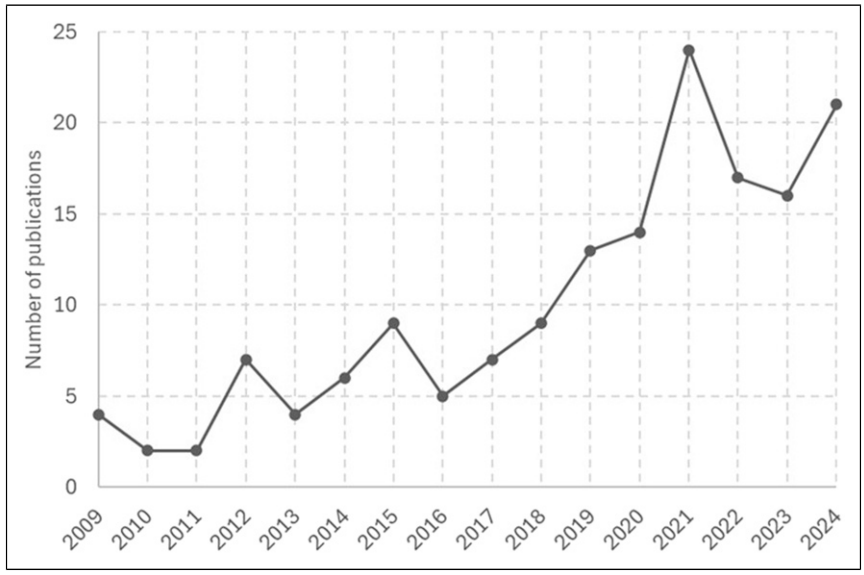

Figure 2. Number of publications by year.

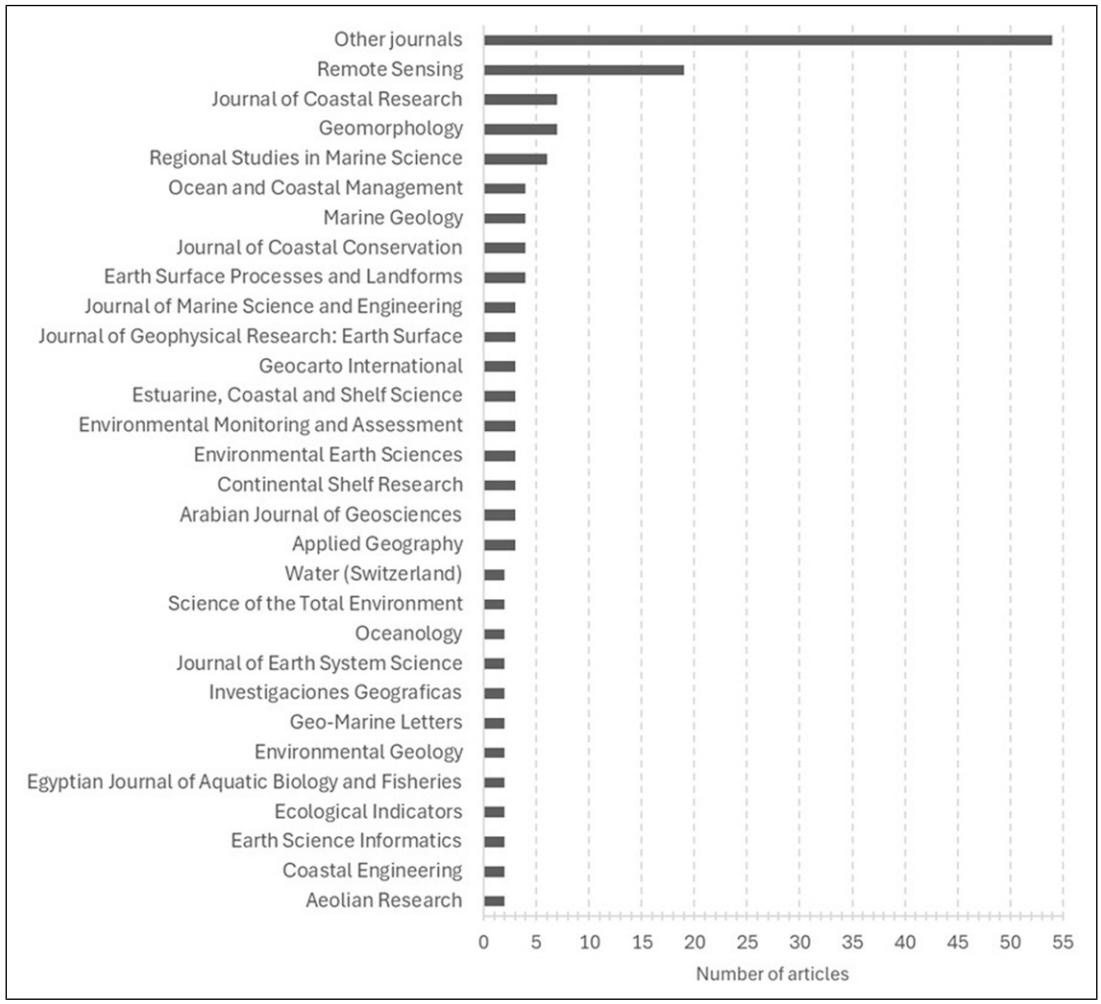

Figure 3. Number of articles reviewed by journal.

et al., 2024; Mishra et al., 2021; Misra and Balaji, 2015; Misra and Ramakrishnan, 2020; Mondal et al., 2020; Munasinghe and Warnasuriya, 2023; Nandi et al., 2016; Natarajan et al., 2021; Natesan et al., 2015; Osanyintuyi et al., 2022; Padma et al., 2024; Pardo-Pascual et al., 2014; Shanmuga Priyaa and Jena, 2021; Silva et al., 2021; Siyal et al., 2022; Sundar et al., 2021; Trinida et al., 2024; Valderrama-Landeros et al., 2022; Vallarino Castillo et al., 2022; Xu et al., 2024; Zhang et al., 2024; Zhou et al., 2024). DSAS calculates rate-of-change statistics and uncertainty metrics from historical shoreline positions. It has been widely used due to its user-friendly interface (Himmelstoss et al., 2024). The input shoreline positions are commonly generated by visual photointerpretation of the satellite imagery and manual digitisation of the shoreline.

CoastSat, which is also commonly used, automatises the process of shoreline delineation (Adebisi et al., 2021; Angelini et al., 2024; Billet et al., 2023; 2024; Castelle et al., 2021; Maneja et al., 2021; McGill et al., 2022; Mu et al., 2024; Valderrama-Landeros et al., 2022; Vos et al., 2020; 2023a). CoastSat uses Google Earth Engine (GEE),

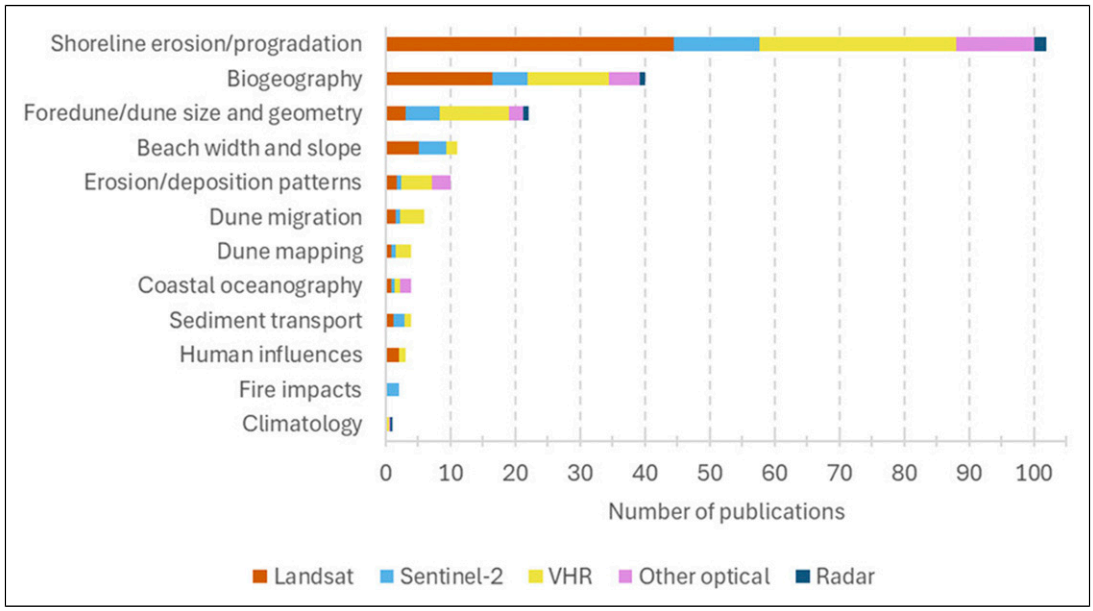

Figure 4. Number of reviewed publications by beach-dune variable and proportion of use of each satellite sensor type. For interpretation of the references to colours in this figure legend, refer to the online version of this article.

image classification and sub-pixel border segmentation to extract satellite derived shoreline (SDS) positions at sandy coasts using Landsat or Sentinel-2 data (Vos et al., 2019). The method combines a Neural Network supervised classification and a sub-pixel resolution border segmentation using a Modified Normalized Difference Water Index (MNDWI). SHOREX is another automatic SDS detection tool which has been used in two studies (Briceño de Urbaneja et al., 2024; Cabezas-Rabadán et al., 2019a; 2019b). It uses Landsat or Sentinel-2 satellite data and an approximate pixel level shoreline and then kernel analysis to extract a sub-pixel shoreline position (Pardo-Pascual et al., 2012; Sánchez-García et al., 2020). The global shoreline dataset ShorelineMonitor was used in one article (Konlechner et al., 2020). ShorelineMonitor consists in a global assessment of the presence of sandy beaches and their rate of shoreline change since 1984 (Luijendijk et al., 2018). The assessment is based on a supervised classification of Landsat and Sentinel-2 imagery. Aside from these tools, there is an increasing number of SDS extraction algorithms, but no algorithm outperforms the others in all cases (Vos et al., 2023b). High-energy meso or macrotidal beaches are particularly challenging (Vos et al., 2023b). Active sensors, precisely interferometric SAR (InSAR), were used to assess shoreline change in Aly et al. (2012) and to map storm surges in Terenzi et al. (2014) in study sites in Egypt and Alaska, respectively.

Biogeography was the second most frequent variable (Figure 4). The assessment usually involved land cover mapping using classification methods (Austrich et al., 2021; Block et al., 2016; Cao et al., 2022; Gürkan and Kayikçi, 2017; Kozhoridze et al., 2022; Mahbub et al., 2020; Nuyts et al., 2020; Ponnambalam et al., 2012; Sambah et al., 2022; Timm and McGarigal, 2012; Touhami et al., 2022; Zhou et al., 2024) or visual photointerpretation and manual digitisation (Cohen et al., 2021; Gómez et al., 2017; Gorczynski et al., 2024; Hamylton and East, 2012; Mendes and Giannini, 2015; Misra and Balaji, 2015; Moulton et al., 2019; Samanta and Paul, 2016; Thomas et al., 2018; Toffani et al., 2024; Veettil et al., 2024). The use of spectral indices such as the normalised difference vegetation index (NDVI) was widespread (DaSilva et al., 2021; 2023; Debaine and Robin, 2012;

Gorczynski et al., 2024; Marzialetti et al., 2019; 2022; Medina Machín et al., 2019; Petrova et al., 2023; Scardino et al., 2023; Shumack et al., 2017; Taminskas et al., 2020; Todaro et al., 2024; Veettil et al., 2020; 2024; Zhou et al., 2024). Sometimes, advanced biogeographic characterisation using landscape metrics or habitat suitability models was used (Block et al., 2016; Sambah et al., 2022; Todaro et al., 2024). Franklin et al. (2024) used random forest and decision trees to model shrub presence in relation to geomorphological variables in a barrier island site in USA. Delbosc et al. (2021) highlighted the lack of data to assess the conservation status of coastal habitats under the European Union Habitats directive. A remote sensing approach could help to homogenise conservation status assessments.

Other frequently assessed variables were foredune and dune size and geometry, beach width and slope, and erosion and deposition patterns (Figure 4). Dune morphology was mostly assessed visually (Cabral and Castro, 2022; Havivi et al., 2018; Hesp et al., 2022; Levin et al., 2009; Manzolli et al., 2023; Nuyts et al., 2020; Patton et al., 2019; Portz et al., 2021; Repkina and Yakovleva, 2023; Rodríguez Paneque, 2024; Toffani, 2020; Toffani et al., 2024; Özcan et al., 2010). Beach width and slope was usually analysed together with shoreline erosion and progradation (Cabezas-Rabadán et al., 2019a; 2019b; Munasinghe and Warnasuriya, 2023; Schellekens and Amani, 2022; Siyal et al., 2022; Vos et al., 2020; Xu et al., 2024). Dune dynamics were measured by Havivi et al. (2018) using InSAR coherence, and by Sam et al. (2015) using satellite stereopairs taken 1 year apart.

Erosion and deposition patterns were often visually assessed (Levin et al., 2009; Nuyts et al., 2020; Repkina and Yakovleva, 2023; Talavera et al., 2024), sometimes aided by other methods such as band combinations (Duarte et al., 2018) or edge enhancement techniques (Baral et al., 2018). Albuquerque et al. (2025) used the Normalized Dune Difference Index (NDDI) to map dunefield extent in a coastal zone of Rio Grande do Sul (Brazil). NDDI is a spectral index specifically designed to highlight the spectral characteristics of sand dunes that uses a SWIR band and the coastal aerosol band available in Landsat data. Román-Rivera and Ellis (2019) highlighted the potential of spatially explicit predictive modelling using satellite data to supply morphodynamic information.

Spatial scales

Most of the publications belonged to the landscape scales (Figure 5). This is not surprising, since the most used satellites were Landsat and Sentinel-2, which have moderate spatial resolution (Table A, Supplemental material). The amount of plot level studies is limited due to the spatial resolution of satellite data, which only reaches 20–30 cm pixel size for the highest resolution sensors (WorldView-3). The following sections describe only the most relevant or innovative studies at each scale.

Plot scale. Two studies assessed variables at this scale. Repkina and Yakovleva (2023) classified and analysed Holocene aeolian deposits. Through visual photointerpretation of images extracted from online

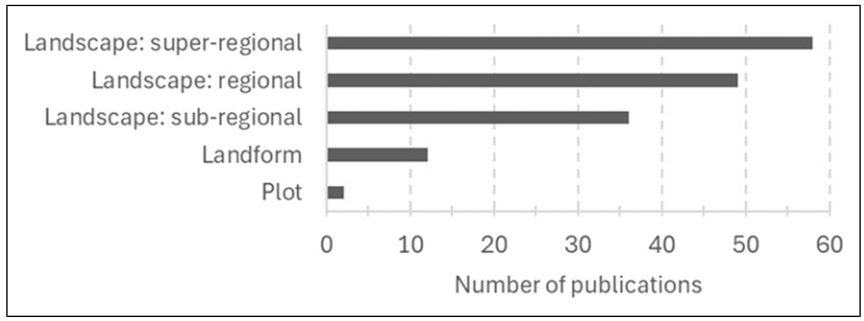

Figure 5. Number of reviewed publications by scale of interest.

globes (Google Earth and SAS Planet), they assessed the morphology and distribution of the dunes and the erosion and deposition patterns in a site in the White Sea coast (Russia). Scardino et al. (2023) used Landsat 8/9 and Sentinel-2 to monitor vegetation heath and water stress on coastal dunes in a study area in the Chiatona coast (Italy) using spectral indices. This vegetation assessment was then linked to erosion and accretion processes using in-situ surveys.

Landform scale. Castelle et al. (2021); McGill et al. (2022); Maneja et al. (2021) and Silva et al. (2021) assessed shoreline erosion and progradation or beach widths. Three of these studies used CoastSat.

The study by Castelle et al. (2021) is especially interesting, as they compared SDS extracted using CoastSat over a 35 year-long period with field data spanning over 10 years in Truc Vert beach (France). Both Landsat and Sentinel-2 datasets were used. They found that SDS using CoastSat can be improved in high-energy meso-macrotidal beaches such as Truc Vert by taking wave runup into account, choosing a different shoreline proxy, or training CoastSat's Neural Network classifier to the site-specific characteristics.

Bentze et al. (2023); DaSilva et al. (2023); Marzialetti et al. (2022); Mendes and Giannini (2015) and Timm and McGarigal (2012) studied biogeographical characteristics of coastal areas.

Marzialetti et al. (2022) used Sentinel-2 and VHR PlanetScope data to upscale drone surveys of the invasive tree *Acacia saligna* in a coastal environment in Italy. They calculated 18 spectral indices as remote sensing variables to build an *A. saligna* invasion model. They modelled *A. saligna* occurrence using a Random Forests machine learning algorithm (Breiman, 2001). Timm and McGarigal (2012) also used Random Forests, but for classification instead of regression. They created detailed maps of coastal dune and salt marsh ecosystems in Cape Cod National Seashore (USA) using VHR QuickBird imagery combined with orthophotography and a digital elevation model (DEM). They used a supervised approach, designing a classification scheme, building a set of 34 predictor variables (including spectral indices and topographic variables) and collecting training samples.

Dune morphology was assessed by Hesp et al. (2022) in Australia and Levin et al. (2009) in Brazil. They both used VHR satellite imagery (RapidEye and QuickBird, respectively), visual photointerpretation and manual delineation to identify aeolian landforms.

Landscape scale

Sub-regional. Shoreline erosion and progradation or beach width were analysed by Amaro et al. (2015); Baral et al. (2018); Billet et al. (2024); Chang et al. (2015); Cohn et al. (2022); Duarte et al. (2018); Fairley et al. (2020); García-Rubio et al. (2015); Mahbub et al. (2020); Mu et al. (2024); Munasinghe and Warnasuriya (2023); Rajagopalan (2011); Repkina et al. (2024); Samanta and Paul (2016); Smith et al. (2021); Sundar et al. (2021); Trinida et al. (2024); Vallarino Castillo et al. (2022) and Xu et al. (2024). Most relied on manual digitisation of shorelines, sometimes aided by spectral indices or visual image enhancement techniques such as band combinations, followed by further analysis of shoreline trends using DSAS. CoastSat was sometimes used.

Fairley et al. (2020) used Sentinel-2 data to assess intertidal bar shape and migration and relate it to coastal dune behaviour in Crymlyn Burrows (United Kingdom). Although this is not the main intended use for CoastSat, these authors adapted the workflow by extracting the pre-processed images before shoreline detection. These were then transformed to grayscale and the sandbars were extracted using histogram thresholding, manually finding a threshold value which separates land and water properly.

Biogeography was assessed by Bonte et al. (2021); Cohen et al. (2021); Ettritch et al. (2018); Mahbub et al. (2020); Marzialetti et al. (2019); Medina Machín et al. (2019); Samanta and Paul (2016); Sambah et al. (2022); Taminskas et al. (2020); Thomas et al. (2018) and Touhami et al. (2022); Cohen et al. (2021); Samanta and Paul (2016) and Thomas et al. (2018) mainly relied on visual photointerpretation and manual digitisation. The NDVI index was a key part of the methods by Marzialetti et al. (2019) and Taminskas et al. (2020).

Ettritch et al. (2018) used linear spectral unmixing (LSU) on a time series of Landsat imagery to

quantify bare soil over time in a stabilised dune system in the Kenfig Burrows National Nature Reserve (United Kingdom). LSU is a technique to analyse the spectral mixture within pixels. It infers sub-pixel pure spectral signatures (endmembers) weighted by their abundances (Garg, 2020) within each pixel.

Bonte et al. (2021); Mahbub et al. (2020); Marzialetti et al. (2019); Medina Machín et al. (2019); Touhami et al. (2022) and Sambah et al. (2022) used land cover classification methods based on random forests, decision tree, support vector machines (SVM) or maximum likelihood algorithms in study sites in France, Belgium, Netherlands, United Kingdom, Bangladesh, Italy and Spain.

Dune and foredune morphology and patterns were assessed by Baral et al. (2018); Bonte et al. (2021); Cabral and Castro (2022); Duarte et al. (2018); Knight and Burningham (2021); Manzolli et al. (2023); Özcan et al. (2010); Patton et al. (2019); Portz et al. (2021); Povilanskas et al. (2009) and Van Kuik et al. (2022). The remote sensing methods used tended to be based on visual photointerpretation or very simplistic.

Knight and Burningham (2021) and Portz et al. (2021) measured transverse dunes migration. Knight and Burningham (2021) used Sentinel-2 data and GEE in South Africa. They extracted the reflectance along a shore-parallel, dune-crossing transect. The inflection points in reflectance between the illuminated and shaded sides of the dunes allowed the identification of dune crests. Portz et al. (2021) used visual photointerpretation on VHR imagery in Lagoa Do Peixe National Park (Brazil).

Van Kuik et al. (2022) quantified surface-area development of foredune trough blowouts and their associated parabolic dunes. They used GEE to automatically assess blowout surface area and shape using Landsat and Sentinel-2 imagery. They applied it to blowout systems in the Netherlands, Denmark and United States. First, a normalized difference water index (NDWI) and the Otsu thresholding algorithm were used to separate land and water. They minimised classification errors using morphological dilation and erosion. Then, a Canny edge detection algorithm was used on the land pixels to identify the transitions between sand and vegetation pixels. These edges were then buffered to determine an area where an Otsu thresholding of NDVI values would be applied to separate sand from vegetation pixels within the blowouts. Since the land cover mosaic in coastal areas is often fine grained causing a medium resolution pixel to contain more than one land cover type, LSU was used then to determine the proportion of each land cover type within a pixel. Land pixels with less than 50% vegetation cover were assigned to blowout.

Regional. Shorelines and beach width at the regional scale were studied by Aadland and Helland-Hansen (2019); Alves and Rossetti (2017); Angelini et al. (2024); Bergsma et al. (2020); Billet et al. (2023); Briceño de Urbaneja et al. (2024); Cabezas-Rabadán et al. (2019a, 2019b); Cenci et al. (2021); Demir et al. (2019); Dhanalakshmi et al. (2019); Duvat et al. (2017); ElKotby et al. (2023); Flores et al. (2020); Foti et al. (2023); Gzam et al. (2013); Hagenaars et al. (2018); Jolivet et al. (2019); Kazhukalo et al. (2023); Kefi et al. (2024); Liu et al. (2020); Mann and Westphal (2014); Markose et al. (2016); Mondal et al. (2020); Nandi et al. (2016); Natarajan et al. (2021); Natesan et al. (2014; 2015); Tappin et al. (2012); Valderrama-Landeros et al. (2022); Veettil et al. (2020); Webb and Kench (2010); Zhang et al. (2024, 2021). Again, most relied on visual photointerpretation and manual digitisation of shorelines. CoastSat was used by Billet et al. (2023) in a coastal area near Buenos Aires (Argentina). SHOREX was used by Cabezas-Rabadán et al. (2019a, 2019b) in Spain. Hagenaars et al. (2018) automatically generated SDS from Landsat and Sentinel-2 imagery with a method similar to the already mentioned by Van Kuik et al. (2022). They applied it to the case study of the Sand Motor mega-scale nourishment project in the Netherlands.

Zhang et al. (2021) propose a NDWI based method to assess shoreline evolution from Landsat imagery using CASPRS (Computer-aided shoreline position recognition software), which uses beach transects and sub-pixel recognition. CASPRS interpolates a point every 1 m of each transect, using bilinear interpolation to calculate the value of each point as a function of the four adjacent pixels.

Subsequently, they used the interpolated transects to generate a NDWI index. The point with the sharpest change in NDWI indicates the waterline within each transect. They applied it to Haiyang beach (China).

Demir et al. (2019) use radar together with optical data. They present a nonparametric fuzzy shoreline extraction method based on Sentinel-1 and RASAT data and use it in two coastal sites in Turkey. They start with a binary classification of the optical RASAT imagery. Then, a fuzzy clustering algorithm is applied to the radar Sentinel-1 data. The fuzzy membership parameters were calculated based on the statistics of all pixels belonging to each of the classes (land and water).

Biogeographical variables were assessed by Block et al. (2016); Franklin et al. (2024); Gürkan and Kayikçi (2017); Marzialetti et al. (2021); Moulton et al. (2019); Nuyts et al. (2020); Timm et al. (2014); Todaro et al. (2024) and Veettil et al. (2020).

(Franklin et al., 2024) modelled shrub presence in relation to geomorphological variables using machine learning algorithms in a barrier island environment in Virginia (United States). Shrub presence was identified on Landsat imagery, and the geomorphological variables were derived from Landsat and LiDAR data.

Marzialetti et al. (2021) explored vegetation biodiversity in relation to remotely sensed spectral heterogeneity in a coastal dune environment in the Tyrrhenian coast (Italy) using VHR PlanetScope imagery. They used linear regressions to investigate the relationship between field alpha biodiversity and spectral variability in the remote sensing data. Beta biodiversity was also assessed through a distance decay model relating field indices and spectral measurements. For the spectral diversity analysis, a dataset of pixels with the same location and date of acquisition as the field data was collected. Spectral heterogeneity was found to be correlated with species diversity. More similar plots were also spectrally closer.

Dune and foredune morphology and erosion and deposition patterns were assessed in the studies by da Motta et al. (2015); Durai et al. (2021a, 2021b); (Franklin et al., 2024); Havivi et al. (2018); Marzialetti et al. (2020); Nuyts et al. (2020) and Toffani et al. (2024).

Marzialetti et al. (2020) used monthly Sentinel-2 imagery to map coastal dunes in a coastal environment in central Italy. They used a supervised iterative approach based on hierarchical clustering and Random forests. The input variables for classification were the per-pixel yearly diversity represented by the Rao's Q index, and three spectral indices representing land cover temporal variability, vegetation biomass, and presence of water and bare surfaces.

Havivi et al. (2018) used InSAR coherence to map dune dynamics in a coastal site in Israel. The data used was TerraSAR-X. InSAR coherence is a method based on the phase difference between two InSAR datasets acquired at a different time. A high coherence between the two datasets indicates high similarity and thus, lack of change. In aeolian environments, InSAR decorrelation occurs rapidly because of erosional and depositional processes. The authors were able to characterise the stability of different dune features (crests, different orientation slopes).

Super-regional. Shoreline erosion/progradation was studied by Anwar and Rahman (2021); Besset et al. (2017); Chu et al. (2013); Dada et al. (2016); Danchenkov et al. (2023); Di Stefano et al. (2013); El Banna and Frihy (2009); Elewa and El Nahry (2009); Elfadaly et al. (2023); El-Zeiny et al. (2022); Emam et al. (2019); Feng et al. (2015); Gómez et al. (2017); Gorczynski et al. (2024); Hamylton and East (2012); Haque et al. (2024); Herlekar et al. (2023); Hoque et al. (2019); Hossain and Saha (2024); Kaliraj et al. (2014); Konlechner et al. (2020); Levin et al. (2017); Liu et al. (2013); Mao et al. (2021); Mbezi et al. (2024); Mishra et al. (2021); Misra and Balaji (2015); Mohd et al. (2018); Osanyintuyi et al. (2022); Padma et al. (2024); Pardo-Pascual et al. (2014); Pourkerman et al. (2018); Schellekens and Amani (2022); Septiangga and Mutaqin (2021); Shanmuga Priyaa and Jena (2021); Siyal et al. (2022); Sylaios et al. (2012); Veettil et al. (2024); Vos et al. (2023a); Zhang et al. (2018); Zhou et al. (2024). Again, most of these relied on visual assessment, spectral index calculation or already mentioned approaches like various supervised land cover classification

algorithms, histogram thresholding, or tools such as CoastSat or ShorelineMonitor.

Mao et al. (2021) measured very large-scale shoreline change in Australia employing Landsat data and GEE. They began by building a yearly composite of Landsat data. This was used to calculate the automatic water extraction index (AWEI), which was segmented into water and land using histogram thresholding. This, together with a DEM, were used to create a mask of land area at high tide, which was overlapped with a vector file of shoreline buffers created previously from ancillary data. With this information, the authors calculate the average shoreline position and the land pixel count within each buffer.

Aly et al. (2012) and Al Fugura et al. (2011) used SAR (ERS-1 and 2 and RADARSAT-1, respectively). Al Fugura et al. (2011) worked in Malaysia and used edge detection methods, followed by a median filter on a moving window to smooth the image. Thresholding was used for the final segmentation. More effective is the method by Aly et al. (2012), which used InSAR coherence in Egypt to quantify erosion/accretion.

Biogeographic variables were assessed by Austrich et al. (2021); Cao et al. (2022); Debaine and Robin (2012); Gómez et al. (2017); Gorczynski et al. (2024); Hamylton and East (2012); Kozhoridze et al. (2022); Petrova et al. (2023); Ponnambalam et al. (2012); Misra and Balaji (2015); Shumack et al. (2017); Veettil et al. (2024) and Zhou et al. (2024). Most of them used methods very similar to the ones already mentioned or relied heavily on simplistic approaches such as manual digitisation.

The most interesting assessment was the one by Austrich et al. (2021). They studied landscape change and habitat fragmentation in dune barriers of the Buenos Aires province (Argentina). They used Landsat imagery and a maximum likelihood supervised classification to identify coastal dune habitat classes based on vegetation cover. Then, they analysed landscape change and structure using landscape metrics in R.

Dune morphological characteristics were assessed by Danchenkov et al. (2023); Levin et al. (2017); Rodríguez Paneque (2024); Sam et al. (2015) and Toffani (2020); Levin et al. (2017) studied coastal dune activity and foredune formation on Moreton Island (Australia) between the years 1944 and 2015 using a wide range of remote sensing data sources, including aerial photographs, LiDAR datasets, and satellite imagery (Corona and Ziyuan-3), together with wind information. They used a minimum distance supervised classification to detect bare sand surfaces in each of the satellite and aerial images. Then, post-classification change detection was performed. This method enables the quantification of area of bare sand, dune movement rate, number and length of foredunes, and coastline position changes. Sam et al. (2015) extracted 3-dimensional information from Cartosat-1 stereopairs of a site in Rajasthan.

Concluding remarks

Satellite remote sensing has a transformative role in monitoring coastal dune environments, offering scalable and repeatable methods. The integration of remote sensing with field methods enhances the understanding of dune dynamics across spatial and temporal scales. The increasing availability of satellite data, and the advances in machine learning and cloud-based platforms have expanded the analytical capabilities.

However, the review underscores research gaps, particularly in leveraging SAR data and automatically addressing high-energy coasts. Future studies should focus on refining existing workflows and incorporating artificial intelligence for automated feature detection. Strengthening interdisciplinary approaches and validating with field observations remain essential for robust coastal research.

Coastal areas are dynamic, requiring effective monitoring methods. This review discusses the integration of remote sensing with traditional field methods, the suitability of various scales of analysis, the growing availability of satellite data, and advancements in computational tools. Our approach emphasizes the importance of a scale-aware framework, as proposed by Walker et al. (2017), which divides research into plot, landform, and landscape scales. As expected, the review points to limited studies at the plot scale and the predominance of studies at the landscape scales (sub-

regional, regional and super-regional). Very large-scale, global studies remain scarce due to data limitations.

In this paper, we have identified widely used satellite datasets such as Landsat missions and Copernicus Sentinel-2, which are favoured for their medium resolution, global coverage, and free availability. VHR data from sources like QuickBird and Pléiades are employed for finer spatial analyses, although their application is often constrained by cost and accessibility. SAR data, despite its advantages in atmospheric penetration and its sensibility to land deformation, appears underutilized compared to optical imagery.

The review points to main trends in terms of tools and research applications. Remote sensing methods and tools predominantly focus on shoreline detection and vegetation mapping. DSAS and CoastSat tools are prominent for shoreline monitoring, and spectral indices and land cover classification algorithms lead vegetation cover analyses. Visual photointerpretation and manual digitisation are still common.

Crucial limitations remain for the application of remote sensing tools to the study of coastal dunes, such as the need to identify methodologies to extract topographic data in this highly dynamic environment (Binetti et al., 2024). However, the increasing availability of satellite images, coupled with improvements in temporal and spatial resolutions, could lead to improved monitoring of coastal dunes, which in turn could enhance our understanding of coastal dune adaptations to sea-level rise and climate change.

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Supplemental Material

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References

Aadland T and Helland-Hansen W (2019) Progradation rates measured at modern river outlets: a first-order constraint on the pace of deltaic deposition. *Journal of Geophysical Research: Earth Surface* 124: 347–364. doi: 10.1029/2018JF004750.

Abd-Elhamid HF, Zeleňáková M, Barańczuk J, et al. (2023) Historical trend analysis and forecasting of shoreline change at the nile delta using RS data and GIS with the DSAS tool. *Remote Sensing* 15: 1737. doi: 10.3390/rs15071737.

Adebisi N, Balogun AL, Mahdianpari M, et al. (2021) Assessing the impacts of rising sea level on coastal morpho-dynamics with automated high-frequency shoreline mapping using multi-sensor optical satellites. *Remote Sensing* 13: 3587. DOI: 10.3390/rs13183587.

Al Fugura A, Billa L and Pradhan B (2011) Semi-automated procedures for shoreline extraction using single RADARSAT-1 SAR image. *Estuarine, Coastal and Shelf Science* 95: 395–400. DOI: 10.1016/j.ecss.2011.10.009.

Al Ruheili AM and Boluwade A (2021) Quantifying coastal shoreline erosion due to climatic extremes using remote-sensed estimates from sentinel-2A data. *Environmental Processes* 8: 1121–1140. DOI: 10.1007/s40710-021-00522-2.

Alaska Satellite Facility (2024) ALOS PALSAR [WWW document]. Alaska Satell Facil. https://asf.alaska.edu/datasets/daac/alos-palsar/ (accessed 11.14.24).

Albuquerque MG, Freitas JG, Pereira BM, et al. (2025) Long-term monitoring of coastal dunes in Rio Grande do Sul southern Brazil: a decadal time series of satellite imagery. *Journal of Coastal Research* 113(1): 499–503. doi: 10.2112/JCR-SI113-098.1.

Alves FC and Rossetti DDF (2017) Late Holocene coastal dynamics and relative sea-level changes in the littoral of Paraíba, northeastern Brazil. *Progress in Physical*

Geography: Earth and Environment 41: 375–392. doi: 10.1177/0309133317709744.

Aly MH, Giardino JR, Klein AG, et al. (2012) InSAR study of shoreline change along the Damietta promontory, Egypt. *Journal of Coastal Research* 28: 1263–1269. doi: 10.2112/JCOASTRES-D-11-00182.1.

Amaro VE, Gomes LRS, de Lima FGF, et al. (2015) Multitemporal analysis of coastal erosion based on multisource satellite images, ponta negra beach, natal city, northeastern Brazil. *Marine Geodesy* 38: 1–25. doi: 10.1080/01490419.2014.904257.

Angelini R, Angelats E, Luzi G, et al. (2024) Development of methods for satellite shoreline detection and monitoring of megacusp undulations. *Remote Sensing* 16: 4553. doi: 10.3390/rs16234553.

Anwar MS and Rahman K (2021) The spatiotemporal shore morphological changes at east Bhola Island in Meghna Estuary of Bangladesh's central coast. *Regional Studies in Marine Science* 47: 101937. doi: 10.1016/j.rsma.2021.101937.

Austrich A, Mapelli FJ, Mora MS, et al. (2021) Landscape change and associated increase in habitat fragmentation during the last 30 Years in coastal sand dunes of Buenos Aires province, Argentina. *Estuaries and Coasts* 44: 643–656. doi: 10.1007/s12237-020-00798-x.

Baral R, Pradhan S, Samal RN, et al. (2018) Shoreline change analysis at chilika lagoon coast, India using digital shoreline analysis system. *Journal of the Indian Society of Remote Sensing* 46: 1637–1644. doi: 10.1007/s12524-018-0818-7.

Bauer BO and Sherman DJ (1999) Coastal dune dynamics: problems and prospects. *Aeolian Environments Sediments and Landforms* 14: 71.

Bentze C, Burningham H and Magee E (2023) Down the rabbit-hole: satellite-based analysis of spatiotemporal patterns in wild European rabbit burrows for better coastal dune management. *Journal of Coastal Conservation* 27: 61. doi: 10.1007/s11852-023-00992-6.

Bergsma EWJ, Sadio M, Sakho I, et al. (2020) Sand-spit evolution and inlet dynamics derived from space-borne optical imagery: is the Senegal-river inlet closing? *Journal of Coastal Research* 95: 372–376. doi: 10.2112/SI95-072.1.

Besset M, Anthony EJ, Dussouillez P, et al. (2017) The impact of Cyclone Nargis on the Ayeyarwady (Irrawaddy) River delta shoreline and nearshore zone (Myanmar): towards degraded delta resilience? *Comptes Rendus Geoscience* 349: 238–247. doi: 10.1016/j.crte.2017.09.002.

Billet C, Bacino G, Alonso G, et al. (2023) Shoreline Temporal Variability Inferred from Satellite Images at Mar del Plata, Argentina. *Water* 15: 1299. doi: 10.3390/w15071299.

Billet C, Alonso G, Danieli G, et al. (2024) Evaluation of beach nourishment in Mar del plata, Argentina: An application of the CoastSat toolkit. *Coastal Engineering* 193: 104593. doi: 10.1016/j.coastaleng.2024.104593.

Binetti MS, Massarelli C and Uricchio VF (2024) Machine learning in geosciences: a review of complex environmental monitoring applications. *Machine Learning and Knowledge Extraction* 6: 1263–1280. doi: 10.3390/make6020059.

Block C, Pedrana J, Stellatelli OA, et al. (2016) Habitat suitability models for the sand lizard Liolaemus wiegmannii based on landscape characteristics in temperate coastal dunes in Argentina. *Austral Ecology* 41: 671–680. doi: 10.1111/aec.12356.

Bonte D, Batsleer F, Provoost S, et al. (2021) Biomorphogenic feedbacks and the spatial organization of a dominant grass steer dune development. *Frontiers in Ecology and Evolution* 9: 761336. doi: 10.3389/fevo.2021.761336.

Breiman L (2001) Random forests. *Machine Learning* 45: 5–32. doi: 10.1023/A:1010933404324.

Briceño de Urbaneja IC, Pardo-Pascual JE, Cabezas-Rabadán C, et al. (2024) Characterization of multi-decadal beach changes in cartagena bay (Valparaíso, Chile) from satellite imagery. *Remote Sensing* 16: 2360. doi: 10.3390/rs16132360.

Cabezas-Rabadán C, Pardo-Pascual JE, Almonacid-Caballer J, et al. (2019a) Detecting problematic beach widths for the recreational function along the Gulf of Valencia (Spain) from Landsat 8 subpixel shorelines. *Applied Geography* 110: 102047. doi: 10.1016/j.apgeog.2019.102047.

Cabezas-Rabadán C, Pardo-Pascual JE, Palomar-Vázquez J, et al. (2019b) Characterizing beach changes using high-frequency Sentinel-2 derived shorelines on the Valencian coast (Spanish Mediterranean). *Science of the Total Environment* 691: 216–231. doi: 10.1016/j.scitotenv.2019.07.084.

Cabral CL and Castro JWA (2022) Coastal dunes migration over the Itaúnas district - Espírito Santo, humid tropical coast of Southeast Brazil. *Journal of South American Earth Sciences* 119: 104016. doi: 10.1016/j.jsames.2022.104016.

Cao C, Su F, Song F, et al. (2022) Distribution and disturbance dynamics of habitats suitable for Suaeda salsa. *Ecological Indicators* 140: 108984. doi: 10.1016/j.ecolind.2022.108984.

Castelle B, Masselink G, Scott T, et al. (2021) Satellite-derived shoreline detection at a high-energy meso-macrotidal beach. *Geomorphology* 383: 107707. doi: 10.1016/j.geomorph.2021.107707.

Cenci L, Pampanoni V, Laneve G, et al. (2021) Evaluating the potentialities of Copernicus very high resolution (VHR) optical datasets for assessing the shoreline erosion hazard in microtidal environments. *Trends Earth Obs* 2: 81–84.

Chang H-K, Chen W-W and Liou J-C (2015) Shifting the waterlines of satellite images to the mean water shorelines considering wave runup, setup, and tidal variation. *Journal of Applied Remote Sensing* 9: 096004. doi: 10.1117/1.JRS.9.096004.

Chu Z, Yang X, Feng X, et al. (2013) Temporal and spatial changes in coastline movement of the Yangtze delta during 1974-2010. *Journal of Asian Earth Sciences* 66: 166–174. doi: 10.1016/j.jseaes.2013.01.002.

Cohen MCL, de Souza AV, Liu K-B, et al. (2021) Effects of beach nourishment project on coastal geomorphology and mangrove dynamics in Southern Louisiana, USA. *Remote Sensing* 13: 2688. doi: 10.3390/rs13142688.

Cohn N, Bosche LV, Midgley T, et al. (2022) Assessing drivers of coastal tundra retreat at point hope, Alaska. *Journal of Geophysical Research: Earth Surface* 127: e2022JF006813. doi: 10.1029/2022JF006813.

Collet I and Engelbert A (2013) Coastal regions: people living along the coastline, integration of NUTS 2010 and latest population grid. *Statistics in Focus* 30.

Cooper JAG, Anfuso G and Rio LD (2009) Bad beach management: European perspectives. In: Kelley JT, Pilkey OH, Andrew J, et al. (eds) *America's Most Vulnerable Coastal Communities*. Geological Society of America.

da Motta LM, Toldo EE, de Almeida LESB, et al. (2015) Sandy sediment budget of the midcoast of Rio Grande do Sul, Brazil. *Journal of Marine Research* 73: 49–69. doi: 10.1357/002224015815848839.

Dada OA, Li G, Qiao L, et al. (2016) Seasonal shoreline behaviours along the arcuate Niger Delta coast: complex interaction between fluvial and marine processes. *Continental Shelf Research* 122: 51–67. doi: 10.1016/j.csr.2016.03.002.

Danchenkov A, Belov N, Bubnova E, et al. (2023) Foredune defending role: vulnerability and potential risk through combined satellite and hydrodynamics approach. *Remote Sensing Applications: Society and Environment* 30: 100934. doi: 10.1016/j.rsase.2023.100934.

Dasilva MD, Bruce D, Hesp PA, et al. (2021) A new application of the disturbance index for fire severity in coastal dunes. *Remote Sensing* 13: 4739. doi: 10.3390/rs13234739.

DaSilva MD, Bruce D, Hesp PA, et al. (2023) Post-wildfire coastal dunefield response using photogrammetry and satellite indices. *Earth Surface Processes and Landforms* 48: 1845–1868. doi: 10.1002/esp.5591.

Davidson-Arnott RGD (2005) Conceptual model of the effects of sea level rise on sandy coasts. *Journal of Coastal Research* 216: 1166–1172. doi: 10.2112/03-0051.1.

Davidson-Arnott RGD and Bauer BO (2021) Controls on the geomorphic response of beach-dune systems to water level rise. *Journal of Great Lakes Research* 47: 1594–1612. doi: 10.1016/j.jglr.2021.05.006.

Debaine F and Robin M (2012) A new GIS modelling of coastal dune protection services against physical coastal hazards. *Ocean & Coastal Management* 63: 43–54. doi: 10.1016/j.ocecoaman.2012.03.012.

Delbosc P, Lagrange I, Rozo C, et al. (2021) Assessing the conservation status of coastal habitats under Article 17 of the EU Habitats Directive. *Biological Conservation* 254: 108935. doi: 10.1016/j.biocon.2020.108935.

Delgado-Fernandez I and Davidson-Arnott R (2011) Meso-scale aeolian sediment input to coastal dunes: the nature of aeolian transport events. *Geomorphology* 126: 217–232. doi: 10.1016/j.geomorph.2010.11.005.

Demir N, Bayram B, Şeker DZ, et al. (2019) A non-parametric fuzzy shoreline extraction approach from Sentinel-1A by integration of RASAT pan-sharpened

imagery. *Geo-Marine Letters* 39: 401–415. doi: 10.1007/s00367-019-00608-9.

Dhanalakshmi S, Kankara RS and Chenthamil Selvan S (2019) Impact assessment of sea level rise over coastal landforms: a case study of Cuddalore coast, south-east coast of India. *Environmental Earth Sciences* 78: 494. doi: 10.1007/s12665-019-8463-1.

Di Stefano A, De Pietro R, Monaco C, et al. (2013) Anthropogenic influence on coastal evolution: a case history from the Catania Gulf shoreline (eastern Sicily, Italy). *Ocean & Coastal Management* 80: 133–148. doi: 10.1016/j.ocecoaman.2013.02.013.

Doody JP (2001) *Coastal Conservation and Management*. Netherlands, Dordrecht: Springer.

Duarte CR, de Miranda FP, Landau L, et al. (2018) Short-time analysis of shoreline based on RapidEye satellite images in the terminal area of Pecém Port, Ceará, Brazil. *International Journal of Remote Sensing* 39: 4376–4389. doi: 10.1080/01431161.2018.1457229.

Durai P, Radhakrishnan NP, Sarunjith KJ, et al. (2021a) Evaluation of various image transformation techniques for the delineation of coastal sand dune features in Tamil Nadu, South India. *Earth Science Informatics* 14: 883–892. doi: 10.1007/s12145-021-00588-4.

Durai P, Sarunjith KJ and Bhaskar AS (2021b) Demarcation of coastal dune morphology and dune patterns using geospatial models: a case study from manapad coastal stretch, Tamil nadu, South India. *Journal of the Geological Society of India* 97: 1408–1414. doi: 10.1007/s12594-021-1880-2.

Duvat VKE, Volto N and Salmon C (2017) Impacts of category 5 tropical cyclone fantala (April 2016) on farquhar atoll, Seychelles islands, Indian ocean. *Geomorphology* 298: 41–62. doi: 10.1016/j.geomorph.2017.09.022.

El Banna MM and Frihy OE (2009) Natural and anthropogenic influences in the northeastern coast of the Nile delta, Egypt. *Environmental Geology* 57: 1593–1602. doi: 10.1007/s00254-008-1434-6.

El-Zeiny A, Hammad H, El-Hassan MA, et al. (2022) Susceptibility of El-Alamein coast to contamination and future prediction of erosion using geostatistical analyses. Egypt. *Journal of Aquatic Biology and Fisheries* 26: 1241–1271. doi: 10.21608/ejabf.2022.268265.

Elewa HH and El Nahry AH (2009) Hydro-environmental status and soil management of the river nile delta, Egypt. *Environmental Geology* 57: 759–774. doi: 10.1007/s00254-008-1354-5.

Elfadaly A, Abutaleb K, Naguib DM, et al. (2023) Tracking the effects of the long-term changes on the coastal archaeological sites of the Mediterranean using remote sensing data: the case study from the northern shoreline of Nile Delta of Egypt. *Archaeological Prospection* 30: 369–390. doi: 10.1002/arp.1898.

ElKotby MR, Sarhan TA and El-Gamal M (2023) Assessment of human interventions presence and their impact on shoreline changes along Nile delta, Egypt. *Oceanologia* 65: 595–611. doi: 10.1016/j.oceano.2023.06.008.

Emam WWM, Khalil MT, Nassif MG, et al. (2019) Applying geospatial technology in assessing the coastal vulnerability of zaranik protectorate to sea-level rise. Egypt. *Journal of Aquatic Biology and Fisheries* 23: 697–719. doi: 10.21608/ejabf.2019.202267.

EO Portal (2012) ZY-3A (Zi Yuan-3A) [WWW document]. EO portal. https://www.eoportal.org/satellite-missions/zy-3a (accessed 11.14.24).

EO Portal (2023) TSX (TerraSAR-X) [WWW document]. EO portal. https://www.eoportal.org/satellite-missions/terrasar-x (accessed 11.14.24).

EO Portal (2024a) ERS-1 (European remote-sensing satellite-1) [WWW document]. EO portal. https://www.eoportal.org/satellite-missions/ers-1 (accessed 11.14.24).

EO Portal (2024b) ERS-2 (European remote-sensing satellite-2) [WWW document]. EO portal. https://www.eoportal.org/satellite-missions/ers-2 (accessed 11.14.24).

ESA (2024a) Sentinel-2: colour vision for Copernicus [WWW document]. ESA Appl. https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-2 (accessed 11.14.24).

ESA (2024b) QuickBird-2 [WWW document]. Earth online. https://earth.esa.int/eogateway/missions/quickbird-2 (accessed 11.14.24).

ESA (2024c) Pléiades [WWW document]. Earth online. https://earth.esa.int/eogateway/missions/pleiades (accessed 11.14.24).

ESA (2024d) RapidEye [WWW document]. Earth online. https://earth.esa.int/eogateway/missions/rapideye (accessed 11.14.24).

ESA (2024e) WorldView-2 [WWW document]. Earth online. https://earth.esa.int/eogateway/missions/worldview-2 (accessed 11.14.24).

ESA (2024f) IRS-P6 (ResourceSat-1) [WWW document]. Earth online. https://earth.esa.int/eogateway/missions/irs-p6-resourcesat-1 (accessed 11.14.24).

ESA (2024g) IRS-1D [WWW document]. Earth online. https://earth.esa.int/eogateway/missions/irs-1d (accessed 11.14.24).

ESA (2024h) PlanetScope [WWW document]. Earth online. https://earth.esa.int/eogateway/missions/planetscope (accessed 11.14.24).

ESA (2024i) SPOT 4 [WWW document]. Earth online. https://earth.esa.int/eogateway/missions/spot-4 (accessed 11 14 24).

ESA (2024j) GeoEye-1 [WWW document]. Earth online. https://earth.esa.int/eogateway/missions/geoeye-1 (accessed 11.14.24).

ESA (2024k) IRS-P5 (Cartosat-1). https://earth.esa.int/eogateway/missions/irs-p5 (accessed 11.14.24).

ESA (2024l) IRS-R2 (ResourceSat-2) [WWW document]. Earth online. https://earth.esa.int/eogateway/missions/resourcesat-2 (accessed 11.14.24).

ESA (2024m) RADARSAT [WWW document]. Earth online. https://earth.esa.int/eogateway/missions/radarsat (accessed 11.14.24).

ESA (2024n) SPOT 1 [WWW document]. Earth online. https://earth.esa.int/eogateway/missions/spot-1 (accessed 11.14.24).

ESA (2024o) ALOS-1. [WWW document]. Earth online. https://earth.esa.int/eogateway/missions/alos (accessed 11 14 24).

ESA (2024p) Sentinel-1: radar vision for Copernicus [WWW document]. ESA Appl. https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1 (accessed 11.14.24).

ESA (2024q) SPOT 6 [WWW document]. Earth online. https://earth.esa.int/eogateway/missions/spot-6 (accessed 11.14.24).

ESA (2024r) WorldView-3 [WWW document]. Earth online. https://earth.esa.int/eogateway/missions/worldview-3 (accessed 11.14.24).

Ettritch G, Bunting P, Jones G, et al. (2018) Monitoring the coastal zone using earth observation: application of linear spectral unmixing to coastal dune systems in Wales. *Remote Sensing in Ecology and Conservation* 4: 303–319. doi: 10.1002/rse2.79.

European Environment Agency (2006) *The Changing Faces of Europe's Coastal Areas (No. 6)*. Copenhagen.

Fairley I, Horrillo-Caraballo J, Masters I, et al. (2020) Spatial variation in coastal dune evolution in a high tidal range environment. *Remote Sensing* 12: 1–25. doi: 10.3390/rs12223689.

Farrell EJ, Delgado Fernandez I, Smyth T, et al. (2024) Contemporary research in coastal dunes and aeolian processes. *Earth Surface Processes and Landforms* 49: 108–116. doi: 10.1002/esp.5597.

Feng Y, Liu Y and Liu D (2015) Shoreline mapping with cellular automata and the shoreline progradation analysis in Shanghai, China from 1979 to 2008. *Arabian Journal of Geosciences* 8: 4337–4351. doi: 10.1007/s12517-014-1515-7.

Flores AM, Méndez DM, Gallardo ES, et al. (2020) Morphodynamics of the northern coasts of the Veracruz State, Mexico: trends over the past four decades (1973-2017). *Investigaciones Geográficas* 103: e60155. doi: 10.14350/RIG.60155.

Foti G, Barbaro G, Barillà GC, et al. (2023) Shoreline erosion due to anthropogenic pressure in Calabria (Italy). *European Journal of Remote Sensing* 56: 2140076. doi: 10.1080/22797254.2022.2140076.

Franklin B, Moore LJ and Zinnert JC (2024) Predicting barrier island shrub presence using remote sensing products and machine learning techniques. *Journal of Geophysical Research: Earth Surface* 129: e2023JF007465. doi: 10.1029/2023JF007465.

García-Rubio G, Huntley D and Russell P (2015) Evaluating shoreline identification using optical satellite images. *Marine Geology* 359: 96–105. doi: 10.1016/j.margeo.2014.11.002.

Garg PK (2020) 10 - Effect of contamination and adjacency factors on snow using spectroradiometer and hyperspectral images. In: Pandey PC, Srivastava PK, Balzter H, et al. (eds) *Hyperspectral Remote Sensing, Earth Observation*. Elsevier, pp. 167–196.

Gómez JF, Byrne M-L, Hamilton J, et al. (2017) Historical coastal evolution and dune vegetation in Isla Salamanca national Park, Colombia. *Journal of Coastal Research* 33: 632–641. doi: 10.2112/JCOASTRES-D-15-00189.1.

Gorczynski LE, Wilson AR, Odhiambo BK, et al. (2024) Coastal forest change and shoreline erosion across a salinity gradient in a micro-tidal estuary system. *Forests* 15: 1069. doi: 10.3390/f15061069.

Gürkan AG and Kayikçi S (2017) Determination of sensitive biotopes using GIS: a case study in

Mediterranean coastal region. *Journal of Environmental Biology* 38: 873–877. doi: 10.22438/jeb/38/5(SI)/GM-01.

Gzam M, Serbaji MM, Ouaja M, et al. (2013) Coastal progradation in response to the recent sea level rise: a case study of El Grine coast, Gulf of Gabes (Southeastern Tunisia). *Arabian Journal of Geosciences* 6: 5007–5016. doi: 10.1007/s12517-012-0713-4.

Hagenaars G, de Vries S, Luijendijk AP, et al. (2018) On the accuracy of automated shoreline detection derived from satellite imagery: a case study of the sand motor mega-scale nourishment. *Coastal Engineering* 133: 113–125. doi: 10.1016/j.coastaleng.2017.12.011.

Hamylton S and East H (2012) A geospatial appraisal of ecological and geomorphic change on diego garcia atoll, chagos islands (British Indian Ocean Territory). *Remote Sensing* 4: 3444–3461. doi: 10.3390/rs4113444.

Haque MM, Haque M and Ghosh MK (2024) The coastal dynamics of the Central Ganges–Brahmaputra–Meghna Delta Coast, Bangladesh: implications for coastal development and sustainability. *Journal of Coastal Conservation* 28: 29. doi: 10.1007/s11852-024-01032-7.

Havivi S, Amir D, Schvartzman I, et al. (2018) Mapping dune dynamics by InSAR coherence. *Earth Surface Processes and Landforms* 43: 1229–1240. doi: 10.1002/esp.4309.

Herlekar MA, Kamble PB, Gawali PB, et al. (2023) Quantitative assessment of shoreline changes along the tropical West Coast, Maharashtra, India: a remote sensing and GIS approach. *Journal of Earth System Science* 132: 31. doi: 10.1007/s12040-023-02047-8.

Hesp PA and Martínez ML (2007) 7 - Disturbance processes and dynamics in coastal dunes. In: Johnson EA and Miyanishi K (eds) *Plant Disturbance Ecology*. Burlington: Academic Press, pp. 215–247.

Hesp PA and Walker IJ (2013) Coastal dunes *Aeolian Geomorphology*. Elsevier Inc., 328–355.

Hesp PA, DaSilva M, Miot da Silva G, et al. (2022) Review and direct evidence of transgressive aeolian sand sheet and dunefield initiation. *Earth Surface Processes and Landforms* 47: 2660–2675. doi: 10.1002/esp.5400.

Himmelstoss EA, Henderson RE, Farris AS, et al. (2024) Digital shoreline analysis system version 6.0. *U.S. Geological Survey software release*. doi: 10.5066/P13WIZ8M.

Hoque MAA, Ahmed N, Pradhan B, et al. (2019) Assessment of coastal vulnerability to multi-hazardous events using geospatial techniques along the eastern coast of Bangladesh. *Ocean & Coastal Management* 181: 104898. doi: 10.1016/j.ocecoaman.2019.104898.

Hossain MS and Saha U (2024) Study on shoreline migration and island dynamics over the last five decades in the Muriganga River using multi-temporal satellite images. *Environmental Monitoring and Assessment* 196: 199. doi: 10.1007/s10661-024-12370-2.

Jackson D and Short A (2020) *Sandy Beach Morphodynamics*. 1st edition. Elsevier.

Jolivet M, Gardel A and Anthony EJ (2019) Multi-decadal changes on the mud-dominated coast of western French guiana: implications for mesoscale shoreline mobility, river-mouth deflection, and sediment sorting. *Journal of Coastal Research* 88(1): 185–194. doi: 10.2112/SI88-014.1.

JPL (2024) Corona program [WWW document]. Mission spacecr. Libr. https://space.jpl.nasa.gov/msl/Programs/corona.html (accessed 11.14.24).

Kaliraj S, Chandrasekar N and Magesh NS (2014) Impacts of wave energy and littoral currents on shoreline erosion/accretion along the south-west coast of Kanyakumari, Tamil Nadu using DSAS and geospatial technology. *Environmental Earth Sciences* 71: 4523–4542. doi: 10.1007/s12665-013-2845-6.

Kazhukalo G, Novikova A, Shabanova N, et al. (2023) Coastal dynamics at kharasavey key site, kara sea, based on remote sensing data. *Remote Sensing* 15: 4199. doi: 10.3390/rs15174199.

Kefi C, Bakouche H and El Asmi AM (2024) Climate-induced vulnerability and conservation strategies for coastal heritage sites in the southern Mediterranean Sea using integrated remote sensing and flood modeling. *Regional Studies in Marine Science* 77: 103618. doi: 10.1016/j.rsma.2024.103618.

Knight J and Burningham H (2021) The morphodynamics of transverse dunes on the coast of South Africa. *Geo-Marine Letters* 41: 47. doi: 10.1007/s00367-021-00717-4.

Konlechner TM, Kennedy DM, O'Grady JJ, et al. (2020) Mapping spatial variability in shoreline change hotspots from satellite data; a case study in southeast Australia. *Estuarine, Coastal and Shelf Science* 246: 107018. doi: 10.1016/j.ecss.2020.107018.

Kozhoridze G, Ben Dor E and Sternberg M (2022) Assessing the dynamics of plant species invasion in eastern-mediterranean coastal dunes using cellular automata modeling and satellite time-series analyses. *Remote Sensing* 14: 1014. doi: 10.3390/rs14041014.

Krebs GD (2023) *KH-9 Hexagon [WWW Document]*. Gunters Space Page. https://space.skyrocket.de/doc_sdat/kh-9.htm (accessed 11.14.24).

Levin N, Tsoar H, Herrmann HJ, et al. (2009) Modelling the formation of residual dune ridges behind barchan dunes in north-east Brazil. *Sedimentology* 56: 1623–1641. doi: 10.1111/j.1365-3091.2009.01048.x.

Levin N, Jablon P-E, Phinn S, et al. (2017) Coastal dune activity and foredune formation on Moreton Island, Australia, 1944–2015. *Aeolian Research* 25: 107–121. doi: 10.1016/j.aeolia.2017.03.005.

Liu Y, Huang H, Qiu Z, et al. (2013) Detecting coastline change from satellite images based on beach slope estimation in a tidal flat. *International Journal of Applied Earth Observation and Geoinformation* 23: 165–176. doi: 10.1016/j.jag.2012.12.005.

Liu J, Huang R, Yu K, et al. (2020) How lime-sand islands in the South China Sea have responded to global warming over the last 30 years: evidence from satellite remote sensing images. *Geomorphology* 371: 107423. doi: 10.1016/j.geomorph.2020.107423.

Luijendijk A, Hagenaars G, Ranasinghe R, et al. (2018) The state of the world's beaches. *Scientific Reports* 8: 6641. doi: 10.1038/s41598-018-24630-6.

Mahbub RB, Ahmed N and Yeasmin F (2020) Towards reducing the data gap in the conservation efforts for sea turtles in Bangladesh. *Regional Studies in Marine Science* 35: 101151. doi: 10.1016/j.rsma.2020.101151.

Maneja RH, Miller JD, Li W, et al. (2021) Multidecadal analysis of beach loss at the major offshore sea turtle nesting islands in the northern Arabian Gulf. *Ecological Indicators* 121: 107146. doi: 10.1016/j.ecolind.2020.107146.

Mann T and Westphal H (2014) Assessing long-term changes in the beach width of reef Islands based on temporally fragmented remote sensing data. *Remote Sensing* 6: 6961–6987. doi: 10.3390/rs6086961.

Manzolli RP, Portz LC, Fontán-Bouzas A, et al. (2023) Contribution of reverse dune migration to stabilization of a transgressive coastal dune field at Lagoa do Peixe national Park dune field (South of Brazil). *Remote Sensing* 15: 3470. doi: 10.3390/rs15143470.

Mao Y, Harris DL, Xie Z, et al. (2021) Efficient measurement of large-scale decadal shoreline change with increased accuracy in tide-dominated coastal environments with Google Earth Engine. *ISPRS Journal of Photogrammetry and Remote Sensing* 181: 385–399. doi: 10.1016/j.isprsjprs.2021.09.021.

Markose VJ, Rajan B, Kankara RS, et al. (2016) Quantitative analysis of temporal variations on shoreline change pattern along Ganjam district, Odisha, east coast of India. *Environmental Earth Sciences* 75: 929. doi: 10.1007/s12665-016-5723-1.

Martínez ML and Psuty NP (eds) (2004) *Coastal Dunes, Ecological Studies*. Berlin, Heidelberg: Springer.

Martínez ML, Gallego-Fernández JB and Hesp PA (eds) (2013) *Restoration of Coastal Dunes*. Berlin, Heidelberg: Springer Series on Environmental Management. Springer.

Marzialetti F, Giulio S, Malavasi M, et al. (2019) Capturing coastal dune natural vegetation types using a phenology-based mapping approach: the potential of Sentinel-2. *Remote Sensing* 11: 1506. doi: 10.3390/rs11121506.

Marzialetti F, Di Febbraro M, Malavasi M, et al. (2020) Mapping coastal dune landscape through spectral Rao's Q temporal diversity. *Remote Sensing* 12: 2315. doi: 10.3390/rs12142315.

Marzialetti F, Cascone S, Frate L, et al. (2021) Measuring alpha and beta diversity by field and remote-sensing data: a challenge for coastal dunes biodiversity monitoring. *Remote Sensing* 13: 1928. doi: 10.3390/rs13101928.

Marzialetti F, Di Febbraro M, Frate L, et al. (2022) Synergetic use of unmanned aerial vehicle and satellite images for detecting non-native tree species: an insight into Acacia saligna invasion in the Mediterranean coast. *Frontiers in Environmental Science* 10: 880626. doi: 10.3389/fenvs.2022.880626.

Maun MA (2009) *The Biology of Coastal Sand Dunes*. Oxford Academic.

Mbezi J, Mango J, Lubida A, et al. (2024) Exploring shoreline changes and their implications in coastal communities using GIS and remote sensing techniques: the case of eastern beaches of Unguja island, Tanzania. *Regional Studies in Marine Science* 75: 103566. doi: 10.1016/j.rsma.2024.103566.

McGill SP, Harris BD, McFall BC, et al. (2022) Morphological analysis of a nearshore nourishment along the atlantic coast of New Jersey, USA. *Journal of Marine Science and Engineering* 10: 1622. doi: 10.3390/jmse10111622.

McLean RF, Tsyban A, Burkett V, et al. (2001) Coastal zones and marine ecosystems, climate change 2001: impacts, adaptation and vulnerability. In: *Contribution of WG II to AR3 of the Intergovernmental*. Cambridge, UK: Panel on Climate Change (IPCC).

Medina Machín A, Marcello J, Hernández-Cordero AI, et al. (2019) Vegetation species mapping in a coastal-dune ecosystem using high resolution satellite imagery. *GIScience and Remote Sensing* 56: 210–232. doi: 10.1080/15481603.2018.1502910.

Mendes VR and Giannini PCF (2015) Coastal dunefields of south Brazil as a record of climatic changes in the South American Monsoon System. *Geomorphology* 246: 22–34. doi: 10.1016/j.geomorph.2015.05.034.

Mishra M, Acharyya T, Chand P, et al. (2021) Analyzing shoreline dynamicity and the associated socio-ecological risk along the Southern Odisha Coast of India using remote sensing-based and statistical approaches. *Geocarto International* 37: 3991–4027. doi: 10.1080/10106049.2021.1882005.

Misra A and Balaji R (2015) Decadal changes in the land use/land cover and shoreline along the coastal districts of southern Gujarat, India. *Environmental Monitoring and Assessment* 187: 461. doi: 10.1007/s10661-015-4684-2.

Misra A and Ramakrishnan B (2020) Assessment of coastal geomorphological changes using multi-temporal Satellite-Derived Bathymetry. *Continental Shelf Research* 207: 104213. doi: 10.1016/j.csr.2020.104213.

Mohd FA, Maulud KNA, Begum RA, et al. (2018) Impact of shoreline changes to pahang coastal area by using geospatial technology. *Sains Malaysiana* 47: 991–997. doi: 10.17576/jsm-2018-4705-14.

Mondal I, Thakur S, Juliev M, et al. (2020) Spatio-temporal modelling of shoreline migration in Sagar Island, West Bengal, India. *Journal of Coastal Conservation* 24: 50. doi: 10.1007/s11852-020-00768-2.

Moulton MAB, Hesp PA, Miot da Silva G, et al. (2019) Changes in vegetation cover on the Younghusband Peninsula transgressive dunefields (Australia) 1949–2017. *Earth Surface Processes and Landforms* 44: 459–470. doi: 10.1002/esp.4508.

Mu K, Tang C, Tosi L, et al. (2024) Coastline monitoring and prediction based on long-term remote sensing data—a case study of the eastern coast of laizhou bay, China. *Remote Sensing* 16: 185. doi: 10.3390/rs16010185.

Munasinghe TN and Warnasuriya TWS (2023) Spatio-temporal behaviour of shorelines due to natural and anthropogenic influences on the Dehiwala-Mt. Lavinia Beach, Sri Lanka: insights towards effective application of satellite-derived data and geospatial techniques. *Ocean & Coastal Management* 242: 106734. doi: 10.1016/j.ocecoaman.2023.106734.

Nandi S, Ghosh M, Kundu A, et al. (2016) Shoreline shifting and its prediction using remote sensing and GIS techniques: a case study of Sagar Island, West Bengal (India). *Journal of Coastal Conservation* 20: 61–80. doi: 10.1007/s11852-015-0418-4.

NASA (2024) *50 Years of Landsat Science [WWW Document]*. Landsat Sci. https://landsat.gsfc.nasa.gov/ (accessed 11.14.24).

Natarajan L, Sivagnanam N, Usha T, et al. (2021) Shoreline changes over last five decades and predictions for 2030 and 2040: a case study from Cuddalore, southeast coast of India. *Earth Science Informatics* 14: 1315–1325. doi: 10.1007/s12145-021-00668-5.

Natesan U, Rajalakshmi PR and Ferrer VA (2014) Shoreline dynamics and littoral transport around the tidal inlet at Pulicat, southeast coast of India. *Continental Shelf Research* 80: 49–56. doi: 10.1016/j.csr.2014.02.018.

Natesan U, Vishnunath R and Kathiravan K (2015) Shoreline oscillation of Dhanushkodi, Rameswaram, India. *Geocarto International* 30: 520–531. doi: 10.1080/10106049.2014.937465.

NIK (2024) *NIK System - RASAT [WWW Document]*. NIK Constr. Trade Ltd Co. https://www.nik.com.tr/content_sistem_uydu.asp?id=57&language=english (accessed 11.14.24).

Nuyts S, O'Shea M and Murphy J (2020) Monitoring the morphodynamic cannibalization of the rossbeigh coastal barrier and dune system over a 19-year period (2001-2019). *Journal of Marine Science and Engineering* 8: 421. doi: 10.3390/JMSE8060421.

Osanyintuyi AJ, Wang Y and Mokhtar NAH (2022) Nearly five decades of changing shoreline mobility along the densely developed Lagos barrier-lagoon coast of Nigeria: a remote sensing approach. *Journal of African Earth Sciences* 194: 104628. doi: 10.1016/j.jafrearsci.2022.104628.

Özcan H, Erginal AE, Akbulak C, et al. (2010) Physico-chemical characteristics of coastal dunes on the Saros Gulf, Turkey. *Journal of Coastal Research* 26: 132–142. doi: 10.2112/08-1109.1.

Padma S, Venkatesan G and Kalpana M (2024) Assessing environmental impact of shoreline changes along the Odisha coast using DSAS and satellite imagery – a study of erosion and accretion patterns. *Asian Journal of Water Environment and Pollution* 21: 229–237. doi: 10.3233/AJW240091.

Pardo-Pascual JE, Almonacid-Caballer J, Ruiz LA, et al. (2012) Automatic extraction of shorelines from Landsat TM and ETM+ multi-temporal images with subpixel precision. *Remote Sensing of Environment* 123: 1–11. doi: 10.1016/j.rse.2012.02.024.

Pardo-Pascual JE, Almonacid-Caballer J, Ruiz LA, et al. (2014) Evaluation of storm impact on sandy beaches of the Gulf of Valencia using Landsat imagery series. *Geomorphology* 214: 388–401. doi: 10.1016/j.geomorph.2014.02.020.

Patton NR, Ellerton D and Shulmeister J (2019) High-resolution remapping of the coastal dune fields of south east Queensland, Australia: a morphometric approach. *Journal of Maps* 15: 578–589. doi: 10.1080/17445647.2019.1642246.

Petrova PG, de Jong SM and Ruessink G (2023) A global remote-sensing assessment of the intersite variability in the greening of coastal dunes. *Remote Sensing* 15: 1491. doi: 10.3390/rs15061491.

Ponnambalam K, Chokkalingam L, Subramaniam V, et al. (2012) Mangrove distribution and morphology Changes in the mullipallam creek, South eastern coast of India. *International Journal of Conservation Science* 3: 51–60.

Portz L, Manzolli RP, Alcántara-Carrió J, et al. (2021) Degradation of a transgressive coastal dunefield by pines plantation and strategies for recuperation (Lagoa do Peixe national Park, southern Brazil). *Estuarine, Coastal and Shelf Science* 259: 107483. doi: 10.1016/j.ecss.2021.107483.

Pourkerman M, Marriner N, Morhange C, et al. (2018) Tracking shoreline erosion of "at risk" coastal archaeology: the example of ancient Siraf (Iran, Persian Gulf). *Applied Geography* 101: 45–55. doi: 10.1016/j.apgeog.2018.10.008.

Povilanskas R, Baghdasarian H, Arakelyan S, et al. (2009) Secular morphodynamic trends of the Holocene dune ridge on the Curonian Spit (Lithuania/Russia). *Journal of Coastal Research* 25: 209–215. doi: 10.2112/07-0927.1.

Psuty N (1988) Sediment budget and dune/beach interaction. *Journal of Coastal Research* Special Issue No. 3: 1–4.

Rajagopalan V (2011) Delineation of shoreline changes using remote sensing and geographical information system. *International Journal of Applied Engineering Research* 6: 1219–1226.

Repkina TY and Yakovleva AP (2023) Aeolian landforms on the White Sea coast: a review of classification and spatial distribution. *Oceanology* 63: 709–718. doi: 10.1134/S0001437023050144.

Repkina TY, Leontiev PA, Krekhov AK, et al. (2024) Coastal dunes of the maida river estuary area (Zimniy coast of the White Sea): spatial distribution and evolution patterns. *Oceanology* 64: 717–730. doi: 10.1134/S0001437024700395.

Rodríguez Paneque R (2024) Beach landforms as indicators of the morphodynamics state of the sandy beaches of the northeastern coast of Cuba. *Investigaciones Geográficas* 113: e60837. doi: 10.14350/rig.60837.

Román-Rivera MA and Ellis JT (2019) A synthetic review of remote sensing applications to detect nearshore bars. *Marine Geology* 408: 144–153. doi: 10.1016/j.margeo.2018.12.003.

Sam L, Gahlot N and Prusty BG (2015) Estimation of dune celerity and sand flux in part of West Rajasthan, Gadra area of the Thar Desert using temporal remote sensing data. *Arabian Journal of Geosciences* 8: 295–306. doi: 10.1007/s12517-013-1219-4.

Samanta S and Paul SK (2016) Geospatial analysis of shoreline and land use/land cover changes through remote sensing and GIS techniques. *Modeling Earth*

Systems and Environment 2: 108. doi: 10.1007/s40808-016-0180-0.

Sambah AB, Rachman MF, Harlyan LI, et al. (2022) Habitat suitability analysis for the olive ridley sea turtle (Lepidochelys olivacea) nesting using geospatial approach. *AACL Bioflux* 15: 1030–1039.

Sánchez-García E, Palomar-Vázquez JM, Pardo-Pascual JE, et al. (2020) An efficient protocol for accurate and massive shoreline definition from mid-resolution satellite imagery. *Coastal Engineering* 160: 103732. doi: 10.1016/j.coastaleng.2020.103732.

Satellite Imaging Corporation (2022a) *SPOT-5 satellite sensor*. Satellite Imaging Corporation. https://www.satimagingcorp.com/satellite-sensors/other-satellite-sensors/spot-5/ (accessed 11.14.24).

Satellite Imaging Corporation (2022b) *IKONOS satellite sensor [WWW document]*. Satellite Imaging Corporation. https://www.satimagingcorp.com/satellite-sensors/ikonos/ (accessed 11.14.24).

Satellite Imaging Corporation (2022c) *WorldView-1 satellite sensor [WWW document]*. Satellite Imaging Corporation. https://www.satimagingcorp.com/satellite-sensors/worldview-1/ (accessed 11.14.24).

Satellite Imaging Corporation (2022d) *Jilin-1 Satellite Sensor [WWW document]*. Satell. Imaging Corp. https://www.satimagingcorp.com/satellite-sensors/jilin-1-satellite-sensor-1m/ (accessed 11.14.24).

Scardino G, Mancino S, Romano G, et al. (2023) An integrated approach between multispectral satellite images and geophysical and morpho-topographic surveys for the detection of water stress associated with coastal dune erosion. *Remote Sensing* 15: 4415. doi: 10.3390/rs15184415.

Schellekens J and Amani M (2022) Coastal erosion detection using Landsat satellite imagery and support vector machine algorithm. *The Journal of Ocean Technology* 17: 54–64.

Septiangga B and Mutaqin BW (2021) Spatio-temporal analysis of wulan delta in Indonesia: characteristics, evolution, and controlling factors. *Geographia Technica* 16: 43–55. doi: 10.21163/GT_2021.163.04.

Shanmuga Priyaa S and Jena BK (2021) Suspended sediments concentration on shoreline change using satellite images for southern Kerala coast. *Journal of Earth System Science* 130: 211. doi: 10.1007/s12040-021-01710-2.

Sherman DJ (1995) Problems of scale in the modeling and interpretation of coastal dunes. *Marine Geology* 124: 339–349. doi: 10.1016/0025-3227(95)00048-4.

Sherman DJ and Bauer BO (1993) Dynamics of beach-dune systems. *Progress in Physical Geography: Earth and Environment* 17: 413–447. doi: 10.1177/030913339301700402.

Shumack S, Hesse P and Turner L (2017) The impact of fire on sand dune stability: surface coverage and biomass recovery after fires on Western Australian coastal dune systems from 1988 to 2016. *Geomorphology* 299: 39–53. doi: 10.1016/j.geomorph.2017.10.001.

Silva APD, Vieira da Silva G, Strauss D, et al. (2021) Headland bypassing timescales: processes and driving forces. *The Science of the Total Environment* 793: 148591. doi: 10.1016/j.scitotenv.2021.148591.

Siyal AA, Solangi GS, Siyal Z-U-A, et al. (2022) Shoreline change assessment of Indus delta using GIS-DSAS and satellite data. *Regional Studies in Marine Science* 53: 102405. doi: 10.1016/j.rsma.2022.102405.

Smith KEL, Terrano JF, Pitchford JL, et al. (2021) Coastal wetland shoreline change monitoring: a comparison of shorelines from high-resolution worldview satellite imagery, aerial imagery, and field surveys. *Remote Sensing* 13: 3030. doi: 10.3390/rs13153030.

Sundar V, Sannasiraj SA, Ramesh Babu S, et al. (2021) Shoreline changes due to construction of groyne field in north of Chennai Port, India. *Environmental Monitoring and Assessment* 193: 830. doi: 10.1007/s10661-021-09590-1.

Sylaios GK, Anastasiou S and Tsihrintzis VA (2012) Restoration of a seashore eroded due to dam operation through beach nourishment. *Ecohydrology and Hydrobiology* 12: 123–135. doi: 10.2478/v10104-012-0010-6.

Talavera L, Costas S and Ferreira Ó (2024) Controls on blowout evolution in southern Portugal: a 49-year analysis. *The Science of the Total Environment* 955: 176769. doi: 10.1016/j.scitotenv.2024.176769.

Taminskas J, Šimanauskienė R, Linkevičienė R, et al. (2020) Impact of hydro-climatic changes on coastal dunes landscape according to normalized difference vegetation index (The case study of Curonian spit). *Water Switz* 12: 1–18. doi: 10.3390/w12113234.

Tappin DR, Evans HM, Jordan CJ, et al. (2012) Coastal changes in the Sendai area from the impact of the 2011 Tōhoku-oki tsunami: interpretations of time series satellite images, helicopter-borne video footage and field observations. *Sedimentary Geology* 282: 151–174. doi: 10.1016/j.sedgeo.2012.09.011.

Terenzi J, Jorgenson MT and Ely CR (2014) Storm-surge flooding on the yukon-kuskokwim delta, Alaska. *Arctic* 67: 360–374. doi: 10.14430/arctic4403.

Thomas ZA, Turney CSM, Palmer JG, et al. (2018) Extending the observational record to provide new insights into invasive alien species in a coastal dune environment of New Zealand. *Applied Geography* 98: 100–109. doi: 10.1016/j.apgeog.2018.07.006.

Thome K (2024) *About Terra | Terra*. Terra EOS Flagship. https://terra.nasa.gov/about (accessed 11.14.24).

Timm BC and McGarigal K (2012) Fine-scale remotely-sensed cover mapping of coastal dune and salt marsh ecosystems at Cape Cod National Seashore using Random Forests. *Remote Sensing of Environment* 127: 106–117. doi: 10.1016/j.rse.2012.08.033.

Timm BC, Smith SM and Greenspan SE (2014) Remotely sensed mapping of ammophila spp. distribution and density at cape cod national seashore. *Journal of Coastal Research* 30: 862–867. doi: 10.2112/JCOASTRES-D-12-00149.1.

Todaro FM, Adamo M, Tavilla G, et al. (2024) Monitoring of habitats in a coastal dune system within the "Arco ionico" site (Taranto, Apulia). *Land* 13: 1966. doi: 10.3390/land13111966.

Toffani M (2020) Estudio morfodinámico de las dunas del campo eólico de Bahía Creek, Río Negro, Patagonia Argentina. *Latin American Journal of Sedimentology and Basin Analysis* 27: 55–79.

Toffani M, Hesp PA, Isla FI, et al. (2024) Evolutionary stages of active to vegetated coastal transgressive dunefields in the San Matías Gulf coast, Argentina. *Geomorphology* 461: 109289. doi: 10.1016/j.geomorph.2024.109289.

Touhami I, Aouinti H, Khabthani MA, et al. (2022) Monitoring land-cover changes in Mediterranean coastal dunes. In: *Northwest Tunisia, Using Remote Sensing Data*. Notulae Botanicae Horti Agrobotanici Cluj-Napoca.

Trinida ABP, Muskananfola MR, Febrianto S, et al. (2024) Analysis of shoreline change along the coast of Rembang, Indonesia, using digital shoreline analysis system. *Songklanakarin Journal of Science and Technology* 46: 4580–4650.

Valderrama-Landeros L, Flores-Verdugo F and Flores-de-Santiago F (2022) Assessing the coastal vulnerability by combining field surveys and the analytical potential of CoastSat in a highly impacted tourist destination. *Geographies* 2: 642–656. doi: 10.3390/geographies2040039.

Vallarino Castillo R, Negro Valdecantos V and Moreno Blasco L (2022) Shoreline change analysis using historical multispectral Landsat images of the pacific coast of Panama. *Journal of Marine Science and Engineering* 10: 1801. doi: 10.3390/jmse10121801.

van Kuik N, de Vries J, Schwarz C, et al. (2022) Surface-area development of foredune trough blowouts and associated parabolic dunes quantified from time series of satellite imagery. *Aeolian Research* 57: 100812. doi: 10.1016/j.aeolia.2022.100812.

Veettil BK, Costi J, Marques WC, et al. (2020) Coastal environmental changes in southeast asia: a study from quang nam province, central vietnam. *Regional Studies in Marine Science* 39: 101420. doi: 10.1016/j.rsma.2020.101420.

Veettil BK, Tran XL and Lopes MS (2024) Mangrove vegetation changes and shoreline erosion along the central coastline of Vietnam: a study from Quang Ngai province. *Environmental Development* 52: 101065. doi: 10.1016/j.envdev.2024.101065.

Vos K, Harley MD, Turner IL, et al. (2023a) Pacific shoreline erosion and accretion patterns controlled by El Niño/Southern Oscillation. *Nature Geoscience* 16: 140–146. doi: 10.1038/s41561-022-01117-8.

Vos K, Splinter KD, Harley MD, et al. (2019) *CoastSat*: a Google Earth Engine-enabled Python toolkit to extract shorelines from publicly available satellite imagery. *Environmental Modelling & Software* 122: 104528. doi: 10.1016/j.envsoft.2019.104528.

Vos K, Harley MD, Splinter KD, et al. (2020) Beach slopes from satellite-derived shorelines. *Geophysical Research Letters* 47: e2020GL088365. doi: 10.1029/2020GL088365.

Vos K, Splinter KD, Palomar-Vázquez J, et al. (2023b) Benchmarking satellite-derived shoreline mapping algorithms. *Communications Earth & Environment* 4: 1–17. doi: 10.1038/s43247-023-01001-2.

Walker IJ, Davidson-Arnott RGD, Bauer BO, et al. (2017) Scale-dependent perspectives on the geomorphology and

evolution of beach-dune systems. *Earth-Science Reviews* 171: 220–253. doi: 10.1016/j.earscirev.2017.04.011.

Webb AP and Kench PS (2010) The dynamic response of reef islands to sea-level rise: evidence from multi-decadal analysis of island change in the Central Pacific. *Global and Planetary Change* 72: 234–246. doi: 10.1016/j.gloplacha.2010.05.003.

Williams BA, Watson JEM, Beyer HL, et al. (2022) Global rarity of intact coastal regions. *Conservation Biology: The Journal of the Society for Conservation Biology* 36: e13874. doi: 10.1111/cobi.13874.

Xu N, Zhou C and Zhang S (2024) Inferring coastal slope of sandy beaches from remote sensing imagery and tidal level data. *Geocarto International* 39: 2405141. doi: 10.1080/10106049.2024.2405141.

Zhang X, Yang Z, Zhang Y, et al. (2018) Spatial and temporal shoreline changes of the southern yellow river (Huanghe) delta in 1976–2016. *Marine Geology* 395: 188–197. doi: 10.1016/j.margeo.2017.10.006.

Zhang X, Tan X, Hu R, et al. (2021) Using a transect-focused approach to interpret satellite images and analyze shoreline evolution in Haiyang Beach, China. *Marine Geology* 438: 106526. doi: 10.1016/j.margeo.2021.106526.

Zhang Z, Wang Z, Liang B, et al. (2024) Shoreline change analysis in the estuarine area of Rizhao based on remote sensing images and numerical simulation. *Frontiers in Marine Science* 11: 1488577. doi: 10.3389/fmars.2024.1488577.

Zheng Z, Du S, Taubenböck H, et al. (2022) Remote sensing techniques in the investigation of aeolian sand dunes: a review of recent advances. *Remote Sensing of Environment* 271: 112913. doi: 10.1016/j.rse.2022.112913.

Zhou Y, Dai Z, Liang X, et al. (2024) Machine learning-based monitoring of mangrove ecosystem dynamics in the Indus Delta. *Forest Ecology and Management* 571: 122231. doi: 10.1016/j.foreco.2024.122231.