MONITORING BEACH EROSION ALONG THE CENTRAL ADRIATIC COAST: THE CASE STUDY OF MOLISE REGION

Gianluigi Di Paola, Grazia Dilauro, Claudia Caporizzo, Carmen M. Rosskopf

Abstract: Coastal areas characterized by sandy shorelines are among the most dynamic environments and subject to deep and rapid changes over time under the influence of natural and anthropic factors. Therefore, reconstructing the geomorphological and anthropogenic evolution, current state and possible near-future trends of a sandy beach is essential for deepening the understanding of its potential future development and better outlining measures for its sustainable management. For this purpose, we have examined the coast of the Molise region in Italy, which is predominantly made of sandy shorelines and characterized by widespread anthropogenic impact mainly due to tourism and the presence of hard defense structures. This coastline has been continuously and differentially monitored using increasingly modern and efficient approaches and tools over time. We began in the late nineties with traditional topographic instruments and later transitioned to high-precision tools such as GNSS and drones. Field measurements mainly concerned shoreline and dune front positions along with sedimentary and morpho-topographic features of both the backshore/foreshore zones and the submerged beach up to the closure depth, allowing for their large-scale analysis and data updating over time. More recently, drone survey campaigns, carried out along strategic or critical coastal stretches between 2019 and 2024, allowing for the rapid creation of digital terrain models and detailed and punctual evaluations of recent morpho-topographic changes of the beach-dune systems. The combination of all validated field survey methodologies, along with the planned campaigns for the near future, represent the monitoring plan outlined for the Molise coast aimed at defining future action strategies to support its sustainable development and the mitigation of the effects associated with the ongoing climate change.

Keywords: Shoreline changes, natural and anthropogenic controls, coastal monitoring techniques, climate change.

Gianluigi Di Paola, ISPRA - Italian Institute for Environmental Protection and Research, Italy, gianluigi.dipaola@isprambiente.it, 0000-0003-4328-1167
Grazia Dilauro, University of Molise, Italy, g.dilauro2@studenti.unimol.it, 0009-0004-2414-5615
Claudia Caporizzo, University of Pegaso, Italy, claudia.caporizzo@unipegaso.it, 0000-0002-8634-6066
Carmen M. Rosskopf, University of Molise, Italy, rosskopf@unimol.it, 0000-0002-5427-5128

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Introduction

Low-lying coastal areas are among the most dynamic environments and particularly sensitive to climate change. They are undergoing worldwide deep and rapid changes over time that can significantly modify their entire morphological structure and equilibrium, and subject to increasing anthropization due to growing tourist activities and the expansion of inhabited centers. To deepen the understanding of the current state and potential future development of a coastal area, the reconstruction of its long to short-term geomorphological and anthropogenic evolution, together with the assessment of possible near future trends, assume a crucial importance. While extensive literature exists on the morphodynamics of natural beaches and their response to wave climate variations or sea level rise (e.g. [10, 18]), fewer studies delve into how beaches morphologically respond to the presence of coastal structures or nourishment interventions (e.g. [14]). Coastal monitoring emerges as an essential instrument for this purpose, indispensable for supporting management and decision-making endeavors, particularly in light of climate change and its associated impacts [3]. Monitoring methodologies can vary, contingent on factors such as duration, spatial coverage, precision, spatial-temporal resolution, and associated costs [5, 16].

For this purpose, the Molise Region coast that represents a typical example of low-lying sandy coast and is characterized by an important anthropogenic pressure mostly related to tourism activities, has been examined

As evidenced by Buccino et al. (2020) [4] and Rosskopf et al. (2018) [17], the Molise coast has experienced intense erosion since the early 1900s that first caused the complete erosion of the Trigno and Biferno deltas, then a more extensive shoreline retreat, and a consistent loss of coastal land in the last 65 years. Shoreline retreat mainly affected the coastal stretches including the Trigno and Biferno mouths but did not spare several other coastal portions in different periods. To contrast further shoreline retreat, hard defense structures, mainly adherent and detached breakwaters, and groins, have been built especially from the 1980s up to 2000. Nevertheless, erosion partly further accelerated its pace over the last twenty years, with the increasing involvement of coastal stretches located south of major river mouths, and peak rates recorded between 2012 and 2019 for the Biferno mouth area [11].

Materials and Methods

The data that gradually emerged from several studies on the shoreline evolution and recent shoreline trends of the Molise coast (see references in Di Paola et al., 2023 and Rosskopf et al., 2018 [11, 17]) highlighted its elevated present-day and near-future fragility suggesting a more detailed monitoring to better understand ongoing dynamics and prevent future degradation. To this purpose, we started to carry out several and different monitoring activities since 2001. In detail, monitoring activities include the realization and analysis of beach profiles appropriately positioned along the coast and connected to an equal number of bathymetric profiles extending up to the closing depth and the periodical sediment sampling both in the emerged (backshore and foreshore) and submerged beach zones. Furthermore, the assessment of shoreline and dune foot positions, as well as of defense structures through topographic data acquired in the field, photogrammetric data and UAV derived data, and, finally, the characterization of the wave climate conditions and related changes over time, are part of them.

Figure 1 provides a detailed view of the Molise coast monitoring, highlighting the interplay between the different tools used to assess various coastal elements.

It should be noted that the monitoring activities concerning the sedimentology of the emerged beach, and the morphology of the submerged beach are not addressed in this study for the sake of brevity. However, they have been included in the scheme in Figure 1 to provide a clear overview of the work undertaken along the Molise Region coast.

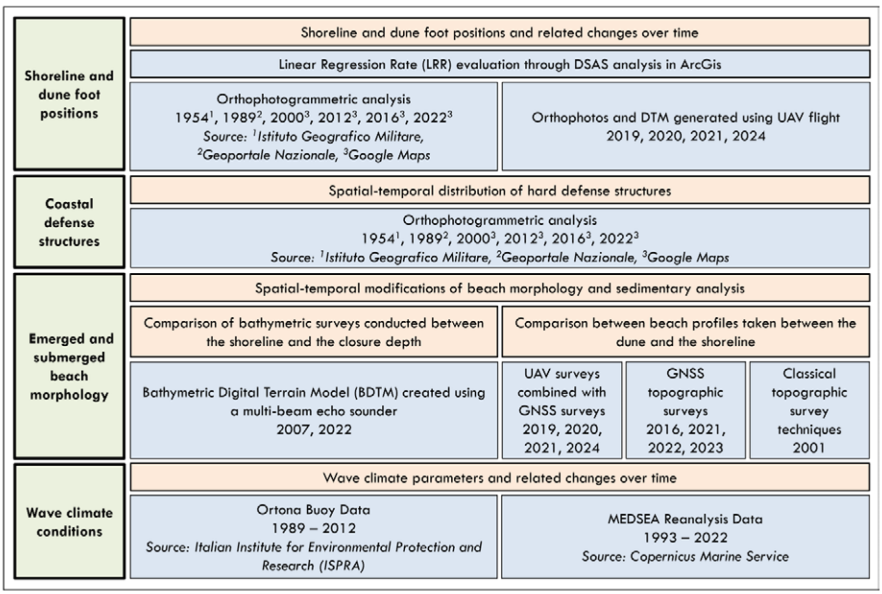

Figure 1 – Flow chart of coastal monitoring of the Molise Region coastline

Shoreline and dune foot positions

In this study the shoreline is defined as the boundary between the dry and wet areas of the beach, while the dune foot is positioned where the beach passes landwards to embryonic dune vegetation or, in areas with intense erosion, at the base of the scarp cut by erosion into the dune front [1, 7, 8]. To evaluate these elements, we used orthophotos from different years covering the entire Molise coastline, along with photogrammetric images and DTMs obtained from drone surveys for more fragile areas (Figure 1). To assess shoreline and dune foot changes, we used the Digital Shoreline Analysis System (DSAS), a freely available ESRI's ArcGIS extension [12]. This tool, by automatically creating regularly spaced transects, provides the Linear Regression Rate (LRR) parameter that represents the average rate of accretion or erosion, which is obtained after fitting a least-squares straight line to each shoreline section for each considered period. In detail, shoreline variations were determined for the whole Molise coast by using 352 transects placed at an equidistance of 100 m. For areas requiring more detailed analysis, a transect spacing of 5 meters was chosen.

Coastal defense structures

The Molise coast is characterized by the widespread presence of hard defense structures that often have been constructed in emergency conditions, i.e. without considering the sedimentary dynamics of the shoreline. As highlighted by several studies (e.g. [4, 17]), these structures have often resulted to be inefficient over time and/or responsible for significant negative effects on adjacent areas. To analyze the spatial-temporal distribution of defense structures, a morphometric analysis was performed in a GIS environment by examining a set of orthophotos and aerial photos taken in different years (Figure 1). Photointerpretation allowed the implementation of a database containing information about types and periods in which defenses were constructed, modified or removed. The identified structures are represented by adherent and detached (submerged and emerged) breakwaters, and by groins.

Beach morphology and sediment features

Another aspect for the thorough analysis of the study coast is the characterization of its morphology, achieved through beach and bathymetric profiles. In detail, beach profiles were traced orthogonally to the shoreline, starting at least from the crest of the dune that marks the landward limit of the backshore, while bathymetric profiles were realized between the shoreline and the closure depth. The beach morphology and related recent changes were investigated over the last 20 years (Figure 1). To realize beach profiles, we initially used a classical methodology based on the use of a theodolite and a grade rod, and afterwards a Global Navigation Satellite System (GNSS) that allowed a faster data acquisition. In recent years, these methodologies were integrated using Digital Terrain Models (DTMs) derived from drone surveys. Data obtained by combining over time such different methods were correlated to assess their reliability, which was proved to be extremely high [15]. The bathymetric profiles were conducted during the summers of 2007 and 2021 using a single-beam echo-sounder along transects created every 200-250 meters, which reached up to 600 meters from the coastline and an average depth of 10 meters below sea level. Periodically, morpho-topographic and morpho-bathymetric surveys were integrated with sedimentological analysis of both the emerged and submerged beach, to assess changes in sediment features and grain sizes along the entire coastal strip.

Wave climate parameters and related changes over time

To characterize the wave climate along the study area, it was necessary to acquire a statistically significant time series of data representative of the incident wave conditions [4, 6]. Both directly measured wave parameters and indirect wave data derived from models simulating wave types based on wind direction and energy (Figure 1) were acquired. In detail, wave parameters recorded by the directional wave buoy located offshore of Ortona at about 56 km north of the Termoli harbour were obtained, including 3-hourly data concerning significant wave height, peak period, and azimuth of the mean wave direction recorded during the period 1989–2012. Wave heights and periods were adjusted by using a virtual buoy located offshore of the coast of Termoli. To integrate the "buoy dataset" of Ortona, the time series with a one-hour interval of significant wave height, mean wave direction, and peak wave period from the "MEDSEA Reanalysis" dataset were acquired for the period from 1993 to 2021 and considered representative for the offshore marine conditions of the investigated physiographic unit [13]. This dataset is based on the WAM (WAve Model) that provides hourly instantaneous data of spectral wave parameters calculated on a grid with a resolution of approximately 4.6 km, covering the Mediterranean Sea and an adjacent portion of the Atlantic Ocean.

Results and Discussion

The multi-instrumental monitoring implemented on the Molise coast has enabled its accurate and diversified analysis, allowing for the characterization of the evolution of numerous morphological elements defining it. Most of the data produced until to date, used to study more general or specific aspects of the Molise coastal system are summarized in the works of Aucelli et al. (2009; 2018) [1, 2], Rosskopf et al. (2018) [17], Buccino et al. (2020) [4], Minervino et al. (2022) [15], and Di Paola et al. (2022; 2023) [8, 10]. This paper presents the general results of this monitoring approach with an in-depth analysis concerning the emerged beach.

The shoreline changes of the Molise Region from the 1950s to the present have been thoroughly investigated, distinguishing long, mid and short-term periods. In the long run (Figure 2A), shoreline retreat affected especially the coastal sectors including the Biferno and Trigno river mouths, with average retreat rates of up to 5 m/year during the last 68 years (Figure 2B, period 1954-2022). Considering instead recent years, data show that increasingly severe erosion affected above all areas close to defense structures, as shown by analyzed data concerning the period 2012-2022 (Figure 2C). The observed relation between the position of defense structures and major erosion hot spots highlights the importance of an accurate and detailed inventory of defenses to understand their impact on coastal dynamics. Data collected show that the coverage percentage of coastal defense structures along the Molise coast increased from 29 % to 62 % between 1989 and 2022 (Figure 2).

The effects of defense structures can only be understood by analyzing in detail the wave climate that characterizes the coast. Specifically, the monitoring carried out over time has shown that the Molise coast is characterized by relatively mild meteomarine conditions, due to its limited fetch and rather moderate wind settings. In fact, 83.5 % of the recorded sea states have a significant wave height of less than 1 m, and only 3.4 % of them correspond to marine storms, assuming that a storm is characterized by a significant wave height greater than 2 m. Furthermore, the waves approach the Molise coast from two prevailing directions: the directional quadrant between NW and NE, and the directional sector approximately from NE to SE, significantly influencing coastal evolution.

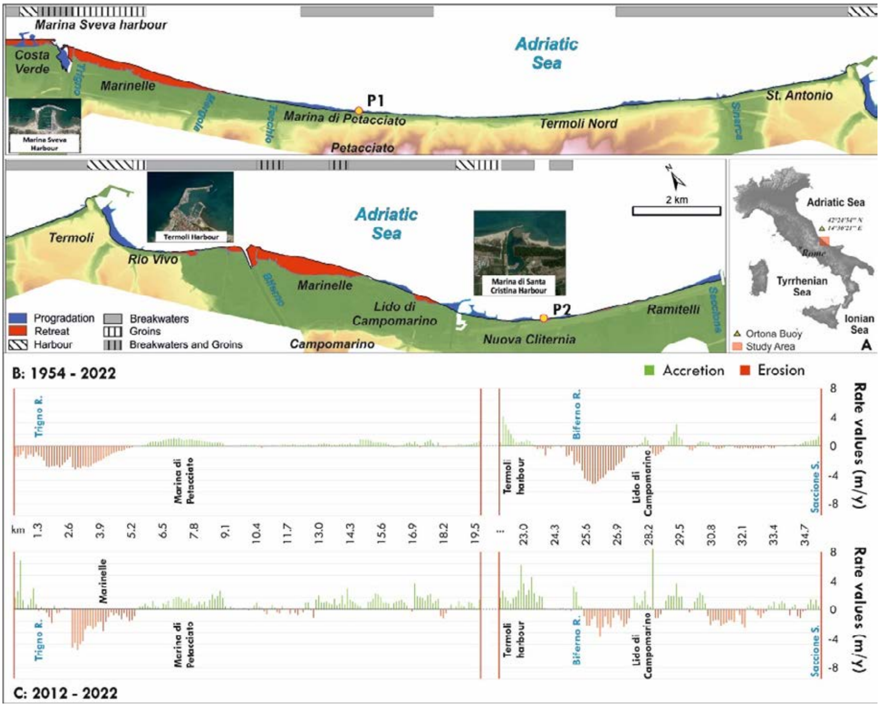

Figure 2 – A: Distribution of progradation and retreat along the Molise coast in the long-term period (1954-2016), extension and location of coastal defense structures and harbours (modified from Di Paola et al., 2020 [9]). B and C: evolution of the Molise shoreline evaluated with DSAS respectively over the long-term (1954-2022) and the short-term (2012-2022).

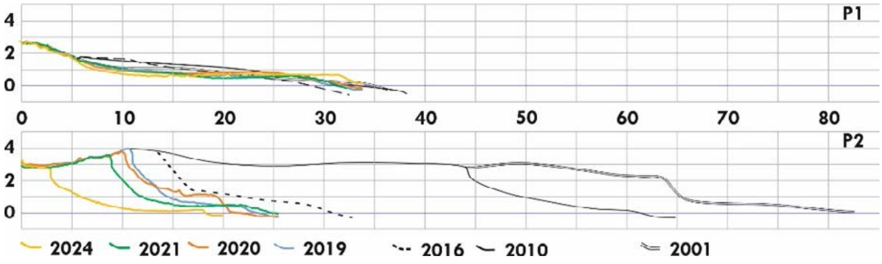

Figure 3 – Comparison between the profiles surveyed from 2001 to 2024 along the beaches of Petacciato (P1) and Campomarino (P2).

The beach morphology is under detailed investigation since 2001. Various instruments were used for its monitoring, as previously described. Figure 3 shows two sequences of profiles realized between 2001 and 2024 in two selected beach stripes, located respectively in the territories of Petacciato and Campomarino. Data were acquired first with a traditional instrumentation, then continued with the use of GNSS technique in 2016 and 2010, and from 2019 onwards with UAV surveys.

The beach profiles of Petacciato beach (P1, Figure 3) evidence an overall substantial stability of both the shoreline and the dune front positions.

The profiles of Campomarino beach (P2, Figure 3), instead, show a very strong erosive trend with a shoreline retreat of about 63 m from 2001 to 2024 (2.7 m/year) accompanied by a dune front retreat of 61 meters, so that the beach remained essentially stable in width over this period.

The main details about the most recent trends of the Campomarino and Petacciato beaches are shown in figures 4 and 5 displaying the orthophotos obtained from UAV flights conducted in 2019 and 2024, respectively.

Figure 4 shows that the Petacciato beach has remained essentially stable in the southern portion, showing some slight retreat of the shoreline in the northern portion. Anyway, the dune foot appears on overall stable.

The Campomarino beach instead (Figure 5) appears to be affected by a clear retreat of both the shoreline and the dune front in its central and southern portions.

Comparing these two areas highlights that the dune foot maintains its position in natural and accretion areas (Petacciato beach, Figure 4), while it responds with pronounced retreat in zones with strong erosive dynamics such as the Campomarino, clearly highlighting the erosive impact of wave run-up on it during storm events. It should be added that the dune foot is sometimes also modified by anthropogenic interventions such as beach cleaning that destroys the embryonic dunes and, in some cases, has been even retreated artificially by scrapers to enlarge the beach for bathing purposes.

Conclusions

The present study has illustrated the monitoring protocol developed for the Molise coast aimed at a better understanding of general and local aspects concerning its evolutionary dynamics and recent to possible near-future trends.

The set of performed surveys and analyses has allowed constructing a valid database upgradeable in space and time according to already defined steps and/or future needs. This database can validly sustain future investigations and action strategies aimed at mitigating the effects of ongoing climate changes, therefore contribute to the definition of sustainable management solutions for the development of coastal areas without compromising their geomorphological and ecological equilibrium and quality.

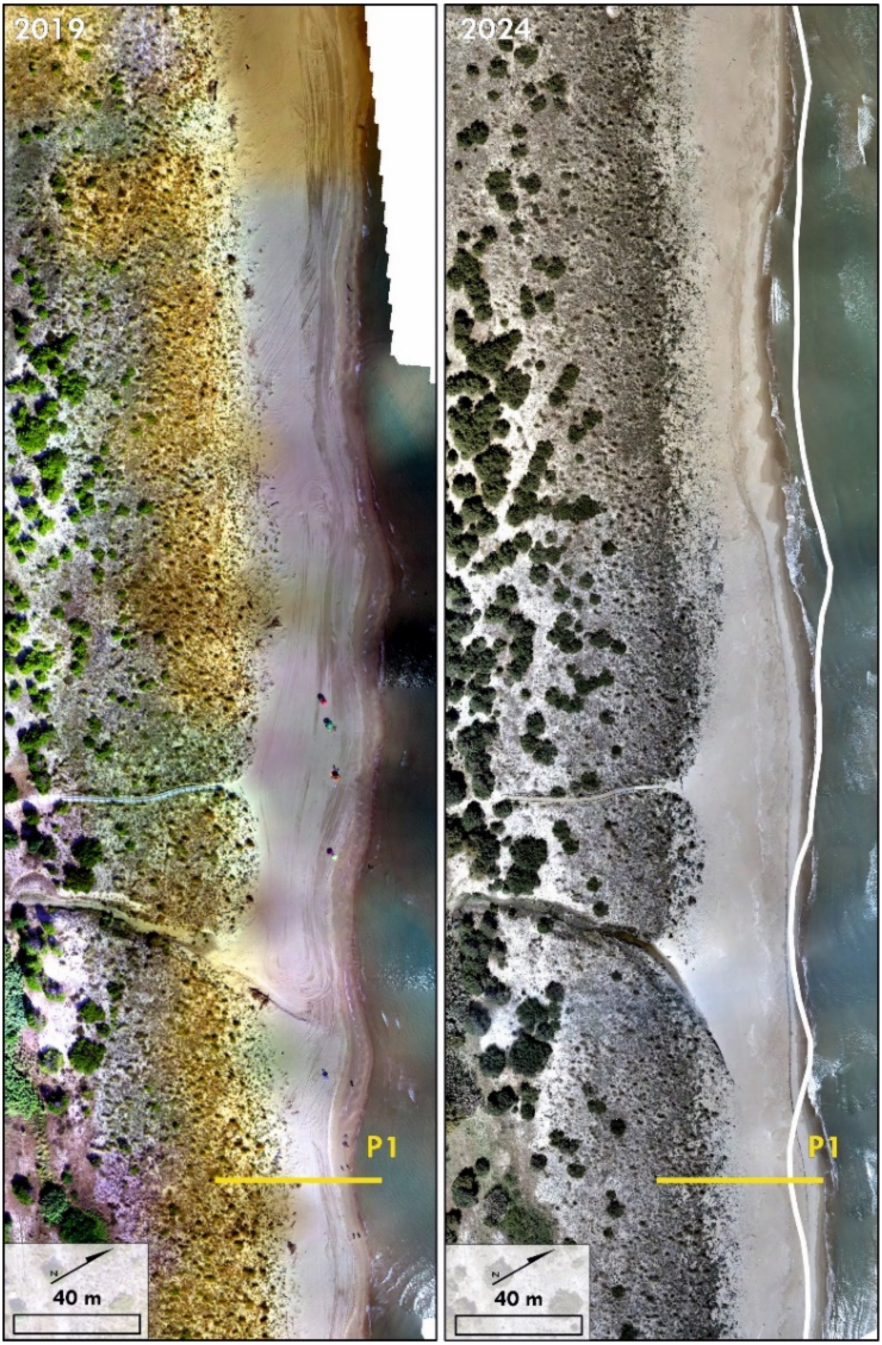

Figure 4 – Comparison between the orthophotos obtained elaborating drone surveys performed in 2019 and 2024 on the Petacciato beach. The 2019 UAV shoreline is marked in white.

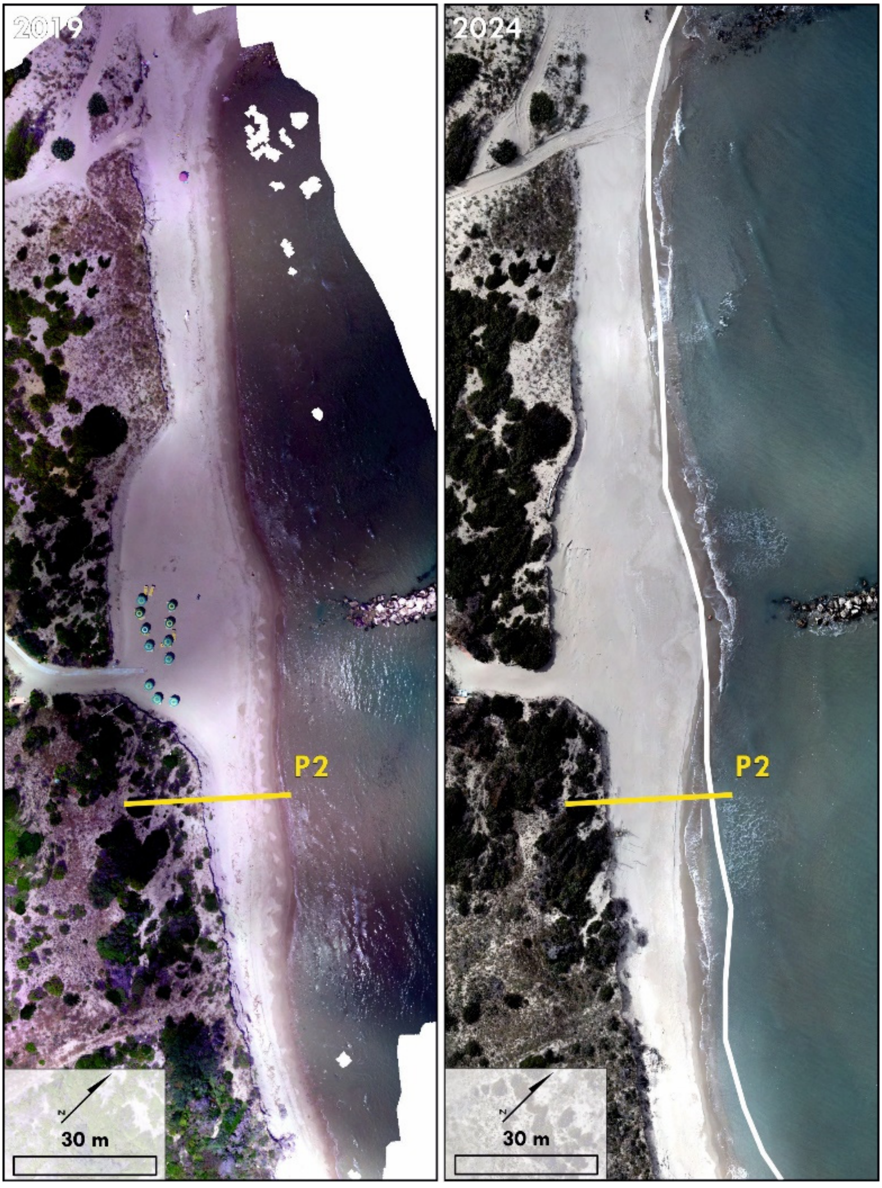

Figure 5 – Comparison between the orthophotos obtained elaborating drone surveys performed in 2019 and 2024 on the Campomarino beach. The 2019 UAV shoreline is marked in white.

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