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Quantifying Transgressive Coastal Changes Using UAVs: Dune Migration, Overwash Recovery, and Barrier Flooding Assessment and Interferences with Human and Natural Assets

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Abstract: The advantages derived from the use of Uncrewed Aerial Vehicles (UAVs) are well-established: they are cost-effective and easy to use. There are numerous environmental applications, particularly when monitoring contexts characterized by rapid morphological changes and high rates of sediment transport, such as coastal areas. In this paper, three different case studies of survey and monitoring with high resolution and accuracy obtained through the use of UAVs are presented; these concern transgressive coastal sites. Results allow for the definition and quantification of coastal landforms and processes, including: (i) The anatomy of a parabolic dune and the rate of landward migration that could interfere with a tourist settlement; (ii) The mode and timing of morphological recovery and realignment of a barrier island overwashed by storm surge episodes; and (iii) The potential flood risk of a progradational spit that is a nesting site of a species of migratory breeding birds of conservation concern. The results demonstrate and confirm that, through a good coupling of drone-sensed quality data and accurate topographic control, quantitative estimates that are useful in assessing the impacts of natural processes involving both human and natural assets can be obtained.

Keywords: coastal monitoring; dune migration; washover; flood risk; barrier island; Piscinas dunefield; Marano and Grado Lagoon; *Sternula albifrons*; UAV survey

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1. Introduction

Along with providing essential ecosystem services such as shoreline protection, improved water quality, fishing resources, and food and habitat for wildlife, coastal zones attract people due to the diversity of leisure activities available [1].

By their nature, coastal environments change rapidly in response to waves, currents, winds, and tides and necessitate frequent and precise geomorphological monitoring [2]. Direct observation, instrumental measurements, or imaging can be used in the short or medium term to monitor the various compartments, such as the nearshore, which includes the shoreface, the beach, and the coastal dunes. The main aim is to assess the modifications induced by sediment transport, which impact coastal landforms, habitats, and human goods [2]. This is crucial in transgressive contexts (such as shoreline retreat, washover, blowout, or transgressive dunefields), which can be induced and/or worsened by the accelerating global sea-level rise [3,4].

As coastal environments are constantly changing, so are the technologies and techniques used to map and monitor them [5]. Since the 2000s, aerial photos captured by

Uncrewed Aerial Vehicles (UAVs) have made coastal monitoring increasingly more affordable and efficient (see review articles of [5–10]). Ref. [11] highlighted that UAV remote sensing technology could possibly serve as the answer to the monitoring objectives that are essential for an efficient coastal management.

The advantages of UAV remote sensing technology for coastal mapping include automated surveys, high repeatability, minimal preparation, quick responses to extreme events, high measurement efficiency, and the generation of Digital Surface Models (DSMs) with high resolution and accuracy or point cloud by Structure for Motion (SfM) photogrammetry [11–14].

Low-cost investigations of vegetation, morphological, and sedimentological changes on beaches, coastal dunes, and estuarine mudflats or tidal flats using photogrammetry via UAVs supported by ground control points (GCPs) show the applicability of UAV remote sensing technology to the study of multiscale geomorphological dynamics caused by erosion, sedimentation, and other processes [12,15–17]. Furthermore, an increasing number of publications are reporting the use of UAVs in the monitoring and evaluation of the physical environment, which affects habitat and, as a result, species, [8,18] establishing it as an indispensable tool in this field.

For an understanding of a wide range of coastal processes at diverse geographical and temporal scales and site-specific demands, a set of case studies covering distinct and expert ways of data collection and processing is crucial.

This work presents the findings of three separate case studies of UAV monitoring in extremely dynamic coastal settings using aerial images and detailed topography to gather exact information on morphology, sediment budget, and plant cover. In the first case study, we attempted to describe the architecture of a parabolic dune and calculate the rate of movement of its active lobes, as well as the associated sand drift risk, in a typical transgressive aeolian setting. In the second case, the investigations assessed the mode and timing of morphological recovery and realignment following storm surge overwashing on a highly dynamic sandy barrier island. Finally, in order to evaluate the possible flood risk that would imperil a nesting colony site of a species of migratory breeding birds of conservation concern, we acquired the micro-topography of a progradational spit and put it in relation to tide level measurements.

The goal of examining these various scenarios is to demonstrate how drone surveys, whose instrumental performance and timing have greatly improved over time, can deliver accurate, high-quality site data even in very dynamic environments, especially when more information is associated with them that can aid in understanding the processes at work. This information can support the assessment of fundamental coastal management issues and the correlated geohazards, ecosystem restoration, and species conservation.

2. Study Areas and Background

This study deals with the monitoring of three study cases in Italy (Figure 1), which represent different sedimentary environments and processes: (i) The transgressive parabolic dune of Piscinas in Sardinia; (ii) A washover fan in Martignano island; and (iii) A prograding spit in Tratauri bank, both of which evolve along the barrier island system of the Marano and Grado Lagoon (MGL) in the northern Adriatic Sea.

2.1. The Transgressive Parabolic Dune of Piscinas

Coastal transgressive dune systems are large-scale, mobile, partially vegetated dune complexes that can decouple from the backshore and migrate inland [19]. Coastal transgressive dunes require abundant sediment and wind energy over century-to-millennial timescales to develop the complicated cut-and-fill sequences seen in mature systems. Control factors such as a high sediment supply, climatic conditions (e.g., arid or semi-arid), vegetation disturbance, and strong wave and wind energy have all been taken into account by [4,19]. Good examples of Pleistocene and Holocene transgressive dunefields have been documented worldwide along strandplain coastlines (e.g., [20–24]). Contemporary active transgressive dunefields are found on many of the world's coasts [23,25–28] and are often well-developed in areas with significant wind energy.

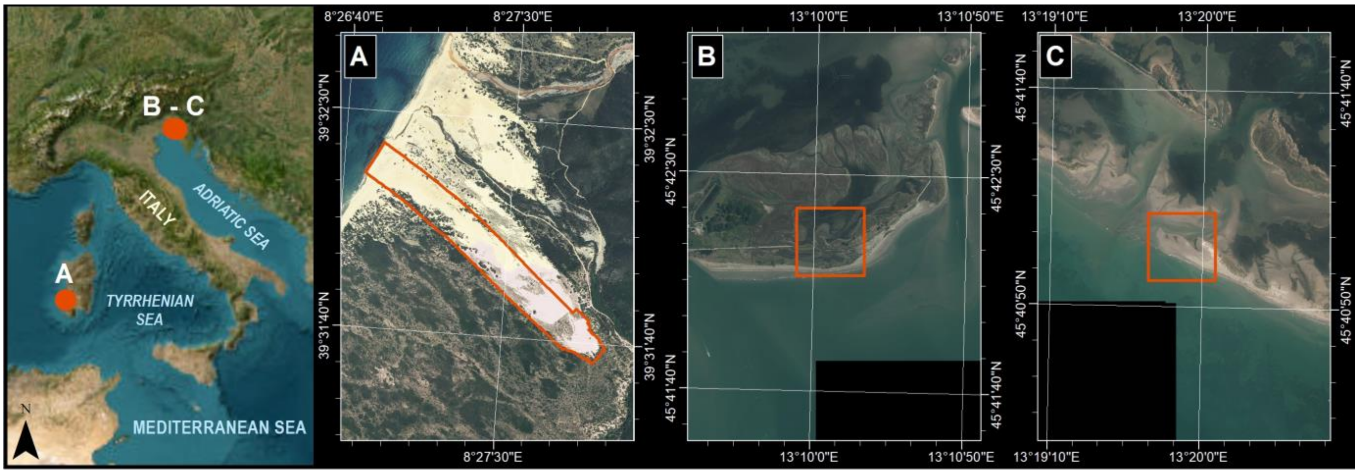

Figure 1. Location of the study sites. In the red boxes: (**A**) the main transgressive parabolic dune of Piscinas; (**B**) the washover fan induced by a storm event in 2013 along the Martignano barrier island; (**C**) the prograding spit, at the western end of the Tratauri bank, and one of the most frequented nesting sites of the Little Tern and Oystercatcher. While A is located in the west coast of Sardinia, both B and C are located along the barrier island system of the Marano and Grado Lagoon.

Parabolic dunes are a common type of transgressive landform. These dunes are typically U-shaped or V-shaped, with two trailing ridges extending from short to elongated. The trailing ridges have a deflation basin upwind that ends in a U- or V-shaped depositional lobe [29–31] and a precipitation ridge (namely slipface). They can be nested or overlap, exhibiting multiple formation episodes. The shape, slope, and type of terrain over which the dunes move, the type and density of vegetation, and the speed and direction of the wind all affect the rates of migration or advancement of these dunes.

The west coast of Sardinia hosts the only examples of active transgressive parabolic dunes in Italy, where they are exposed to strong winds from the northwest. Aeolian activity was significant also in the past, as testified by the extensive outcrop of Middle and Upper Pleistocene aeolianites all along the west coasts [32–34].

The monitored dune is the main parabolic dune of Piscinas (Figure 1A). Here, the wind regime is typically bimodal: winds from the 290°–330° direction (the Mistral) are predominant, either in terms of frequency or strength. The Sirocco winds, from 120°–150° are subordinate [35]. The dune of Piscinas, along with the Monte Arcuentu, are included in the Zone of Special Conservation and Zone of Special Protection (ITB040031), inside the EU Natura 2000 Network. This area is very rich in several species of animals, vegetation, and habitat [36], enhancing its naturalistic value.

2.2. The Dynamic Barrier Islands of the Marano and Grado Lagoon

Barrier islands are important landforms that protect the inland, bays, and estuaries from sea storms; they can be found on about 12% of the world's coasts [37] and are notable for their highly dynamic evolution. Transgressive processes, such as landward migration as a result of relatively rapid sea level rise or continuous storms, are typical modes of barrier evolution. The most common storm-related phenomenon is washover, which occurs when the wave run-up level and/or storm surge level (water level above predicted tide) exceeds the beach crest height, causing water and sediment to move landward [38]. The result is the formation of sand bodies toward the lagoon or the protected bay, with the washover fan being the most common. Washover fans can evolve through processes of channel fill, fan deposition, and subsequent salt marsh colonization by vegetation [39,40], or aeolian deflation and reworking. In this way, washover processes are the primary mechanism by which barriers can increase in width and migrate landward [41–43]. In addition to transgressive processes, progradational trends can coexist on barrier islands thanks to sediment supply and longshore transport prominence [44–48]. Longshore constructive processes result in spit lengthening, nearshore bar welding, and breach closure or inlet migration [48,49]. Spit progradation occurs at different speeds and modes of berm accretion [50]; depressions between newly formed barriers can evolve into parallel swales or enclosed cat's-eye ponds [51,52]. Barrier islands have a notable naturalistic value for their vegetation richness and because they are the ideal habitat for many bird species, both resident and migratory [53]. New washover deposits are ecologically important as they increase habitat diversity and sustain more or less endangered species of birds [54–57].

The MGL is located in the northern Adriatic Sea, between the mouths of the Tagliamento and Isonzo rivers, covering an area of around 160 km^2. The lagoon is protected from the sea by a system of low-elevation sandy barrier islands and sand banks, that are constantly and rapidly evolving [58,59]. These landforms are periodically overwashed and breached by storm events, but they are also characterized by significant longshore transport and consequent rapid spit construction and progradation. The local wind climate is affected by the strong wind from the ENE (the Bora), which is predominant in frequency and strength [60,61]. The Sirocco wind is also statistically significant but subordinate in terms of strength. Tides are semi-diurnal with a mean range of 76 cm [62], and a mean spring-neap tide range of 105 and 22 cm, respectively [63]. An unusual rise in sea level may result from a confluence of spring tides, seiches, southerly winds, and low atmospheric pressure (known as "acqua alta"). Due to the Bora and the Sirocco winds, the wave regime is typically bimodal. According to data recorded at the wave buoy OGS–DWRG1 (located offshore at the coordinates 13.24° E, 45.56° N, −16 m depth), the mean significant wave height (Hs) is less than 0.5 m. Events with Hs greater than 0.5 m account for 25% of the overall record, with prevailing waves from the SE (10.7%) and ENE (10.5%). The Sirocco has the highest recorded waves, with Hs = 4.4 m [60]. The yearly wave energy flux for the northern Adriatic area is 1.95 kW/m, calculated using 11 years (1999–2006 and 2009–2013) of tri-hourly wave data from the Ancona buoy (Rete Ondametrica Nazionale, RON network). The longshore drift is directed from the Isonzo River mouth toward west.

The MGL has a great naturalistic value, both for the mosaic of habitats and for the richness of species. It is the Zone of Special Conservation and Zone of Special Protection inside the EU Natura 2000 Network, according to the European Directives 92/43/CEE and 2009/147/CE. More than 300 bird species are observed, of which 126 are nesting, probable, or confirmed. At a national level, it is one of the most relevant sites in the Adriatic for resting and wintering of water birds [64].

The barrier islands are the most important and preferred nesting site of the Little Tern (*Sternula albifrons*), whose typical habitat is the exposed sand substrate with scarce vegetation cover [65,66]. This species nests in the MGL barrier islands and, in recent years, within some fish farms in the lagoon basin, but its overall population is declining, falling from 250 pairs observed in 1984 [67] to 112–129 pairs in 2022 [68].

For our specific analysis, two cases were selected along the barrier island system of MGL, as indicated in Figure 1: a washover fan created by a storm event in 2013 on the Martignano barrier island (Box B) and a prograding spit at the western end of the Tratauri bank (Box C). To date, this is the only frequented nesting site of the Little Tern (*Sternula albifrons*) along the coastline.

3. Materials and Methods

Over a seven-year period, UAV surveys were conducted on three distinct environments (Figure 1) that reflect specific sedimentary dynamics in transgressive domains: a parabolic migrating dune in Piscinas, Sardinia; a washover fan in Martignano barrier island, MGL; and a prograding spit in Tratauri bank, MGL.

The UAV surveys in Piscinas were meant to assess the migration of the parabolic dune after the winter season and describe its current state; the surveys in Martignano and the Tratauri Bank were designed to evaluate the post-storm evolution of a washover and determine the microtopography to support nesting bird monitoring.

Despite the advancement of technology during the timeframe in question and the deployment of various aircraft models, a common protocol for all the surveys can be defined, as is detailed below. Each UAV survey was carefully planned, checking out the regulated or prohibited fly zones and calculating the best UAV flight paths. The flight lines were designed to be orthogonal to the symmetry axis of every area captured by the photos. To achieve high accuracy in the georeferenced photogrammetric model, a large number of GCPs were positioned on the ground during each survey, materialized with 50 × 50 cm plastic square targets, and printed with coded symbols to aid recognition on photographs during data processing. All the GCPs were georeferenced with centimetre-level accuracy in the specific coordinate system (WGS84 UTM 32 North or WGS84 UTM 33 North, depending on the site), using a GNSS (Global Navigation Satellite System) Stonex S9III NRTK (Network Real Time Kinematic) receiver (Manufacturer: Stonex Srl, Paderno Dugnano, Italy) connected through GSM (Global System for Mobile Communications) to the HxGN SmartNeT reference station network for real-time GNSS correction. For the conversion of ellipsoidal heights into orthometric ones, referring to the National vertical datum (IGM42 by Military Geographic Institute), the corresponding GK2 IGMI grids were used.

Following each flight, the photographs were downloaded to the ground station to be checked for quality (focusing, contrast, blurring, etc.). At the end of each survey day, a quick low-resolution photogrammetric model was created to check for photograph orientation issues and coverage gaps. This check was performed to ensure that no areas were overlooked and to determine whether the flight should be repeated. The photogrammetric models were processed using the SfM algorithm with Agisoft Metashape Professional v.1.7 software. The final products were: a point cloud (sparse cloud and dense cloud), a mesh, a textured mesh, a DSM, contours, and an orthomosaic. The characteristics of each survey, including the type of drone and sensor used, flight plans, GCPs, acquired surfaces, errors, resolution, and accuracy of the main outputs, are summarized in Table 1.

Table 1. For each study site, the table reports the year of the UAV survey with the main characteristics of the cameras and flight plan, acquisition details, and output resolution. Manufacturer information of UAVs and cameras: Dji (Manufacturer: DJI, Shenzhen, China); Neuthech (Manufacturer: Neutech, Mogliano Veneto, Italy); Sony (Manufacturer: Sony Group, Tokyo, Japan).

	Piscinas			**Martignano**		**Tratauri**
Acquisition year	**2014**	**2015**	**2016**	**2018**	**2021**	**2014**
Type of UAV	Neutech NT4-contra	Neutech NT4-contra	Neutech NT6	Dji Phantom 4	Dji Phantom 4 Pro	Neutech NT4-contra
Camera model	Sony NEX-7 (20 mm)	Sony NEX-7 (20 mm)	Sony ILCE-5000 (20 mm)	Dji FC6310 (8.8 mm)	Dji FC6310 (8.8 mm)	Sony NEX-7 (20 mm)
Average flight height from the ground (m)	95	106	160	77	27	67
Image acquisition overlap (%)	70	70	80	80	80	70
Image acquisition sidelap (%)	70	70	70	80	80	80
Useful Photographs Acquired (number)	3911	445	281	785	1497	167
Surveyed GCPs (number)	291	58	37	46	12	20
RMSE (Root Mean Square Error) XYZ on the GCPs (cm)	2.5~3.8	2 ~2.6	0.6	2.2	3.8	4.8
Surveyed area (m^2)	65×10^4	12×10^4	29×10^4	55×10^4	15.7×10^4	8×10^4
Orthophoto GSD (Ground Sampling Distance) (cm/pix)	1.5~2	1.8~2	3	2	1.5	2
DSM (Digital Surface Model) GSD (cm/pix)	3~4	3.6~4	6	4	3	4

In Piscinas, the first survey, conducted in November 2014, before the beginning of the winter season, covered the entire area of the parabolic dune, while the second, conducted in May 2015, in the middle of the spring season and theoretically after the strong winds period, focused on monitoring the migrating lobes. Unfortunately, during the survey days, strong Mistral winds blew, and only some lobes were acquired. The photogrammetric models were loaded and analysed in ESRI ArcGIS v.10.8. DSMsoD (Digital Surface Models of Difference) were created utilizing the DSMs of the two surveys to assess the erosional and depositional effects of the aeolian transport. To estimate sand displacements, 10 profiles were extracted from the DSMs of the three compared lobes.

Three UAV surveys were conducted on the Martignano barrier island between 2016 and 2021 (Table 1) to determine the evolution of a washover. The surveys were compared to other available orthophotos from 2010 (courtesy of the Friuli Venezia Giulia Civil Protection Dept.) and 2014 (courtesy of the Friuli Venezia Giulia Region, AGEA flight) to provide a complete evolutionary picture of the area, which allowed us to quickly map the structure of the washover after its creation. After being processed with SfM algorithms, each spatial dataset was loaded into ESRI ArcGIS for spatial analysis and sedimentary volume estimates. Because the resulting 2021 DSM is influenced by dense and abundant vegetation and a lower number of GCPs, it was not used to calculate the sedimentary budget and DSMoD for the entire washover system. Instead, two cross-sections were extracted from all three years DSMs in the central and less vegetated sectors, one nearly parallel to the main axis of the washover and the other parallel to the shoreline, to better emphasize the topographic evolution of the area and to make volumetric estimates of the collected sediments. However, the cross-section parallel to the axis of the washover was manually corrected by filtering the vegetation signal to prevent volumetric computation errors almost exclusively in the 2021 DSM.

About 8×10^4 m^2 of the westernmost prograding spit on the Tratauri bank has been surveyed using UAV to provide supporting data for the monitoring of the most important waterbird breeding populations of conservation concern in the MGL. The bird monitoring was carried out by the Department of Mathematics and Geosciences at the University of Trieste in collaboration with the Biodiversity Service of Friuli Venezia Giulia Region in accordance with Habitat Directive 92/43/CEE and Birds Directive 2009/147/CE. Five bird censuses were conducted between May and July 2014 to monitor the Little Tern nesting colony: on 15 May, 21 May, 3 June, 24 June, and 9 July. A NRTK GNSS receiver was used to determine the position and elevation above m.s.l. (National datum IGM 42) of the nesting site. In order to also know the morphological evolution of the site, the previous shoreline position was digitized on the available aerial orthophotos taken in 2012 (courtesy of the Friuli Venezia Giulia Civil Protection Dept.), 2011, and 2014 (courtesy of the Friuli Venezia Giulia Region, AGEA flights), and the morphology and distribution of plant cover were observed. The UAV-obtained DSM was compared to the maximum tide levels recorded by the Grado tide gauge (courtesy of the Istituto Superiore per la Protezione e la Ricerca Ambientale) during each time interval between two consecutive nesting censuses. The DSM was classified according to altitude ranges, and the position of the nests compared to different elevation areas, for assessing their vulnerability to inundation.

4. Results

4.1. Piscinas

Orthophotos and DSM from the 2014 survey were used to describe the morphological characteristics of the main parabolic dune. The dune was aligned with the prevailing direction of the Mistral wind and extended in an elongated shape for about 2 km inland from the shore. In addition, the landform varied largely in elevation, starting from approximately 1.5 m above m.s.l. near the shore to a maximum height of almost 113 m near the southernmost portion of the dune. It includes five large sandy accumulations shaped like depositional lobes, which are typical of parabolic dunes (Figure 2). This information allowed us to classify the Piscinas dune as a multilobed parabolic dune. Each lobe had an upwind surface with an average slope of 5° to 8°, often ending in a small flat stretch (the crest) and terminating with a short, steeply inclined surface (from 15° for the first lobe to over 30° for the last lobe) that constitutes the precipitation ridge (slipface).

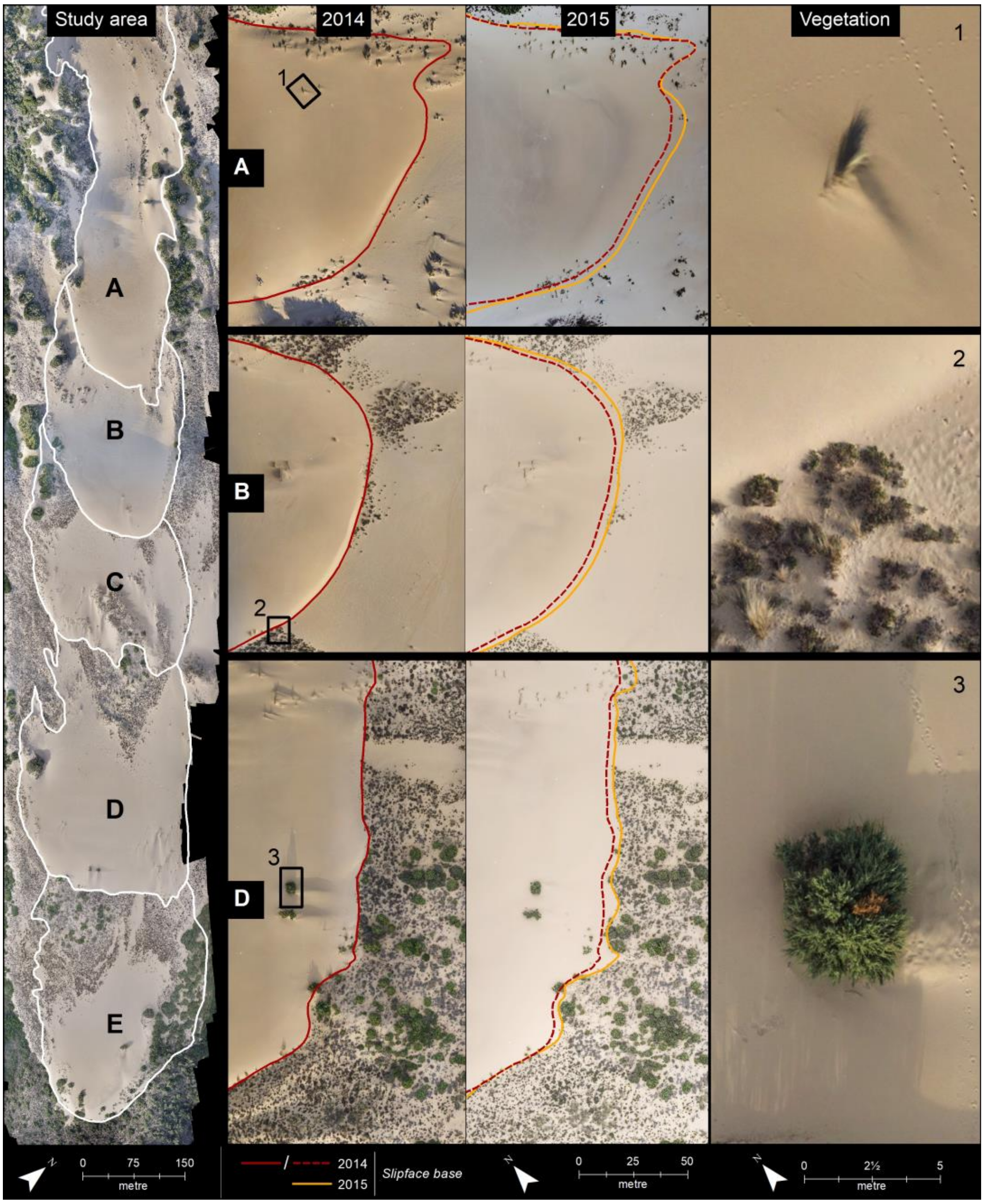

Figure 2. The main parabolic dune of Piscinas. On the left is the UAV orthophoto of 2014, with the representation of the five lobes ((**A**–**E**), white lines). In the middle, a comparison of the three monitored lobes (surveys of 2014 and 2015) with the representation of the migration that occurred after 6 months. Zoom boxes on the right allow to appreciate the different types of vegetation identified (box 1: Marram grass; box 2: bushes; box 3: arboreal shrubs). See the text for major details.

Each aeolian sub-environment was recognized using either the accurate topographic data or the various types of vegetation, easily identified thanks to the remarkable resolution (right side of Figure 2): (1) the Marram grass characteristic of active areas with continuous aeolian deposition, which was frequently detectable in the lateral margins of the lobes or near the crest (i.e., lobe A in Figure 2); (2) the bushes of the downwind area, typical of the areas with low wind energy (i.e., lobe B in Figure 2); and (3) the stabilizing arboreal shrubs, which were typical of the inactive trailing ridge and the current cover surrounding the dune (i.e., lobe D in Figure 2).

Since each lobe was completely unvegetated, they have been recognised as active fronts of the parabolic dune's migration. Table 2 provides a summary of some data about the length and elevations of lobes.

Table 2. Topographic and migration lobe parameters. The length of the lobes is the distance between the end of the precipitation ridge of the previous lobe and the end of the precipitation ridge of the current lobe. The length of the first lobe is measured from the backshore to the end of the precipitation ridge of the same lobe.

Lobe	Max Length (m)	Elevation (m above m.s.l.)	Cross-Section	Mean Dune Displacement in 6 Months (m)	Mean Lobe Displacement in 6 Months (m)
A	790	From 4.5 to 56.5	1 2 3	3 4 6	4.3
B	220	From 38 to 71	4 5 6	2.5 3 2	2.5
C	195	From 53.5 to 83	-	-	-
D	340	From 69 to 104	7 8 9 10	1 6 3 3.5	3.4
E	330	From 65 to 108	-	-	-

The second UAV survey permitted the acquisition of data for assessing the morphological changes of three of the five lobes after six winter months of aeolian activity (Figure 3). Figure 3 reports three examples of the 10 cross-sections extracted from the DSMs to analyse the topographic variations of the three lobes. The accuracy of the surveys can be observed in these profiles, where spikes indicating the vegetation are identical in both years. As expected, the wind deflation affected the stoss side of the lobes, especially along the profile of Lobe B, whereas deposition of the eroded sand occurred on the lee side, from the crest to the whole downwind side. The process induced a dune migration, quantified for each lobe as an average rate (Table 2) obtained by the sections presented in Figure 3: rates are higher in the central profiles, indicating a tendency of the lobes to migrate in a parabolic shape. The migration rate was not uniform across the whole dune: Lobe A migrates 4 m in 6 months, Lobe B migrates 2.5 m in 6 months, and Lobe D migrates 3.4 m in 6 months. The amounts of sand involved in the migration was calculated from the DMSoD (Figure 3) and was likewise substantial: 2145 m^3 for Lobe A, 1801 m^3 for Lobe B, and 3781 m^3 for Lobe D.

4.2. Martignano Barrier Island (Marano and Grado Lagoon)

By comparing the collected orthophotos (Figure 4), it is possible to reconstruct the main morphological changes of the Martignano barrier island between 2010 and 2021, focusing on the shoreline position, emerging areas with stable vegetation or with bare sand (with significant and recent sand deposition), intertidal salt marshes, pioneer beach vegetation, and foredune vegetation.

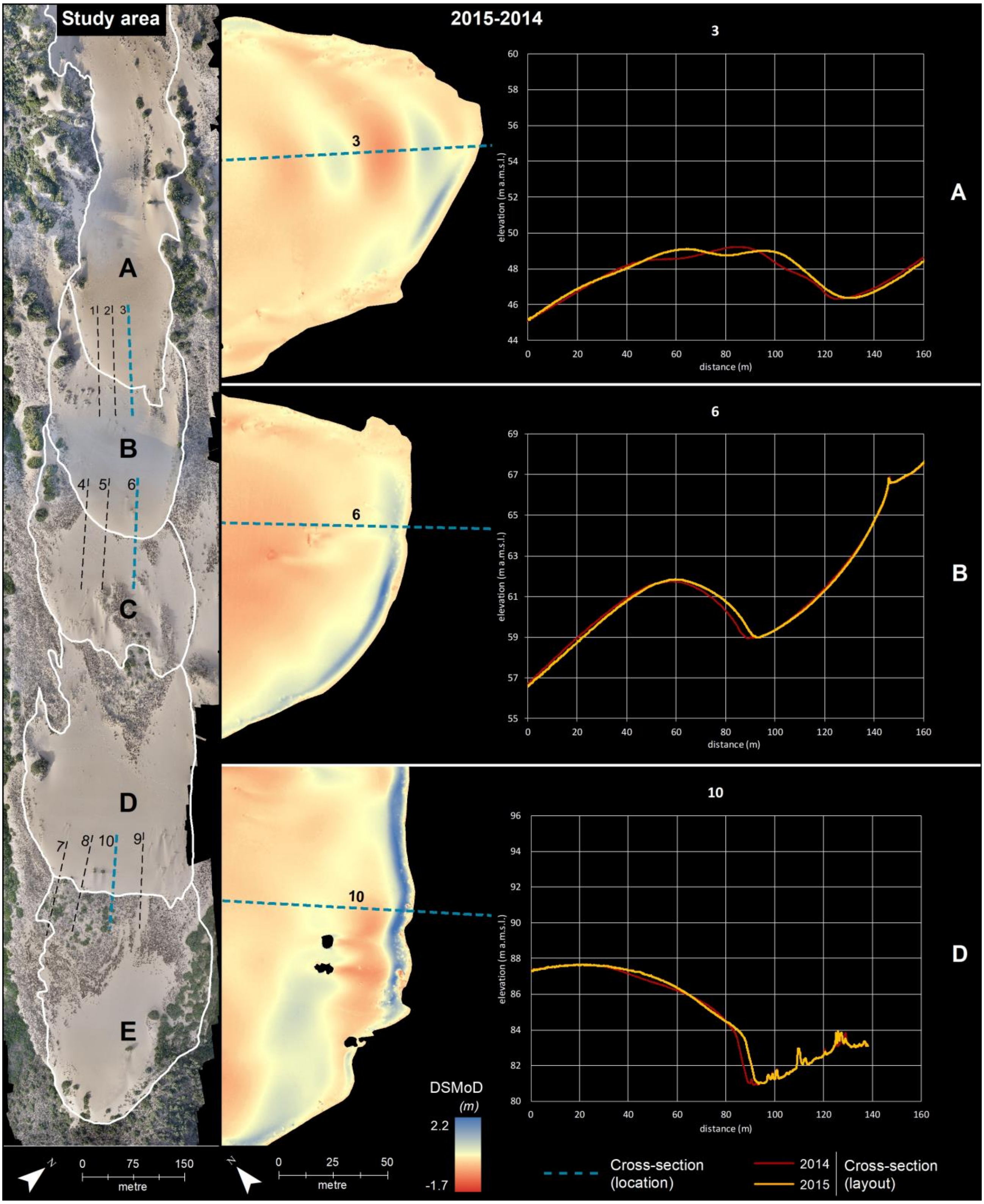

Figure 3. The morphological changes observed in the main parabolic dune of Piscinas after the six months of monitoring. On the left, the representation of the five lobes and the position of the extracted cross-sections; the blue ones were selected for comparison. In the middle, DSMoD of the three monitored lobes (A, B and D) with the selected cross-section. On the right, the extracted cross-sections representing the morphological variation of the monitored lobes between the two surveys.

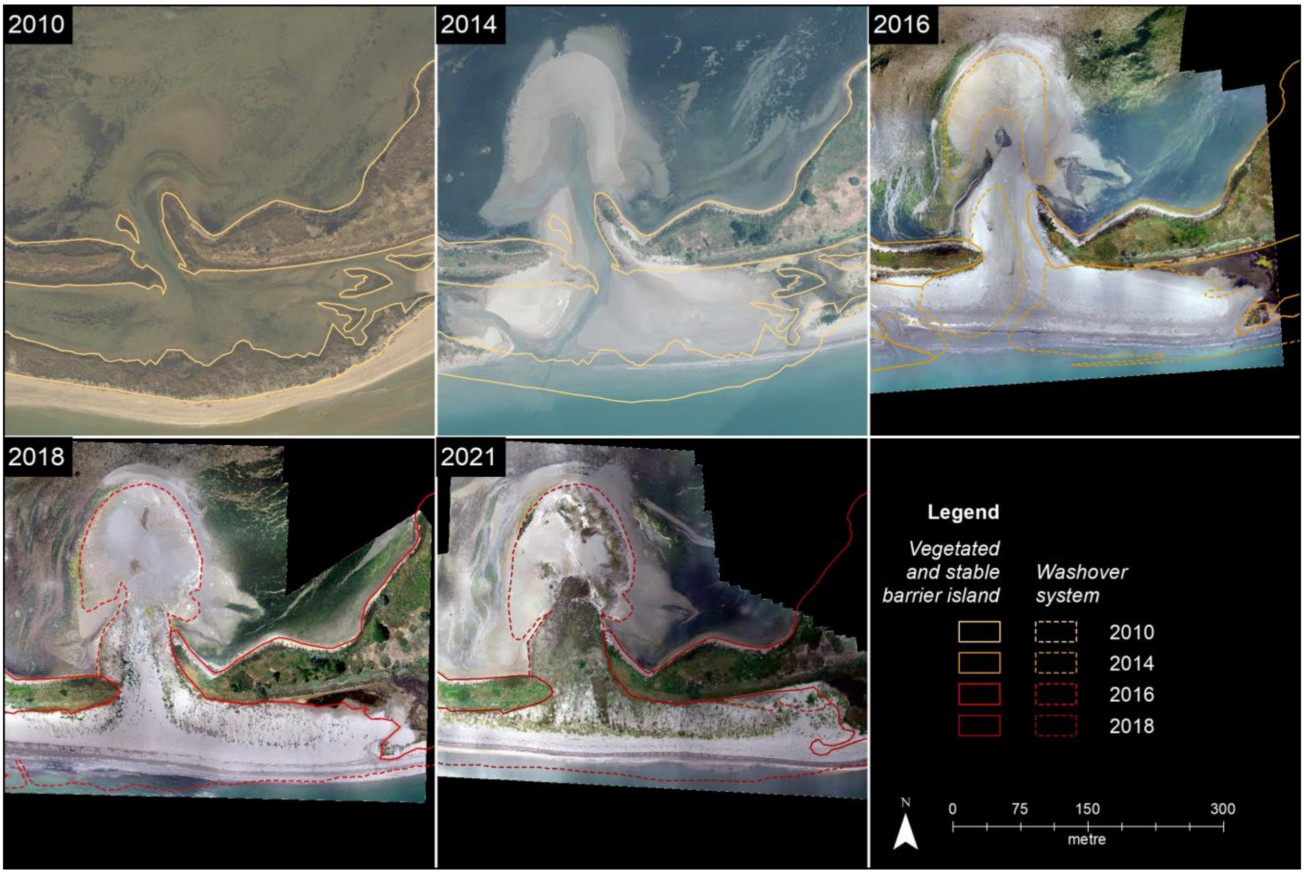

Figure 4. Evolution of the Martignano washover between 2010 and 2021. In each orthophoto, the edges of vegetated and stable barrier island, as well as the washover system, has been mapped for the current year, and overlapped with the previous one.

In 2010, a composite system with two barrier islands, one more active seaward and one stabilized landward, was observed. The latter exhibited relict landforms: a breach and a poorly evident older washover fan. The 2014 orthophoto reveals that a significant breach has occurred, resulting in the formation of a washover structure involving both the barrier island and consisting of a washover mouth (approximately 350 m wide), a sedimentary overflow, a washover channel, and a washover fan approximately in the same position as the relict one. According to the orientation of the washover system and wave data analysis [69], the breach was most likely caused by the impact of two severe storms: the first on 31 October 2012, with Hs = 4.10 m from the SE, and the second on 11 February 2013, with Hs = 3.77 m from the SE. The entire washover system extended approximately 340 m inland from the shoreline, which has receded approximately 80 m since 2010. The 2016 drone orthophoto shows the washover mouth and channel partially filled with sediment but still connected to the fan. Only a small part of the ancient barrier facing the sea has survived to the east, while the rest has been entirely eroded. The shoreline has been rectified and has retreated a maximum of 30 m since 2014. In 2018, the vegetation started to develop at the mouth and backshore. The washover channel, which was filled with sand but not jet vegetated, is still recognizable. In 2021, the vegetation totally stabilized the areas previously occupied by the mouth and the washover, while the washover fan preserved the whole configuration with rare pioneer plants that have begun to colonise the peripheral intertidal sectors. The photo also depicts the formation of vegetation typical of the foredunes on the backshore. Since 2010, the shoreline has moved more than 100 m landward.

The DSM created thanks to the UAV 2016 and 2018 surveys, as well as the DSMoD between these two years, permits the quantifying of the progressive rapid filling of the area of the washover mouth and the suture of the beach system (Figure 5). Positive values to the south (in green), in the zone corresponding to the previous washover mouth, indicate sedimentation up to 0.80 m thick, whereas the fan sector can be considered stable. Comparing the topographic profiles obtained from the surveys' DSM (2016, 2018, and 2021) confirms these findings (Figure 5). The DSM profile A-A' reveals that in 2016, there were two steps flanked by a channel in the fan area (between 0 m and 110 m distance), which were most likely caused by the two different storm events that resulted in the superimposition of the washover fan. While the inner portion of the washover fan has stayed unchanged over the years, the channel has progressively filled (e.g., at the progressive 100 m, there is a vertical increment of 0.13 m between 2016 and 2018, as well as between 2018 and 2021). The majority of the deposition happened along the beach between 2016 and 2018, regenerating the foredune, with an estimated volume of 78.1 m^3/m of sand, corresponding to a sedimentation rate of 13.3 cm/y. The isolated spikes depicted in the 2018 profile represent the plant grown on the washover system. The peak pattern of the 2021 profile makes this trend much clearer, confirming the resuture of the washover mouth, the spread of vegetation, and the system's current stability. Compared from 2016–2018, sedimentation rates from 2018–2021 have decreased to 2.7 cm/year with the highest rate on the lee side of the foredune. The B-B′ profile is consistent with the A-A′ profile, showing the total closing of the washover mouth in 2018 as well as the formation of extensive vegetation cover that consolidated the landform in the same year.

4.3. Tratauri Sand Bank (Marano and Grado Lagoon)

In 2014, a colony of Little Tern (*Sternula albifrons*) established itself and nested on the western 450-m-long end of the Tratauri bank, together with two nests of Eurasian Oystercatcher (*Haematopus ostralegus*) and one nest of Kentish Plover (*Charadrius alexandrinus*) [70]. According to field surveys and comparisons of drone orthophotos and traditional aerial photos, the nesting site is the terminal part of a newly formed spit that grew to the northwest 350 m from 2011 to 2014 at a rate of 116 m/y (Figure 6A). At the time of the monitoring, the spit still had poor maturity characteristics for at least a kilometre: mostly bare sand, a flat shape, and a maximum elevation of just over a metre above m.s.l. (Figure 6B).

Seaward, the beach exhibits the typical wave-dominated features, such as the beach face and the berm. Landward, a small step connects the bank to vast intertidal sandy or muddy flats leading to the lagoon. The scarce and discontinuous vegetation has a low degree of complexity, being of the pioneer type; only the association of *Cakiletea maritimae* is prevalent.

The five censuses conducted on the site allowed for the observation of several nesting phases: the first on 14 May and the last on 9 July 2014. The number and spatial distribution of nests have changed over time. The number of nests reached a maximum on June 3 with 55 nests and then decayed rapidly. Spatially, the colony was mainly located on the landward side of the spit, ultimately being moved eastward (Figure 7). Despite the fact that the temporal evolution of the nests' number could be considered natural (with an increase, a maximum, and a decrease phase), a very low reproductive success has been observed during the census. Analysing the microtopography on the 0.10-m-classified DSM, we can put the position of the nests in relation to the micro-relief. The choice of the nest sites appears not to be completely influenced by the elevation above m.s.l. (Figure 7). Most of the nests are located on elevations that are not directly affected by high water levels during the time considered; many nests are found on the landward side of the bank, which appears to be the lowest and thus most vulnerable to high tides but is better protected from waves. By classifying the nests according to the different tidal maximum levels for each time interval between one avifauna census and the next, we can finally assess which positions may have been at risk of flooding (see the histogram in Figure 7).

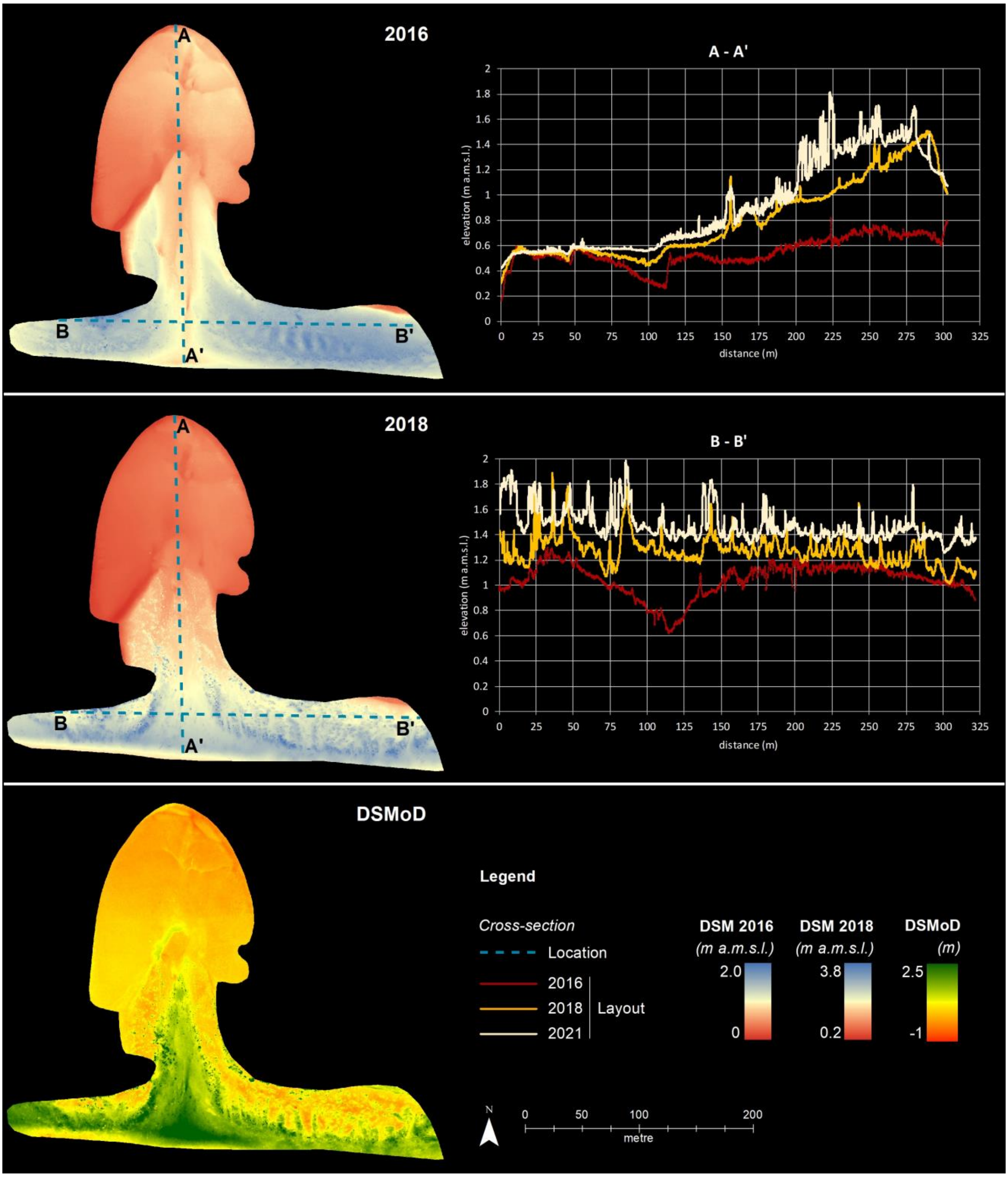

Figure 5. Topographical changes of the Martignano washover. On the left column, the DSM of 2016 and 2018, and the DSMoD relative to the comparison between the two years. On the right column, the cross-extracted sections A-A′ and B-B′, reporting the changing elevation of the complete dataset, including the 2021 survey.

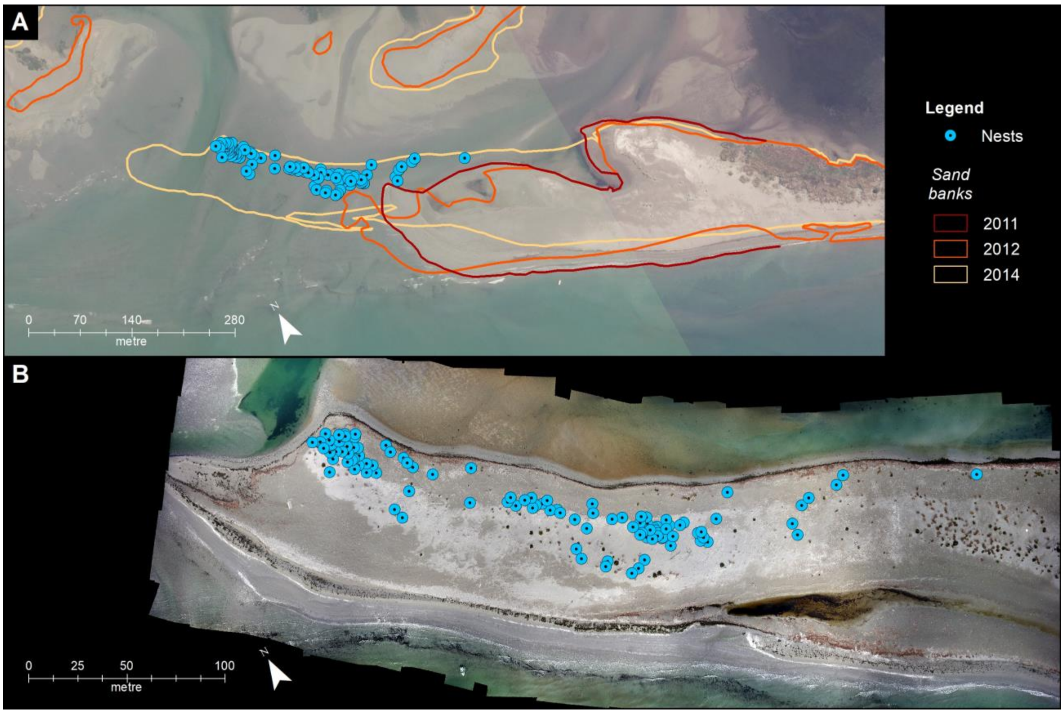

Figure 6. (**A**) Morphological evolution and spit migration of the Tratauri bank from 2011–2014 (basemap = 2011 orthophoto); (**B**) Orthophoto derived from drone survey carried out in 2014 along the western tip of the bank occupied by the nests of Little Terns (*Sternula albifrons*).

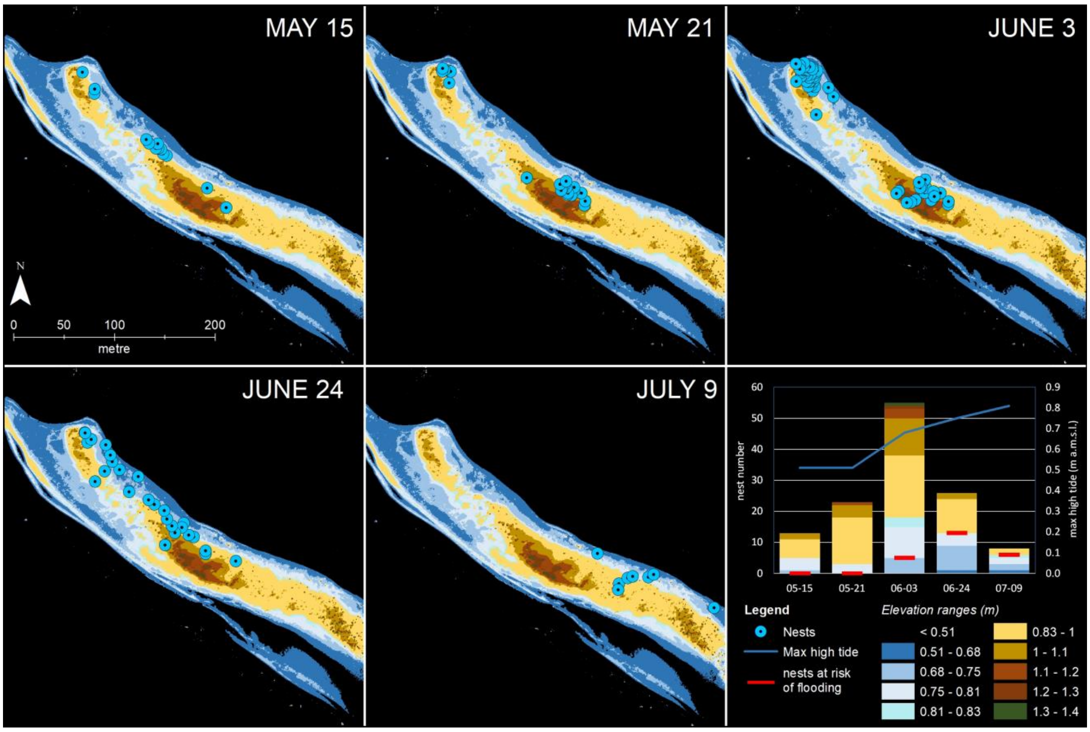

Figure 7. Distribution of the nests of the Little Tern on the Tratauri bank at the different census surveys in 2014. The histogram represents the evolution of the nests' number over time. For each census date, nests are classified according to elevation classes using the same colour in the maps and histogram; the red line on the histogram represents the division between nests at high risk of flooding (below the line) and "safe" nests (above the line).

5. Discussion

5.1. The Transgressive Dune Anatomy and Migration

The findings of the UAV surveys allow us to classify the Piscinas dune as a parabolic multilobate aeolian dune with five distinct depositional lobes. Our work concentrates on some of the active lobes, identifying source zones and deposition zones along a typical source-to-sink pathway. Currently, over each observed lobe, the onshore Mistral winds that affect the area are topographically accelerated along the stoss slope, thus eroding the surface and transporting the sand through the crest into the precipitation ridge and beyond it. This mechanism of deflation and deposition by wind, here precisely detected by UAV monitoring, is extensively reported in the literature (e.g., [71–73]), and it results in the landward migration of the lobes. The origin of the available sediment could be explained by the cannibalization of the Quaternary aeolianites that constitute the oldest transgressive dunes [35]. In fact, generally, cannibalization of old dunes is prevalent, especially when newer dunes migrate across relict dunes [30]. Thanks to the UAV surveys, we registered a migration rate between 2.5 and 4.3 m per six months of monitoring. These values are higher than the 1.6 m per year reported by [35] as the result of monitoring the final lobe only (lobe E), although comparable with those reported by other authors under similar environmental conditions (e.g., [74,75]).

As demonstrated in this case study, UAV surveys permit the acquisition of information on dune migration and pathways. As a consequence, it is possible to make assessments on potential sand drift hazards. This assessment furnishes, in a unique case at the national level, an evaluation of the potential risk due to the presence of the natural elements of the SIC area and, particularly, the touristic resort about 300 m beyond the terminal lobe. Indeed, considering (i) an average migration rate of 3.4 m per six months; (ii) this rate can be approximated to an annual rate because of the monitoring period (during the winter and spring seasons the winds are the strongest); and (iii) the distance of the resort, the touristic site can be reached by the terminal lobe at least in 88 years. Monitoring dune migration is essential to prevent sand invasion. Due to the fact that only six months of monitoring were done, our approach produced a first estimation. In similar circumstances, longer-term monitoring would be more effective over the course of a few years or more in order to assess the seasonality of the wind climate, as well as the variability in sand drift potential at the yearly scale.

In general, where settlements, tourism facilities, or natural protected areas are adjacent to transgressive dunefields, knowledge of dune morphodynamics and potential risk due to sand drift is necessary. The magnitude of the migration rate and the volume of sediment involved aid in determining appropriate specific mitigation actions or adaptation policies in order to prevent habitat loss and disruptions to human assets.

5.2. The Washover Formation and Recovery

The case of Martignano Island represents an example of monitoring storm effects and subsequent natural recovery processes. Given the capacity to generate both DSMs and orthophotos, the series of UAV surveys over time supported by previous data enables not only the qualitative and quantitative detection and evaluation of morphological and ecological changes but also the computation of sedimentary budgets.

Because we began monitoring this site well after the storm that caused the washover, we have only been able to quantify the first stages of evolution in terms of evolutionary mapping rather than sedimentary volumes. A shorter interval monitoring frequency, on the other hand, would not have resulted in more information about the evolution of washover in its complexity. We also noticed that the lower number of GCPs in the 2021 survey compared to previous ones, as well as their concentration in the central part of the study area, caused elevation error propagation at the DSM's edges. As a result, the comparison area is limited to the error-free central sector, confirming the importance of maintaining a consistent pattern of GCP positioning during monitoring to produce reliable results.

Despite these limitations, this work allows us to interpret important aspects of the dynamics of the Martignano barrier island, which can be used to assess its resilience to storms and the transgressive process associated with global sea level rise. We were able to deduce that the island breach occurred between 2012 and 2013, at the same location as a previous breach, indicating the presence of an erosive hot spot, thanks to the availability of wave recordings and aerial photos. The absence of human physical constraints in this small section of the barrier island allowed for the rapid formation of a new sand body landward (the washover fan). The shallow depth of the backbarrier wetlands, which provides a small accommodation space for the sedimentary supply from the beach, aided this. As several authors [38,45,76] have pointed out, these sandy deposits can represent a remarkably important part of the barrier island in terms of sedimentary budget and extent, allowing the barrier to be preserved during transgressive trends. The sandy structure of the washover fan currently exists as a relict landform in the backbarrier area; this condition has allowed the generation of a new habitat suitable as foraging sites for populations of the Greater Flamingo (*Phoenicopterus roseus*), as discovered by [57], demonstrating the importance of episodic events, such as storm surges, in generating new landforms and habitats that can support biodiversity in lagoon ecosystems.

Furthermore, the sediment budget of 101.4 m^3/m, which correspond to a sedimentation rate of 6.9 cm/year for the entire surveyed time span on the A-A′ cross-section (Figure 5), along with the full morphological recovery of the washover channel in 8 years before being vegetated in 2021, leads to the conclusion that the area is affected by a significant sedimentary supply. The existence of a consistent longshore sediment transport is confirmed if we take into account that the barrier island did not fragment after the event and that the beach and foredunes have recovered. This supports a previous study of the nearby Sant'Andrea tidal inlet [77] and shows that there is an ongoing process of sediment bypass from the Sant'Andrea ebb-tidal delta.

5.3. The Spit Evolution and Inundation Risk for Avifauna

This case study emphasizes the importance of combining wildlife data with geomorphological observations, especially in highly dynamic coastal environments where UAV surveys are currently the best option for mapping small areas with high resolution and accuracy. Thanks to the rapid natural formation of new emerging sandy bodies (prograding spits), the Tratauri bank (barrier islands of the MGL) provides a resource for the Little Tern as an alternative nesting site to the adjacent beaches, which are fully exploited for beach tourism. Indeed, the search for new habitats has become an essential but highly uncertain issue [78] at the worldwide level because of the increasing anthropization of the beaches [79] in the 19th and 20th centuries, which caused the distribution and abundance of these birds to decrease significantly. Theoretically, the relative remoteness of the location and the existence of protection regulations are variables that support the reproductive success of the Tratauri Bank; other factors, most notably predation, work against it. Our findings demonstrate that the nesting colonies have selected a location whose genesis is very recent (within the last two years), located a few centimetres above the high tide level, and highly floodable during severe tides, storms, or high water. Due to the rising spring tides in the study year, the risk of nest flooding rose during the nesting and breeding seasons.

The accuracy and resolution of the UAV survey appear to be acceptable in light of the slight differences in elevation detected in the nesting region, although accuracy is still contingent on the setup of enough ground control points and the precise nest's location. The need for such high resolution, high elevation accuracy, and a specific time for surveying excludes the possibility of using other remote sensing techniques such as satellites or LIDAR (Laser Imaging Detection and Ranging) surveys at the regional level. Another factor that influences the choice of the most pertinent mode of survey is the colony disturbance brought on by direct ground observations and/or by the UAV, which varies for each bird species and depends on many factors related to the aircraft model and overflight modes [80]. In any case, the rapidity of the survey, both via direct ground and by UAV, represents a condition that can restrict the disturbance. In terms of timing, a survey at the start of the breeding season in the areas considered most suitable for nesting allows for the optimization of two aspects: the need to check the morphological changes brought on by the wave's action during the winter and the avoidance of colony overflight during the reproductive phase.

The availability of such a micro-topographic model can be a valid tool to be used for conservation and management purposes: to know the precise characteristics of the areas chosen by the bird species, to assess the flooding risks, and eventually to take protection measurements.

6. Conclusions

This work presents three case studies in which coastal dynamics play an important role, with implications for the environment and human issues. UAV monitoring with high resolution and accuracy allows for the detection of quantitative geomorphological effects of varying origin (wind, storms, waves) in areas where regular institutional monitoring surveys (aerial or LIDAR) or satellite data are not available or have insufficient resolution. Ad hoc UAV surveys allow us to capture high-quality images that are relatively simple to elaborate in order to obtain quantitative data on various aspects: a digital terrain model and terrain description to generate geomorphological maps; an assessment of plant cover as an indicator of sediment movement or stability; a quantification of morphological changes; and sediment budget in the short or medium term to identify and analyse processes in place.

The assessment of sand drift in an aeolian transgressive dunefield is the most important result in the first analysed case (Piscinas). The Piscinas dune was identified as a parabolic multilobate aeolian dune with five distinct depositional lobes distinguished by source and deposition zones along a typical source-to-sink pathway. The dune is moving landward, and a risk assessment of sand drift into the Natura2000 protected area and tourism resort was completed. Integration with climate models as a basis for future appropriate, specific mitigation actions, or adaptation policies could be the next step.

The main result of the second case (Martignano Island) was the assessment of the barrier island's resilience capacity to transgressive phenomena. The entity of washover deposit as a result of storm impacts, as well as the progressive post-storm beach recovery and suture of the barrier island, were detected and quantified. The data indicate that the beach–dune system with vegetation recovered completely in eight years, with a mean accumulation of 101.4 m^3/m of sediments along the breaching axis.

The third case (Tratauri barrier island) demonstrates how the UAV-acquired micro-topography could represent a low-impact approach for developing a risk assessment for the flooding of bird nests in newly formed coastal sectors.

The naturally high dynamics of the examined coastal environments can be a risk factor and a point of contention between human use and nature preservation. This work lays the groundwork for the development of a protocol that allows for the understanding and acceptance of the results obtained from these technologies in order to provide useful information to decision-makers for future coastal management. This is made possible by aerial drone acquisitions and the characterization of ongoing physical processes.

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