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RESEARCH PAPERS

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DISCUSSION & REPLY

DEPARTMENTS

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Geomorphological Features of Coastal Dunes along the Central Adriatic Coast (Abruzzo, Italy)

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ABSTRACT

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The main geomorphological features of dunes/beaches were investigated along the central Adriatic coast of Italy (Abruzzo). Nine foredune areas typified by established dunes and incipient dunes were investigated through detailed geomorphological surveying and an analysis of historical maps and photographs (aerial and land). The dunes are located along both low and high coasts. The morphology is typical of foredunes, with elongated fields parallel to the coastline. The total linear extension is ~15,500 m; established dunes are more extended than incipient ones and occupy the greatest portion of the total surface area (~1,500,000 m^2). Analyses of historical maps and photographs (aerial and land) led to the reconstruction of coastal dune morphology from the beginning of the 1800s to the turn of the 20th century, showing a surface reduction >80%. Accelerator mass spectrometry ^{14}C dating, carried out on samples of *Helix* sp., outlines the minimum age of Abruzzo dune systems at about 730 ± 40 years before present. The overall study enabled the reconstruction of different geomorphological arrangements of the dune areas, allowing us to define the dunes of the Abruzzo coast as seminatural foredunes, with mainly direct and locally indirect management control. The reconstruction of dune evolution identifies Abruzzo's oldest recognizable period of aeolian deposition in the late Middle Ages; aeolian deposition was widely active until the early 1900s and dunes were a significant morphological component of the Italian coastal landscape. The first significant human-induced processes began in the 1900s; over the last 50 years human activity has played an important role in the coastal morphogenesis, with direct and indirect effects on coastal dune reduction and removal heavily affecting the whole coastal system.

ADDITIONAL INDEX WORDS: *Coastal dunes, geomorphological survey, historical maps, historical aerial and land photos, historical dune variations, AMS datings, geomorphological setting.*

INTRODUCTION

Coastal geomorphological features are the result of a close combination of lithostructural arrangement, continental morphogenetic erosive/depositional processes and late-Quaternary marine processes, and, particularly in recent times, intense anthropogenic development (Finkl, 2004; Masselink and Hughes, 2003). A wide range of literature is available relating to the morphodynamics of Italian coasts and erosive processes influencing beaches (D'Alessandro and La Monica, 1999; National Group for Coastal Environment Research, 2006 and references therein) and an important contribution on beach dynamics is given by a national research project that recognised the presence of coastal foredunes all along the Italian coast, including the Abruzzo region (Fierro, 2002). However, concerning the Abruzzo coast, little information is available about the geomorphological setting of coastal dune areas and the relationships between historical geomorphological evolution and human activities well known in other parts of Italy and on a world scale (Masselink and Hughes, 2003; Nordstrom, 2000; Simeoni and Bondesan, 1997).

The aim of this paper is to provide a historical reconstruction of coastal dunes in the central Adriatic coast of Italy within the Abruzzo region during the last few centuries. The geomorphological data analysis defines the present morphological features and the geomorphological setting in the different physiographic coastal sectors of low coast—coastal plains bounded by variably wide beaches—and high coast—cliffs or paleocliffs with discontinuous beaches at the base. Combining geomorphological surveys with data coming from historical maps and photos and radiometric dating, it was possible to define their historical changes due to natural processes and human activities (Arens and Wiersma, 1994; Hesp, 2002; Klijn, 1990; Masselink and Hughes, 2003). In conclusion, this study allowed for a reconstruction of the last phases of the Abruzzo coast shaping and gives indications of the main natural morphogenetic processes and human-induced factors that have brought about the current morphology of the main coastal dunes in the central Adriatic area.

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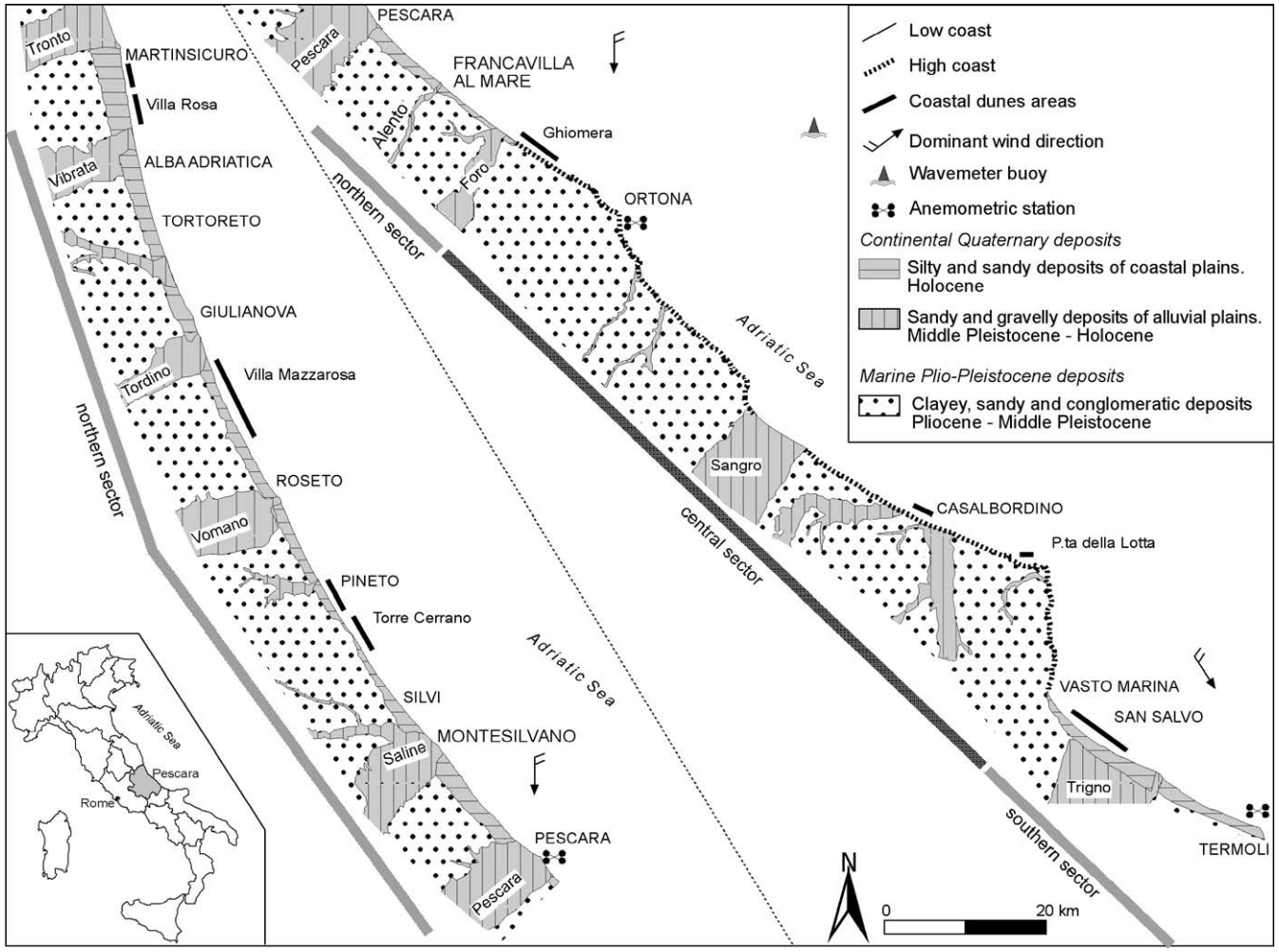

Figure 1. Geolithological diagram and physiographic elements of the piedmont and coastal areas; locations of the nine areas of coastal dunes.

STUDY AREA

The Abruzzo coast, located on the western side of the mid-Adriatic area, stretches along a total length of 125 km from the mouth of the River Tronto to that of the River Trigno (Figure 1; D'Alessandro *et al.*, 2003a). The general physiographical features distinguish a northern 90-km-long sector of low coast (from the River Tronto to the River Foro) with five dune areas (Martinsicuro, Villa Rosa, Villa Mazzarosa, Pineto, Torre Cerrano, Figure 1), a central 26-km-long sector of high coast (from River Foro to Vasto Marina) with three dune areas (Ghiomera, Casalbordino, Punta della Lotta, Figure 1), and a southern 9-km-long tract of low coast (from Vasto Marina to River Trigno) with one dune area (Vasto–San Salvo, Figure 1). The up-county hill areas are made up of mesa and plateau reliefs (with elevations up to 60–150 m in the central and southern areas and up to >250 m in the northern area) on clay–sand–conglomerate lithotypes referable to the uplifted Plio-Pleistocene marine regressive succession (D'Alessandro, Miccadei, and Piacentini, 2003b; SGI, 2010a, 2010b, 2010c).

The main rivers (Tronto, Tordino, Vomano, Pescara, Sangro, Trigno) flowing from SW or WSW intersect the coast mainly perpendicularly, with flood alluvial plains up to several kilometres in width, generally made up of a thin layer of Quaternary alluvial deposits (D'Alessandro, Miccadei, and Piacentini, 2008; Della Seta *et al.*, 2008). Short steep streams flow on the sea-facing slopes of the high coast or mesa relief, draining directly into the sea or the coastal plain.

General meteomarine conditions are those typical of the central Adriatic Sea, although influenced by local relief (D'Alessandro, Genevois, and Marino, 2001; Medatlas Group, 2004; Regione Abruzzo, 2000). Anemometric data for the area are supplied by the stations of Pescara and Termoli (Figure 1; managed by the Italian Company for Air Navigation Services) and Ortona (Figure 1; National Mareograph Network, ISPRA). In the northern sector (Pescara station) among offshore winds, between the NW and SE quadrant, the prevailing wind is the Levanter (east wind) and the dominant wind is the Tramontane (north wind). In the southern sector (Termoli station) the Mistral (northwest) and the Tramontane (north) are both

Table 1. *Sets of topographic maps, aerial photos, and orthoimages used for historical analysis.*

Type	Year	Name	Source	Scale
Topographic maps	1811–1820	Topographic map of Castellamare Adriatico and Pescara	State Archives, Pescara	1:20,000
Topographic maps	1908	Topographic map of Italy	IGMI	1:50,000
Aerial photos	1954	Volo base	IGMI	1:33,000
Aerial photos	1987	Volo regione Abruzzo	Regione Abruzzo	1:33,000
Orthoimages	1999	Volo Italia 2000	Regione Abruzzo	1:10,000

IGMI = Istituto Geografico Militare Italiano.

dominant and prevailing (D'Alessandro, Genevois, and Marino, 2001). Among land winds, the Libeccio (southwest) often blows very strongly, although for limited periods of time. Studies on the basis of recent wavemeter recordings, supplied by the wavemeter buoy of Ortona (Figure 1; National Wavemeter Network, ISPRA), indicate that the most frequent sea states, characterised by higher wave height, are northerly, between NW and NE. Among the significant sea states, characterised by wave height >0.5 m, the most frequent has a height >2 m; the greatest wave heights are *ca.* 6 m, and have a <1% frequency of occurrence (Regione Abruzzo, 2000).

The northern and southern coastal sectors (Figure 1) are characterised by a low coast with coastal plains up to 1200 m wide, made of Holocene continental, transitional, and marine deposits (Parlagreco *et al.*, 2011; SGI, 2010a, 2010b, 2010c, and references therein). The plains are connected with the hills by straight or moderately undulating slopes with colluvial cover and slope deposits, overlying the Plio-Pleistocene bedrock. The main landforms are dunes and beaches on the seaside of the coastal plain, whereas shallow and deep landslides involve the inland slopes.

The central sector is typified by a high coast without a coastal plain. The main landforms are active and inactive cliffs and paleocliffs made of clay–sand–conglomerate lithotypes referable to the Plio-Pleistocene marine succession. They define the eastern seaward termination of the mesa reliefs, with summit elevations between 25 and 120 m above sea level (asl) (D'Alessandro *et al.*, 2003a). Within some bays there are mainly gravel beaches directly fed by cliff erosion; sand beaches with coastal dunes can be found at the foot of paleocliff landforms. Morphological dynamics are very active both on the cliffs—where erosion is caused by marine action controlled by lithological and structural features—and on coastal slopes, by means of extensive landsliding (Buccolini, Crescenti, and Sciarra, 1994; Cancelli *et al.*, 1984; D'Alessandro, Genevois, and Marino, 2001).

All along the coast, in northern, central, and southern sectors, the beaches, typically <50 m wide, are mainly sand, whereas they are gravel only close to the major river mouth. Since the 1800s they have been going through an alternating advancing and retreating. Starting in the second half of the 20th century, more than 50% of the beaches have been subject to marine erosion that, locally, has also affected the dunes and some coastal strips protected by offshore barriers. A moderately brief advancing phase occurred up to the 1970s, related to deforestation and inland extensive agricultural practices that influenced the sediment supply to the coast (D'Alessandro and La Monica, 1999; D'Alessandro *et al.*, 2003a). The widespread erosive process was mostly related to fluvial management and regulation and river channel quarrying, which progressively reduced the sediment supply for beach natural nourishment. Moreover, the intense urbanization of coastal areas produced an intense alteration of the dune areas with negative effects on the dune–beach sand flux (National Group for Coastal Environment Research, 2006).

Moreover, the beaches' morphodynamics has been deeply modified by the construction of marine facilities and infrastructures, causing an alteration of a very complex longshore drift characterised by a not-univocal direction along this coast. Morphosedimentary features resulting from erosive/depositional processes of beach near river mouths or marine works show a longshore drift toward NW (Adamoli, 1994); on the other hand, wavemeter recordings indicate prevalent northern waves, with consequent longhshore drift toward SE. The complexity of this theme is outlined by further studies suggesting local variations of longshore drift with coastal sectors characterized by opposite directions (Dal Cin, 1989).

METHODS

This study has been carried out through: (i) detailed geomorphological surveying, (ii) analysis of historical maps and photographs (aerial and land), (iii) accelerator mass spectrometry (AMS) ^{14}C dating. The geomorphological survey was carried out in two phases (in accordance with the procedure indicated by Fierro [2002]). The first survey stage included interpretation of aerial photographs and colour orthoimages (Table 1). This enabled measurement of beach width, recognition and mapping of the dune areas, measurement of dune main morphometric parameters, characterisation of their state of activity, and local coastline direction. The subsequent field geomorphological survey (2004–2006) allowed for a detailed landform analysis, measurement of direction and height of dune crests, and direction of blowouts. Field surveys on coastal plain and hill slope areas also allowed the performance of an analysis of the morpholithostratigraphical relations with the back-dune zones. Resulting data, representative of the current morphological conditions of the coastal dunes, were organised in a database and managed in geographic information system using the legend defined for the Italian coastal dunes database (Valpreda, 2006). Taking into account the evidence for rapid morphological modifications and the extensive anthropogenic pressure in these areas (urbanization, industrial areas, agricultural activities, river management), the survey was combined with historical maps

and photograph analysis to highlight the variability of the dune areas over time.

The historical analysis has been performed using maps, aerial photos, and colour orthoimages and land photos from 1811 to 1999 (Table 1). This phase of the research enabled the observation of variations that occurred over the last 2 centuries all along the Abruzzo coast, particularly within the nine dune areas, and the assessment of the relations with human development and urbanisation.

Radiometric dating with AMS ^{14}C on shells of pulmonary gastropods contributed to the general chronological characterisation of deposits (analysis done and certified by Geochron Laboratories Krueger Enterprises Inc., Cambridge, Massachusetts, USA, Lab. Code GX-31578-AMS). Shells were sampled in the inner part of dunes, consistently with the method already applied by similar studies in nearby Adriatic areas (Cacciapaglia, De Santis, and Palmentola, 2006; Dini, Mastronuzzi, and Sansò, 2000; Mastronuzzi and Sansò, 2002). The shells were cleaned thoroughly in an ultrasonic cleaner, then leached thoroughly with diluted HCl to remove additional surface material that may have been altered, ensuring that only fresh carbonate material was used. The cleaned shells were then hydrolyzed with HCl under vacuum and the carbon dioxide recovered for analysis.

Finally, the correlation of present dune morphology, related surface landforms, historical variations, and dating, allowed for the delineation of the main geomorphological processes involving the dune areas and their present setting and historical evolution.

RESULTS

Geomorphological Survey

The geomorphological survey was carried out on the nine areas with coastal foredunes, describing those in the northern, central, and southern sectors (Figure 1). All these areas are characterised by incipient dunes (D1), with sporadic grassy vegetation and located toward the beach, and established dunes (D2), stabilised by dense, mainly shrubby vegetation, in the rear (Figures 2, 3), whose morphometric parameters are summarised in Table 2.

In the low-coast northern sector, running from NNW-SSE to NW-SE, the dunes develop at the border of a coastal plain, variably in width from a few hundred metres to >1200 m (CP, Figure 2a). Coastal plain is absent in the Torre Cerrano area and dunes develop at the foot of the hill slope (S, Figure 2b), frequently affected by gravitational processes. The coastal plains are characterised by widespread human landforms, related to urban development and intense agriculture on the coastal plains (Figures 2a, 2c). Locally there are coastal pinewoods on slightly undulating topography and on mainly sand deposits (P, Figure 2d), often presenting the typical appearance of plantations due to the regular tree pattern.

The dune areas' linear continuity is interrupted at river mouths and urban areas. Within the five areas, beaches are mainly sand and range in width from about 10 m to 20 m. Behind the beach, incipient dune areas are very small (Table 2) and cover a maximum surface >140,000 m^2 (Villa Mazzarosa) with crest lines up to 2.5 m (Pineto), extending in directions varying between NNE-SSW and NW-SE (Figure 2e). Established dunes are from small to very small (Table 2) and present a maximum extension of 350,000 m^2 (Villa Mazzarosa); the crest height reaches 4 m (Pineto), with a direction from N-S to NW-SE. Incipient dunes and established dunes are broken by blowouts generally perpendicular to crest direction, initiated by human activities of pedestrian trampling, track creation, housing and resort development, and developing as a result of aeolian erosion.

The sands of the established dunes are characterised by plentiful shells and fragments of pulmonary gastropods *Helix* sp., sampled in the areas of Villa Rosa, Villa Mazzarosa, Torre Cerrano, and Casalbordino. Radiometric AMS ^{14}C dating was carried out on a sample at Torre Cerrano (sample no. GX-31578-AMS) obtained from inside an established dune at a height of about 1 m asl and about 25 m from the coastline (Figure 2f). The dating determined an uncalibrated age of 730 $\pm$ 40 years.

In the high-coast central sector, with a direction of the coastline typically between NW-SE and WNW-ESE, the dunes develop at the foot of paleocliffs, covering sandstone and conglomerate rockfall deposits (PC, Figures 3a, 3b). The linear continuity parallel to the coastline is interrupted by cultivated fields and seaside resorts at Ghiomera and Casalbordino; the dune field of Punta della Lotta is delimited by cliffs and by the Vasto harbour.

The beaches are mainly sand and have widths ranging from 25 m to 45 m. An exception is given by Casalbordino beach, which is gravel prevalent and has a width <10 m, being affected by intense erosional processes (B, Figure 3c). Incipient dunes are very small and cover a maximum surface area of <37,000 m^2 (Casalbordino). Detailed field surveys show dune crest heights up to 3 m (Punta della Lotta), oriented in a WNW-ESE and E-W direction. Established dunes extend on surface areas of maximum 68,000 m^2 (Casalbordino) with crest heights varying from about 2 m to 3.5 m, with a WNW-ESE or E-W direction (Table 2). Incipient dunes and established dunes are broken by NE-SW to N-S blowouts, generally initiated by human activities of pedestrian trampling and track creation.

In the low-coast southern sector, oriented NW-SE, dunes develop at the border of a coastal plain varying in width up to 900 m. Within the coastal plain widespread urban and industrial areas, as well as intense agricultural activities, are present (Figure 3d). Locally, there are small coastal pinewoods on predominantly sandy soils. The linear continuity parallel to the coastline of the dune field is interrupted by the urban areas of Vasto Marina and San Salvo Marina.

The beach is from *ca.* 20 m to 50 m in width and is mainly sand. Behind the beach, a small incipient dune field covers an area of >85,000 m^2. The detailed survey of the crests shows heights varying from 1 m to 3 m, and direction mostly WNW-ESE (Table 2). Established dunes have a surface area >230,000 m^2 with crests varing in height from 1.5 m to 3 m, and WNW-ESE oriented (Table 2). Both incipient and established dunes are broken by blowouts with mainly N-S orientations, generally related to human activities of pedestrian trampling and track creation (Figure 3d).

Figure 4 summarizes the main parameters of dune field on a regional scale: the total linear extension is about >15,000 m

Figure 2. Geomorphological field characteristics of the coastal dunes (incipient D1, established D2) of the northern sector of the Abruzzo coast. (a) Martinsicuro, typical view of the northern sector of low coast; dune (D) developed at the edge of the coastal plain (CP) extending up to the first hill slopes (S). (b) Torre Cerrano, hill slope (S), without a coastal plain, with dunes at the foot. (c) Martinsicuro, human modifications and management of dune area. (d) Torre Cerrano, extensive pinewood (P) behind dunes. (e) Martinsicuro, in the foreground incipient dunes with grassy vegetation, next to the beach (B); in the background dunes stabilised by denser vegetation. (f) Torre Cerrano, sampling of *Helix* sp. (detail in inset) on established dunes.

Figure 3. Geomorphological field characteristics of the coastal dunes (incipient D1, established D2) in the central and southern sector. (a) Ghiomera, typical view of the sector of high coast, showing dunes developed at the foot of a paleocliff (PC). (b) Punta della Lotta, view of incipient dunes and established dunes, between the beach (B) and the paleocliff (PC); arrows indicate the blowouts. (c) Casalbordino, incipient dunes, intensely eroded; in the foreground the pebbly beach (B). (d) Vasto Marina, established dunes crossed by orthogonal blowouts and urbanisation behind.

(8780 m in the northern sector, 3880 m in the central, and 2940 m in the southern one); the surface area is little less than 1,500,000 m^2 (>950,000 m^2 in the northern sector, >210,000 m^2 in the central, and >320,000 m^2 in the southern one). Established dunes are more extended than incipient ones and occupy the greatest portion of the surface areas: 80% of the total area in the northern sector, 58% in the central, and 73% in the southern one. The crest heights are generally <3 m; higher dunes with heights >3 m are more common in D2 of the northern and central sectors. The crest axis direction is generally parallel or slightly oblique to the coastline.

Analysis of Historical Maps and Photographs

As shown by the analysis of maps and photographs dating from the 1800s to the beginning of the 1900s (Table 1), almost the entire low coast (northern and southern sectors) and locally the high coast, for a length of ~85 km, are characterised by dunes, with directions parallel to the coastline or slightly oblique or arcuate near the main river mouths. Wide coastal dune areas are clearly represented in maps from the first years of the 1800s. Extensive dune fields, labelled as "Le Dune" (The Dunes) in 1800 topographic maps, are well outlined in the area of the mouth of River Pescara (D, Figure 5a), for a total length >20 km, ~8 km toward north and ~12 toward south. This includes the present Ghiomera dune area, now having a total length as limited as ~1500 m. Backward dune areas are characterised by extensive pinewoods (P, Figure 5a) and by historical urbanization and land photographs testify their persistence at least until the first years of the 1900s (Figure 6a). The pinewoods are on undulating terrain on mainly sand deposits, which are referable to dunes consolidated by pine trees (Figure 6b). Swamps and marshlands occupy wide areas of the coastal plain, close to the mouth of the main

Table 2. *General morphometry of the incipient dunes (D1) and the established dunes (D2) in the three sectors of Abruzzo coast (from aerial photointerpretation and field survey). L: length; W: maximum width; A: surface area; H: crests height asl; Dc: crests direction; Dcl: coastline direction; Lb: beach width; Dbl: blowouts direction; *: AMS ^{14}C dating on shell of pulmonary gastropod* Helix *sp.*

	Incipient Dunes (D1)					Established Dunes (D2)						
Location	L (m)	W (m)	A (m^2)	H (m)	Dc	L (m)	W (m)	A (m^2)	H (m)	Dc	Dcl	Lb (m)	Dbl
Northern sector													
Martinsicuro	600	60	22,650	1–1.5	NNE-SSW	500	30	10,095	2	~N-S	NNW-SSE	20–32	~E-W
Villa Rosa	450	40	9263	1	NNE-SSW	500	52	16,567	2	~N-S	NNW-SSE	10–15	~E-W
Villa Mazzarosa	1265	130	140,601	1	NNW-SSE	2420	190	351,848	2	~N-S	NNW-SSE	25–30	Not present
Pineto	550	20	7040	2.5	NNW-SSE	1700	180	260,063	3.5–4	NNW-SSE	NNW-SSE	25–30	~NE-SW
Torre Cerrano*	885	10	6411	1–2	NW-SE	2450	70	125,829	2.5	NW-SE	NNW-SSE	15–25	~NE-SW
Central sector													
Ghiomera	1470	43	29,183	1.5	WNW-ESE	1550	50	34,492	1.8–2	NW-SE	NW-SE	25–30	~NE-SW; N-S
Casalbordino	1750	45	36,851	1.5–2	WNW-ESE	800	100	68,328	3–3.5	WNW-ESE	WNW-ESE	25–30	~N-S
Punta della Lotta	680	50	22,459	2–3	~ E-W	470	80	19,728	3	~E-W	WNW-ESE	40–45	~N-S
Southern sector													
Vasto Marina; San Salvo	2685	53	85,740	1–3	WNW-ESE	2590	125	237,209	1.5–3	WNW-ESE	NW-SE	20–50	~N-S

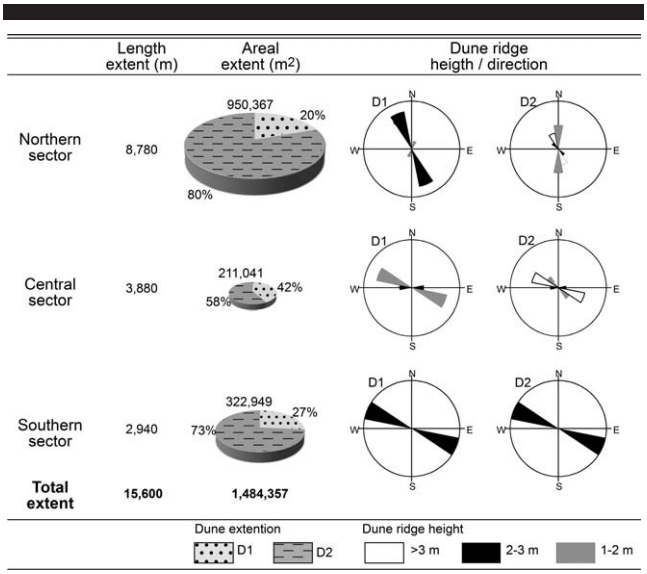

Figure 4. Main geomorphological field characteristics of dune areas for the northern, central, and southern sectors. The length extent refers to the incipient D1 and established D2 dunes. Size of pie charts indicates the extent of surface areas covered with dunes; percentages refer to dune extension with respect to the total for each sector.

rivers within the northern low-coast sector, fed by floods at river mouths or directly by river-mouth bifurcations. In the example of the River Pescara (L, Figure 5a) these are indicated in the historical maps by names as "Stagno Palada" (Palada Pond) and "Palude Vallicella" (Vallicella Swamp), testifying to the natural state of the coastal plain.

The progressive development of human activities on coastal plains is already evident from panoramic photographs taken at the beginning of the 1900s, and this development progressively extended to the established dune areas (D, Figure 6c). Details given by land photography enable the recognition of dune fields up to a few hundred metres wide, with varying vegetation covering the coastal lands of Pescara and Francavilla al Mare (D, Figure 6d).

Aerial photos from the mid-1900s show the role played by harbour wharfs and piers building, and by river-mouth embankments in the coast and dune modifications. As in the case of the River Pescara, these structures deeply modify beach and river-mouth morphodynamics, with erosive processes in the northern side. The river mouths and the coast near harbour areas become clearly asymmetrical, much more advanced in the southern sector, with extensive dune fields partly stabilised by shrubby vegetation (D, Figure 5b). The mid-1900s aerial photos also show the impact of littoral communication lines on the coastal plain all along the coastal area (*i.e.,* Figure 5b). As outlined by the orthoimages acquired in 1999, the historical coastal dune areas are completely occupied by the Pescara urban area, seaside resorts, and marina (Figure 5c).

Similar indications are provided by the topographic maps of the early 1900s, in other parts of the low-coast northern sector (River Tordino area). Dunes are well recognisable north and southward of the river mouth, for a total length of >10 km,

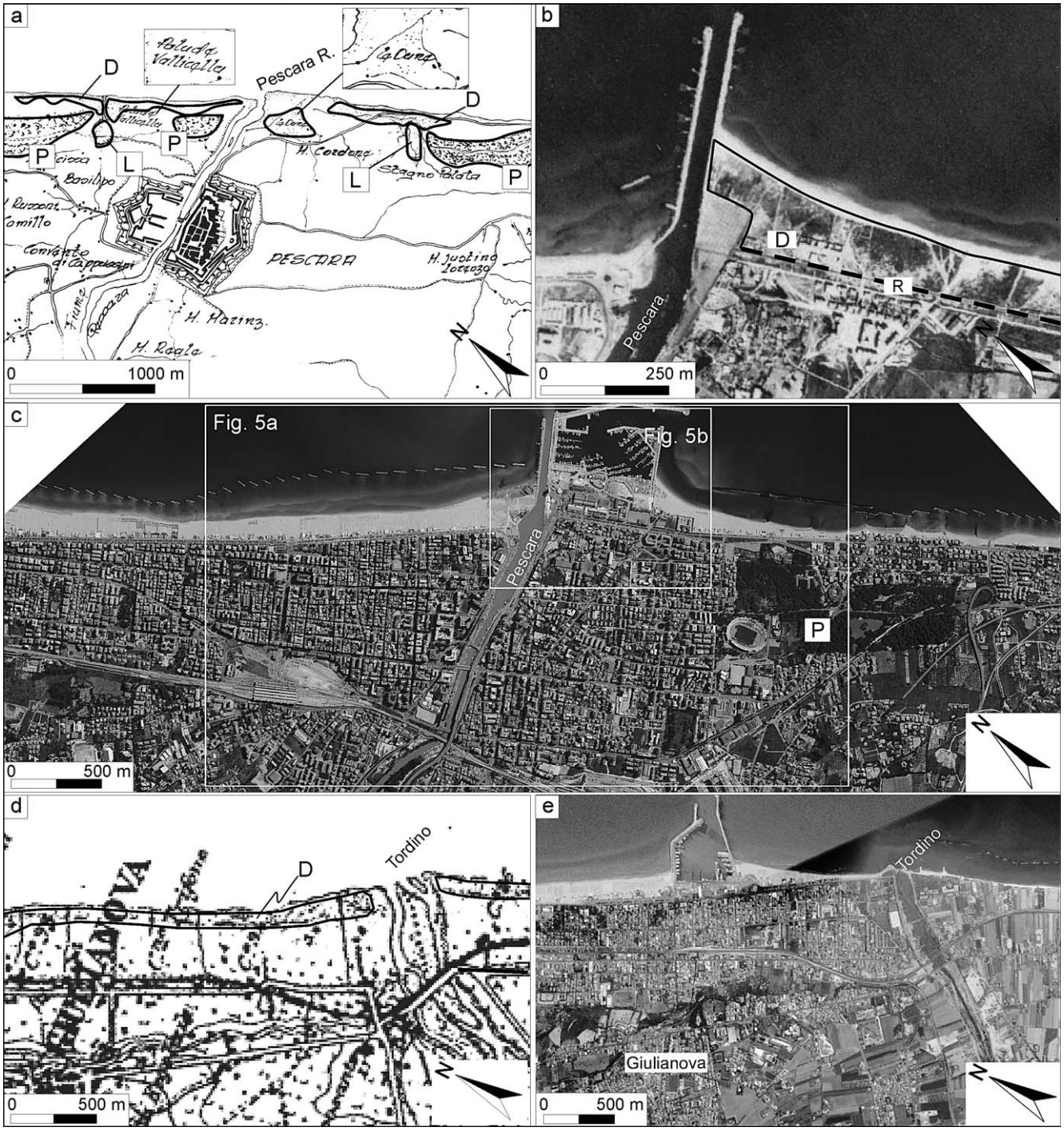

Figure 5. Examples of historical cartography and aerial photos of the Abruzzo coast. (a) Dune fields near the mouth of the River Pescara (D), labelled as "Le Dune", in the topographic map of Castellamare Adriatico and Pescara in 1811–1820 (reconstruction of F. Campanella, 1991—State Archives, Pescara); coastal pinewood (P) and back dune swampland (L). (b) Aerial photo of the mouth of the River Pescara in 1954 (photo of Italian Military Geographic Institute), showing dune fields (D; R indicates national road). (c) Pescara area in orthophoto of Abruzzo Region (1999), highlighting the complete anthropization of dunes shown in Figures 5a and b. (d) Coastal dunes (D) between mouth of the River Tordino and Giulianova, in 1908 (map of Italian Military Geographic Institute). (e) Coastal area between mouth of the River Tordino and Giulianova, orthophoto of Abruzzo Region (1999), showing the developement of urban area of Giulianova on coastal dunes (Figure 5d).

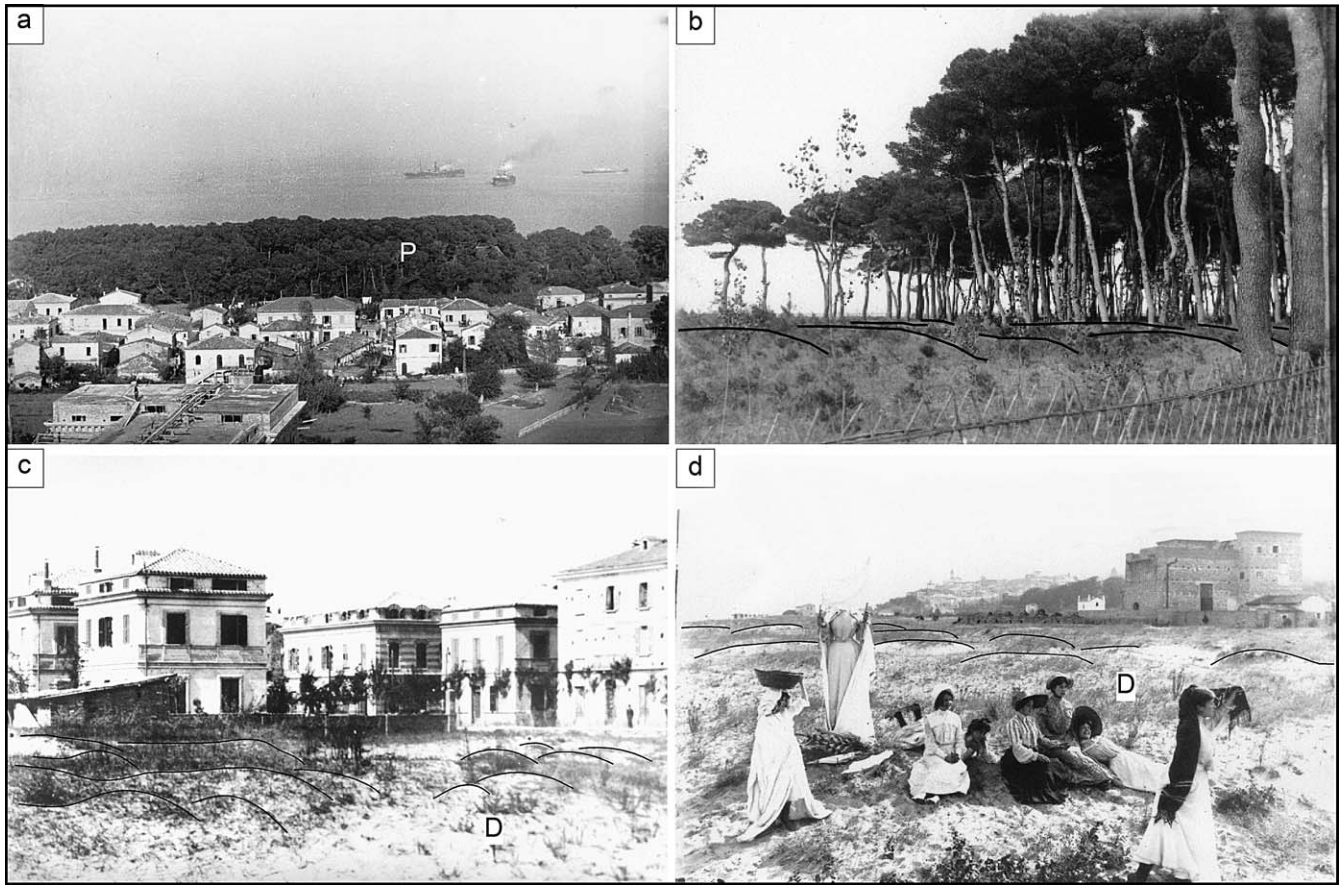

Figure 6. Examples of historical photographs of the area between Montesilvano and Francavilla al Mare at the beginning of the 1900s. (a) Pescara, coastal pinewood (P) north of the mouth of the River Pescara (P. De Antonis collection, Archive of Museo delle Genti d'Abruzzo). (b) Pescara, pinewood on dunes south of the mouth of the River Pescara (O. Cipollone collection, Archive of Museo delle Genti d'Abruzzo). (c) Pescara, detail of dunes at the beginning of the 1900s, with back dune plain already built up (O. Cipollone collection, archive of Museo delle Genti d'Abruzzo.) (d) Francavilla al Mare, extensive dune field (D) close to the mouth of the Alento river (O. Cipollone collection, archive of Museo delle Genti d'Abruzzo).

located in a natural-state coastal plain (D, Figure 5d). Comparison with year 1999 orthoimages shows that foredunes have been completely deleted by the development of the Giulianova urban area toward the coast, and that the construction of the harbour deeply influenced morphosedimentary processes, with the consequent variation of the coastline shape (Figure 5e).

In the central sector, the comparison of cartography and aerial photos from the early 1950s with orthoimages acquired in 1999 outlines the recent geomorphological variation of the high coast of the Punta della Lotta area, characterised by the promontory cliffs of Punta della Penna and Punta della Lotta, between which Vasto harbour wharfs were built in the ~1950s. In 1954, the area west of the promontories is characterised by cliffs at whose foot is a beach of a few metres in width (Figure 7a). The harbour wharf construction changed the pattern of coastal sedimentation in adjacent areas, inducing a significant accretion due to interference of the longshore drift. Comparison with the 1999 orthoimage shows that the western side of the promontories is now characterised by the beach of Punta della Lotta in front of a wide incipient and established dune field (Figure 7b), with an overall coastal advance of around 200 m.

DISCUSSION

Dune Features

The analysis carried out allows us to identify the geomorphological characteristics of the nine dune areas along the central Adriatic coast between the mouths of the rivers Tronto and Trigno (Abruzzo region). The morphology is characterised by shore-parallel dune ridges formed on the top of the backshore by aeolian sand deposition within vegetation. The crest axis orientations of incipient and established dunes are generally parallel with the coastline, arranged in a direction consistent with dominant winds.

The overall morphological parameters (Table 2) indicate dune fields from small to very small: surface area always <1 km^2; length <5.0 km; width <1 km; height <5 m (according to Davies, Williams, and Curr, 1995). The relation between width and length is generally <0.1, showing mainly elongated

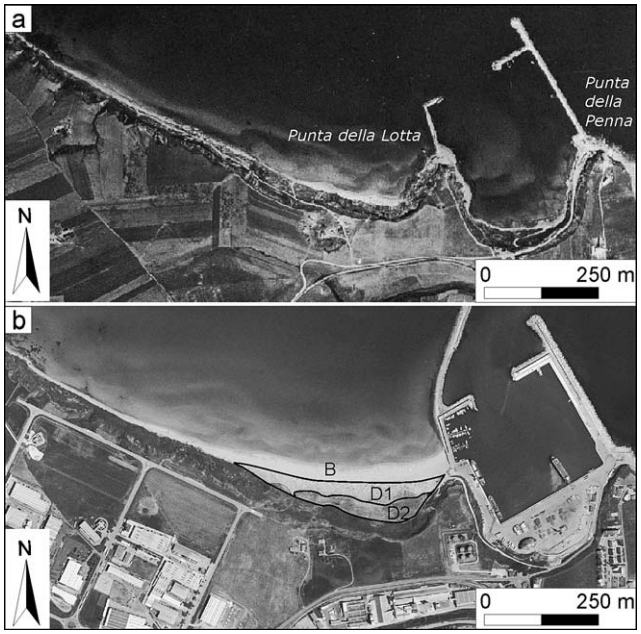

Figure 7. Punta della Lotta, Vasto. (a) Aerial photo showing a cliff with a small beach in 1954 (photo IGM). (b) Orthophoto showing a large dune field that, including the beach, has a width of 200 m, in 1999 (photo Abruzzo Region).

foredune fields stretching parallel to the coastline, with a moderate transverse development. The small extension of dune fields is linked to the human impact, the generally limited width of beaches, and the minimum potential sediment supply, causing regressive foredunes with very limited or no deposition (Arens and Wiersma, 1994).

The analysis of historical maps and photos allows us to estimate a >80% reduction of the dune areas from a total length of ~85 km at the turn of the 20th century to a present total length of >15 km (Figure 8). The analysis shows that intense human development, starting from the coastal plain, has gradually involved the foredune fields, similarly to what has happened in other coastal areas of the Adriatic sea (Cencini, 1995; Simeoni and Bondesan, 1997; Simeoni *et al.*, 2006). Urbanization and human activities have heavily modified very extensive dune fields with foredunes and coastal plains with swamps and marshland. The dune reduction is due to direct sand removal for residential and industrial buildings, for agricultural purposes, or for the construction of littoral communication lines, and to indirect effects of buildings, roads, and vegetation changes on sediment fluxes. In some cases, on the other hand, opposite effects are given by anthropogenic activity (*i.e.,* Vasto harbour building) that has induced the formation of a new beach and of a new dune field (Punta della Lotta, Figure 8), forming a barrier on longshore drift.

An important role in dune reduction is also played by intense coastal erosion that, over the last 40 years, has reduced the width of the beaches, involving at least 12% of the incipient dunes within the studied areas. Furthermore we may add that, during the last 3 decades, the most intensive management efforts (nourishment and dyke realization) have involved areas undergoing coastal erosion. These activities interfered with natural processes and indirectly influenced the foredune form (Arens and Wiersma, 1994; National Group for Coastal Environment Research, 2006; Van der Meulen and Salman, 1996).

Geomorphological Setting

The detailed geomorphological survey and historical analysis—also extended to the coastal plains—enabled the recognition of different geomorphological arrangements of hill slope, cliffs, coastal plains, dunes, and human activities. This allowed for the identification of three main Abruzzo coastal types with dunes: (1) dunes that developed at the coastal plain edge, in the low-coast northern and southern sectors (Fcp, Figures 8,9); (2) dunes that developed at the foot of the hill slopes, locally in the low coast northern sector (Fcs, Figures 8,9); (3) dunes that developed at the foot of cliffs, on rockfall deposits, in the high-coast central sector (Fpc, Figures 8,9).

The different geomorphological arrangements are summarized in Figure 9. In the low-coast northern and southern sectors, established and incipient dunes generally developed on the coastal plain and are interfingered with the beach (Figure 9a,g) in an area moving from continental to transitional and marine environments (Parlagreco *et al.*, 2011; SGI, 2010a, 2010b). Silty and peat deposits are also present, related to old marshes and swampland located between coastal plain and dunes, as outlined by the analysis of historical maps and photos. Locally, the coastal plain is absent and the dune deposits lie on gravitational deposits of the hill slopes (Figure 9b). Lateral continuity of dune areas is broken by the flood plains of the main rivers and wide areas of dunes have been removed by intense agricultural activity (Figure 9c) and by the development of coastal settlements (Figure 9d). Pinewoods developed on older dunes (Figure 9d), as shown by the historical images and already partly revealed by botanical studies (Pirone, 1995; Tammaro and Pirone, 1979, 1981). These pinewoods, even though already mentioned in 1574 by the Domenican Serafino Razzi in his "Viaggio in Abruzzo" (from Pirone, 1982), are locally the results of a coastal reforestation during the early 1900s (Cencini and Varani, 1991).

In the high-coast central sector, coastal plain is absent and the dunes lie on landslide deposits associated with the retreat of the paleocliffs (Figure 9e,f). Some areas are affected by intense erosion processes related to wave action, which involve the incipient dunes behind narrow gravel beaches (Figure 9f).

Historical Evolution

The interpretation of new geomorphological data, recent historical variations, and geomorphological setting, compared with previous studies in nearby areas, define the historical evolution of central Adriatic coastal foredunes that can be summarized as follows.

After the Holocene last phase of coastal plain progradation (Parlagreco *et al.*, 2011) and older aeolian morphogenetic phases that occurred about 2500 years before present (docu-

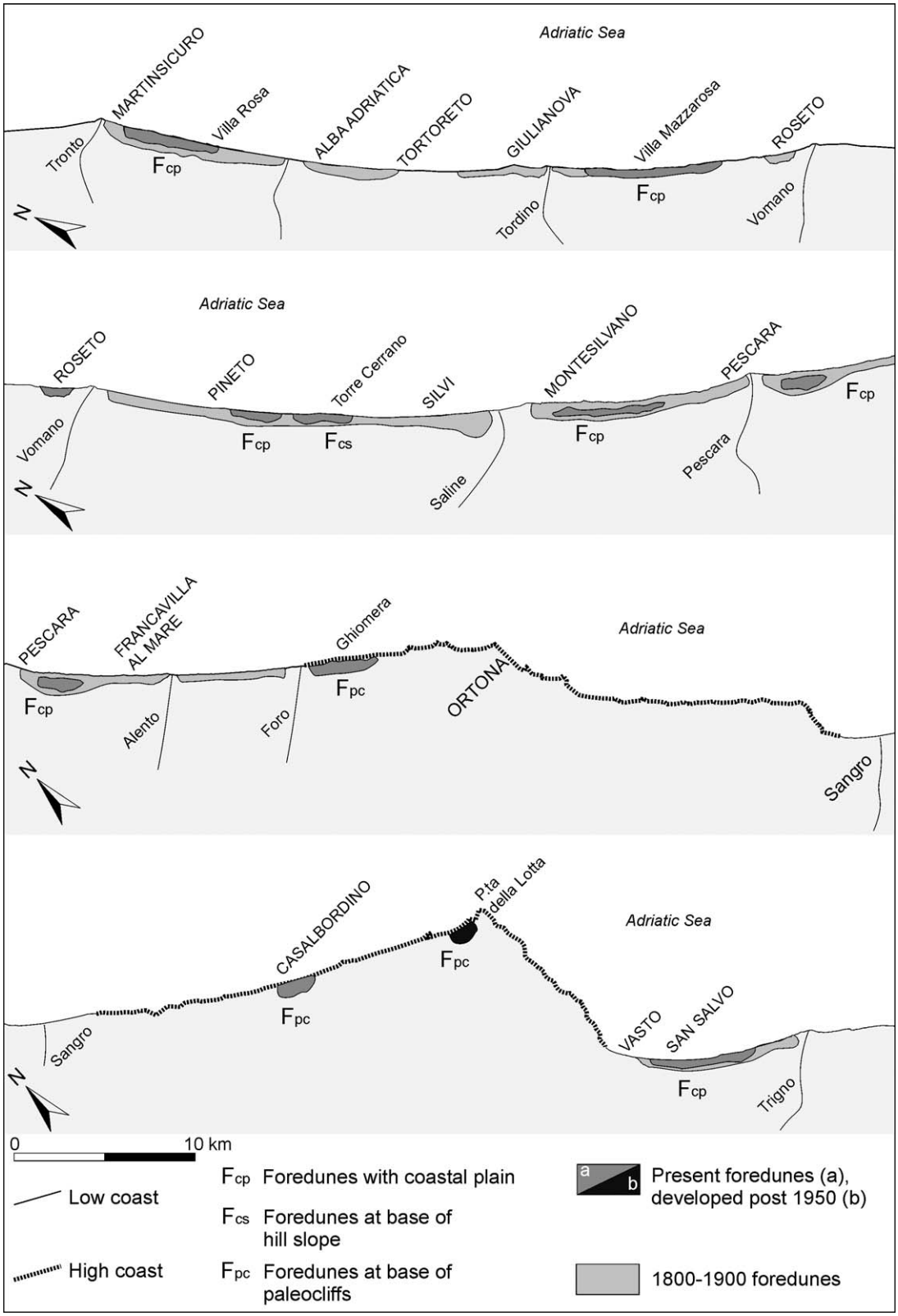

Figure 8. Scheme of dune distribution changes from 1800 to 2000.

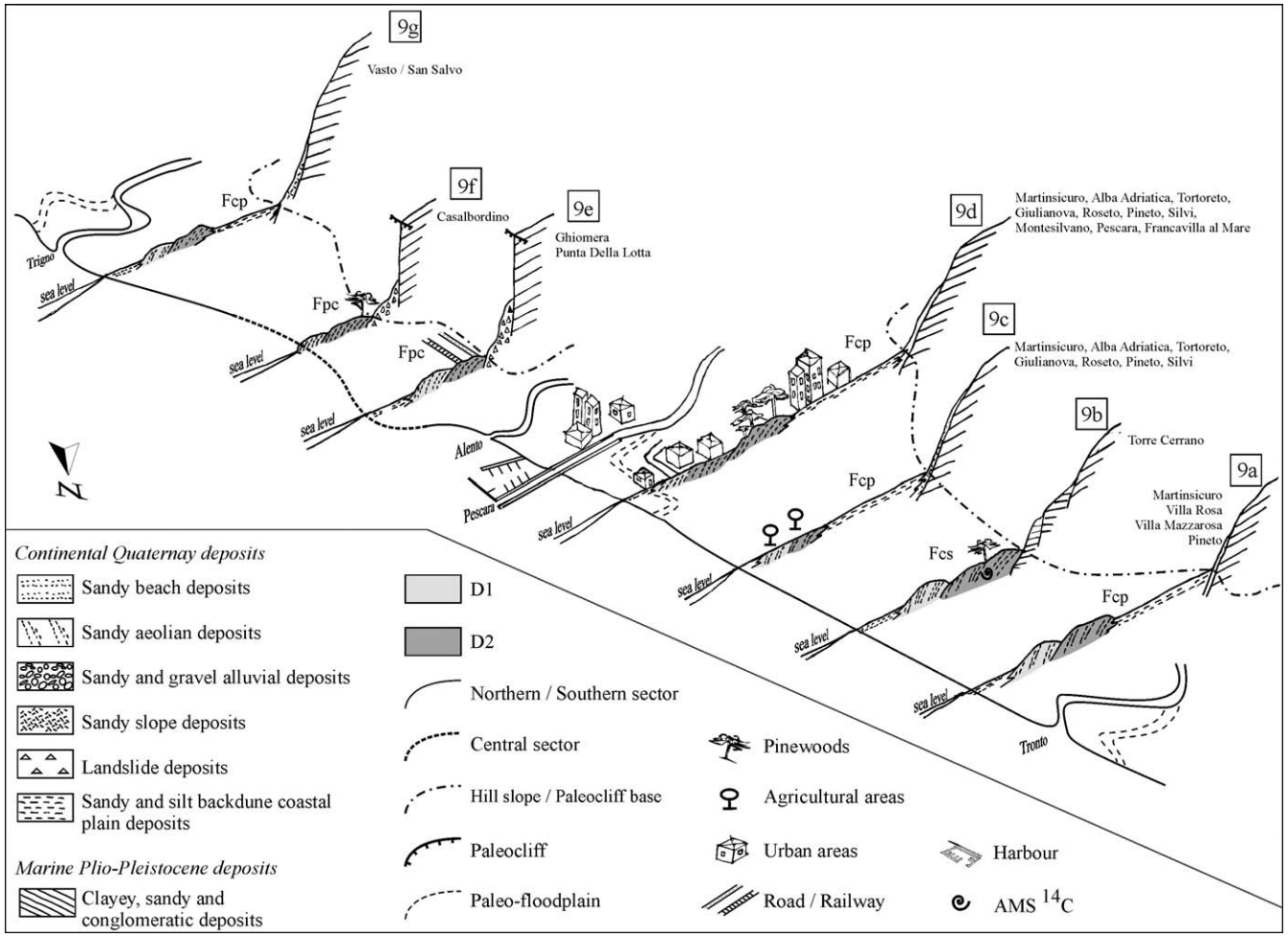

Figure 9. Main types of dune, in relation with geomorphological setting of back dune areas and anthropogenic activities. (a) Dunes developed at edge of coastal plain. (b) Dunes developed at foot of hill slopes. (c) Dunes developed at the edge of the coastal plain and deleted by agricultural activity. (d) Dunes modified and deleted by coastal urbanization; relict strips of coastal pinewood on old consolidated dunes. (e) Dunes developed at the foot of paleocliffs, on landslide deposits. (f) Dunes, developed at the foot of paleocliffs, subject to intense erosion. (g) Dunes developed at the edge of the coastal plain.

mented in the Apulia region, southern Adriatic area, by Mastronuzzi and Sansò, 2002), the oldest recognizable period of aeolian deposition in Abruzzo can be dated back to the late Middle Ages. A first geochronological indication that outlines a minimum age of the dune formation in Abruzzo is given by the radiometric dating (Figure 9b), which indicates an uncalibrated age of 730 ± 40 years. This is in line with results from other Italian sectors (Mastronuzzi and Sansò, 2002; Cacciapaglia, De Santis, and Palmentola, 2006). The intense anthropogenic presence makes it difficult to collect further geochronological indications about more ancient aeolian deposits and the dated dunes currently appear to be the oldest ones, providing a minimum age of the present dune systems.

The resulting landforms are the current established dunes (D2), locally consolidated by the woodland vegetation in the low-coast sector. In the high-coast sector, local morphosedimentary conditions prompt dune growth on the fall deposits of some paleocliffs. Although coastal areas already featured some elements of human activity, their effect on coastal morphogenesis was negligible and dune evolution was mainly related to natural processes (Cencini, 1995).

At the beginning of the 1800s, the landscape was characterised by incipient and established dune areas (D_{in}-D_{es}, Figure 10, lower) extending along most of the coast for a total length of ~85 km (out of 125 km) and broken only by river mouths or cliffs of the high coast and by historical urbanization on the coastal plain (HU, Figure 10).

In low-coast sectors dunes consolidated by pinewoods were already well established (P, Figure 10); the coastal plains had extensive swamps and marshlands (L, Figure 10) generally fed by river-mouth bifurcations. In the high-coast sectors, dune formation followed the inactivation of some tracts of cliffs (C, PC, Figure 10) related to the growth of beaches by fluvial bed loads, longshore drift, and sand sediments eroded from adjacent active cliffs (Figure 10, lower left). Until the early 1900s aeolian deposition was widely active and dunes were a

Figure 10. Block diagrams summarising main evolutive stages of coastal sectors with dunes (in gray). Beginning 1800s: the sectors of low coast have incipient and established dunes (D_{in}, D_{es}), partly already consolidated by pinewoods (P) extending along most of the coast; coastal plains (CP) show swamps and marshland (L), generally fed by river branching near mouth, and historical urbanization (HU). In sectors of high coast, with active and inactive cliffs (C), dunes develop at foot of paleocliffs (PC). Beginning 1900s: phases of anthropogenic activities and urban development involving initially back dune areas, with reclamation of marshland and, progressively, pinewood areas and dunes. 1950–today: intense urban development (U) also on incipient dunes, modification of coastal dynamics due to building of port facilities with formation of new beaches and dunes, and new areas of intense coastal erosion.

significant morphological component of the Central Adriatic coast as well as of the Italian coastal landscape (Cencini, 1995).

The 1800s–1900s turn represents a crucial stage in dune modifications (Figure 10, centre). At the end of the 1800s, the Adriatic littoral communication lines were completed. They locally modified natural processes by directly and indirectly contributing to foredune reduction, deleting portions of dunes, or reducing the sediment flux (D_{in}-D_{es}, Figure 10). Agricultural activity and the development of urban areas had also led to the reclamation of the original natural environments, *e.g.,* the extensive swamp and marshland areas behind the dunes (Figure 10, Gorgoni Lanzetta, 1993; Staffa, 2002). Reclamation of land for agriculture included the plantation of pinewoods on dunes to protect cultivation areas from salty marine winds (Cencini, 1995). In the larger urban areas, built-up zones extended into established dune areas; at many river mouths the first wharfs and piers were built for a growing maritime traffic, inducing the asymmetrical advance of coast and related dunes. In the 1900s, the first significant human-induced processes began, with an intensification of agricultural activities and ongoing urban development, added to the historical ones, influencing mainly low-coastal areas (U-HU, Figure 10; coherently also with Kiss, Sipos, and Kovács, 2009; Van der Meulen and Salman, 1996).

Since the mid-1900s to date, previous incipient and established dunes (D_{in}-D_{es}) have become the present established dunes (D2, Figure 10, upper right), whereas new small incipient dunes have been forming (D1, Figure 10). After a temporary coast advancing—up to the 1970s—due to the consequences of deforestation and inland extensive agricultural practices in the sediment supply to the coast, intense erosion has affected most of the coastline, locally involving coastal dunes. In the low-coast sectors, most of the urban settlements close to the coast have extended their built-up areas to the beach edge (U, Figure 10, upper right), occupying the foredune zones (D2), pinewoods, and part of the beaches (P-B, Figure 10; see also Muzii, 1923; Foderà, 1954; Gorgoni Lanzetta, 1993; Simeoni *et al.*, 2006). The back dune swamps and marshland have disappeared completely, whereas only a few strips of coastal pinewoods have survived (P). The building of new port facilities has deeply modified the morphosedimentary dynamics of the coastline, creating in some cases new beaches with dunes (D1–D2, Figure 10, upper left). In summary, since the 1950s established dunes (D2) have dramatically decreased, whereas new incipient dunes (D1) have hardly been growing, heavily affecting the whole coastal system.

CONCLUSIONS

The overall analysis of the coastal dunes of the central Adriatic area (Abruzzo, Italy) highlights the occurrence of small to very small incipient and established dunes in both low- and high-coast sectors. Nine dune areas are present, for a total coast length of >15 km. These can be defined as seminatural foredunes, with mainly direct and locally indirect effects of coastal management (according to Arens and Wiersma, 1994; Williams *et al.*, 2001).

Their arrangement is associated with meteorological and marine conditions comparable with the present ones. Strong feedback relationships exist between coastal and aeolian processes on the one hand and human activity and foredune management on the other.

In conclusion, this work provides some indications on the main natural and human-induced morphogenetic phases, within a few centuries time span, that have brought about the current morphology of main coastal dunes in the Adriatic central area and can be summarized in the following phases:

- the initiation of the present dune systems can be dated back at least to the late Middle Ages;
- in the 19th century the coastal landscape is widely characterised by dune areas extending along most of the Abruzzo coast (for a total length of ~85 km out of 125 km);
- in the first half of the 20th century the dune area reduction begins, mostly due to the human activities in the coastal plain (urban settlements, communication lines);
- in the second half of the 20th century previous incipient and established dunes become the present established dunes (D2); after a temporary coast advancing, dune reduction dramatically increases (up to >80%) particularly on established dunes, due to the expansion of urban settlements within the whole coastal plain, and is associated with a parallel beach erosion and coast retreating (except for some local cases). In this framework new incipient dunes (D1) have hardly been growing, heavily affecting the whole coastal system.

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