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THE ROLE OF *POSIDONIA OCEANICA* ON PARTICLE SEDIMENTATION PROCESSES IN COASTAL SHALLOW-WATERS

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Index

Abstract

The *Posidonia oceanica* is the endemic seagrass of Mediterranean Sea, subjected to a diffuse regression in last 50 years. Sedimentary flux is one of the ecological factors of the seagrass ecosystems and makes an important theme for the conservation of coastal natural resources. The present work investigates the vertical sedimentation flux on *P. oceanica* meadow and the linkage between the sedimentary dynamic and benthic community structure. The experimental investigations about sedimentation of organic and inorganic matter were monthly conducted on a meadow placed at 7 m depth in Civitavecchia (Italy), throughout the year 2015-2016, by the use of sediment traps. Hydrodynamic experiments were integrated to sediment dynamic observations. Fauna assemblage were analysed seasonally. The experimental investigations conducted on *P. oceanica* meadow have demonstrated the role of seagrass on particles sedimentary process and how this interaction has a direct implication on the structure of fauna assemblage. The vagile fauna is strongly dependent to the growth of leaves, while the population of rhizomes is more susceptible to sedimentary dynamic regime of particles, that causes a shift of trophic categories. The capacity of a *P. oceanica* meadow in particles retention, especially during the maximum growth of leaves, favours the accumulation of organic matter and sediment that contribute to matte accretion and provide habitat and feed for benthic species that live in the rhizome-matte stratum.

1. Introduction

Estuaries and coastal areas have remained strategic points of human settlement through history, resulting in persistent and intense impacts on coastal ecosystems (Lotze et al., 2006). The over-exploitation of natural resources over centuries has led to the gradual transformation of the coastal habitats.

Marine sediments represent sites of carbon metabolism and preservation of large regional and global importance, and it is well known that continental margin sediments provide a major sink for organic carbon (Hedges and Keil, 1995).

The Mediterranean coastal area is widespread colonized by seagrass *Posidonia oceanica* which is a vascular marine plant that supports highly complex and productive ecological systems (Den Hartog, 1977; Pergent and Pergent-Martini, 1991). Much attention has been focused on the physical and biological role of the *P. oceanica* in the marine environment assigning to this vascular plant a fundamental ecological role in coastal ecosystems (Hemminga and Duarte, 2000) and recognized worldwide such as a coastal hotspot for biodiversity (Myers et al., 2000) and nursery area.

It was studied the architectural role of the seagrass canopy in the structuring of rich faunal assemblages (Bell and Westoby, 1987; Klumpp et al., 1992; Heck et al., 1989; Ferrell and Bell, 1991). It's well demonstrated the role of the *P. oceanica* in the enhancement of sediment accumulation by trapping suspended particles and limiting sediment resuspension, and the function of dense below ground network of roots and rhizomes in the stabilization of the substrate (Gacia and Duarte, 2001). It was demonstrated the linkage of the health of seagrass meadows to several factors as light, nutrient, trace metals, sediment accumulation rates and grain-size, organic carbon (C_{org}) stocks and its accumulation rates (Serrano et al., 2016). In particular, *P. oceanica* meadows are very sensitive to water and sediment enrichment with organic matter and nutrient.

Human development in coastal areas has caused a significant shift in ecosystem dynamics and scientific evidence of the adverse effects of anthropogenic fluxes are of concern due to the continuous decline in seagrasses (Orth et al., 2006; Serrano et al., 2016; Montefalcone et al., 2015; Brearley, 2005). The use of soil can cause a qualitative and quantitative change of substance and sediments entering into the sea, causing pollution, alteration of sedimentary balance and contamination of sediments. Untreated sewage outlets, fish farm effluent or runoff from fertilized agricultural areas are serious threats to neighbouring *P. oceanica* meadows. Multiple human pressures and the degradation of coastal ecosystems can result in the progressive replacement of seagrasses by opportunistic macrophytes and algae and the impoverishment of ecosystem functioning and services (Costanza et al., 1997; Duarte, 2000; Montefalcone et al., 2015).

The synergic interactions among disturbances together with their duration and magnitude, may lead to a shift in ecosystem dynamics and the loss of seagrass ecosystems (Duarte, 1995; Montefalcone et al., 2015).

P. oceanica can cope with sedimentation rates that not exceed 4-5 cm yr^{-1} (Gacia and Duarte, 2001) and are very sensitive to erosion. Coastline transformation and urbanization sharply reduces sediment inputs to the submerged coastal habitats promoting meadow erosion. Coastal construction may alter the pattern of coastal currents thus producing siltation or erosion of seagrass meadows.

The alteration of fine particles sedimentation may interfere with photosynthesis processes (Ruiz and Romero, 2003) and ecological condition of canopies. The light limitation seems to be less relevant in seagrass regression (Ruiz and Romero, 2003) with respect to the over-sedimentation produced by the increase of fine fraction of sediment (Manzanera et al., 1998) and the chemical variation of the seabed sediments (Montefalcone et al., 2015). These factors induce canopy mortality (Manzanera et al.,1998) and changes in the ecological condition of communities associated with *Posidonia* meadows (Montefalcone et al., 2015). The high loading of terrigenous sediments can dilute the biogenic carbonate deposited in the sediments, with the decline in carbonate concentration enhanced further by a possible decline of the community of calcifying organisms inhabiting meadows and a reduction in biological diversity (Montefalcone et al.,2015).

In the Mediterranean Sea, organic and trace metal pollution has increased over the last 20 years (Bethoux et al., 1990; Bethoux et al., 1998), and this has had a perceptible effect on marine environments (Delgado et al. 1999). The increase in concentrations of potentially phytotoxic, non-nutrient chemicals (e.g. *Pb, Al, As, Cd* and *Cr*) contribute to seagrass decline (Delhaize & Ryan, 1995; Schlacher-Hoenlinger & Schlacher, 1998; Shanker et al., 2005).

The increase of loading of nutrients can lead to the proliferation of epiphytic algal communities that shadow the seagrass leaves, reducing seagrass light harvest and enhancing leaf grazing (Ruiz et al., 2001). In addition, the algal enrichment of detritus in seagrass sediments can have 'bottom-up' effects, altering primary production dynamics as well as benthic faunal community structure (e.g. Bishop et al., 2010; Montefalcone et al., 2015).

The deposition of organic matter is likely to be particularly important within the meadows of the Mediterranean species of *P. oceanica*, which develop communities with high biomass (Duarte & Chiscano, 1999) and the tissues of which decompose very slowly (Romero et al. 1992; Mateo & Romero, 1997). The nature and accumulation rate of organic detritus in seagrass sediments can alter benthic faunal community structure (e.g. Bishop et al., 2010; Montefalcone et al., 2015) and may led to a gradual loss of the filtering and buffering capacity of seagrass meadows (Duarte, 1995; Cloern, 2001). An increment of organic matter increases sediment microbial activity, producing anoxia and

increasing sulphate-reduction rates in the sediment. The excess of hydrogen sulphide rapidly reacts with oxygen pumped through the seagrass roots, and may even penetrate the plant tissues, enhancing *P. oceanica* mortality (Frederiksen et al., 2007).

In a broader context, the rise of seawater temperature linked to climate change contribute to steep declines in seagrass shoot abundance, overall growth and reproduction in *Posidonia* meadows (Marbà & Duarte, 2010; Thomson et al., 2015).

The coastal area, object of the study, located along the Italian coast on the north-eastern Tyrrhenian Sea, is characterised by a widespread presence of *P. oceanica* meadows listed in two SCIs of EU-Habitat Directive. The coastal area counts many activities, such as electric power plant, harbour, fish farm, urban centres and tourism, that cause multiple pressures on marine resources. These activities are in conflict with coastal ecosystem and *P. oceanica* meadows, also in this area, account a clear regression in last 50 years (Telesca et al., 2015).

2. Objectives and scopes

The present work investigates the vertical sedimentation flux on *P. oceanica* meadow and the variation of benthic community structure associated to this seagrass. The study aims to understands the effect of *P. oceanica* on sedimentary processes and how these influence the community structure associated to this vascular plant.

The work is separated in two part: in the first part is proposed a frame about sedimentation processes, a short summary of benthic zonation in the coastal area, a general description about *P. oceanica* with a focus on its role on hydro-, morphodynamic processes and the general structure and trophism of faunal assemblage associated to this vascular plant.

The great human alteration on sedimentary fluxes in the study area, makes the sedimentary dynamic, an important theme for the conservation of coastal natural ecosystems.

In the second part of this work we present the experimental investigations conducted on *P. oceanica* meadow that demonstrate how the interaction between sedimentary processes and the seagrass has a direct implication on the structure of fauna assemblage.

3. Sedimentary processes and coastal benthic ecosystem

3.1. Sedimentary processes

Sediment is an integral part of coastal system and the term “sediment” refers to sand, silt, clay, gravel, and bioclastic material that are transported by waves and currents along or near the coast but also by wind, along desert or arid coastline or between beach and dune.

Sedimentary processes occurring along coastal areas are very complexes and result from the interaction between deep processes (tectonics with subsidence/uplift) and superficial processes (climate, sea level change and hydrodynamic) (Cloetingh 2007). The pattern and distribution of sedimentary facies in depositional basins are under sediment fluxes control (Jones and Frostick 2002). Land-ocean sediment fluxes are one of the most important components in the sediment cycle of the Earth system and are also a major influencing factor in the processes of land-ocean interactions in coastal zones (Einsele 1992). The fluxes of continental water and sediment to a continental shelf largely depend on a region's climate and local drainage-basin characteristics, which together affect the hydrology of contributing rivers (Jonesand Frostick, 2002; Burt and Allison, 2010). There are certainly other local factors that impact sediment delivery, including the anthropic influence.

In order to fully understand the coastal morphology in a specific area, it is necessary to have some knowledge of the geology of the area and of the sediment supply from the rivers. Other more special factors may influence the characteristics of the coastal area, such as the local flora and fauna as in the cases of coral coastlines and mangrove coastal areas. The sediment budget is an accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual outlet from a defined landscape unit like a drainage basin (Reid et al., 1996). Sediment budget moves from land to sea through four main coastal compartments which are trapping sediments over a given period or are providing sediments at other coastal compartments (shore, coastal dunes and cliffs, costal hinterland watersheds and rivers, nearshore zone and beyond offshore zone forming a sink on a short period beyond the depth of closure – nevertheless the sediments of offshore compartments can be mobilized in case of severe climatic changes involving the decrease of sea level).

Coastal dynamic processes drive sedimentary and bio-chemistry evolution of the benthic layer. The water-sediment interface is characterised by a high chemical and biological activity, and the importance of sediment processes relative to processes in the water column increases with reduced water depth (Smith, 1974). Waves and currents generate shear stress and turbulence that drive diffusive boundary layer fluxes (Boudreau, 1997), ventilation of porous bottoms (Shum and Sundby, 1996), as well as resuspension (Blomqvist and Larsson, 1994; Soulsby, 1997). The total sedimentary flux is composed by flux of primary settling matter (*Fp*) and flux of resuspended sediment (*Fr*) (Pejrup et al., 1996). The primary settling matter is defined as sediment particles, including terrigenous matter, dead autochtonous organic matter, or shell and skeletal fragments that have not yet been deposited at the bottom at the measuring site. Resuspended sediment consists of the same components, but has been deposited from one to several times previously.

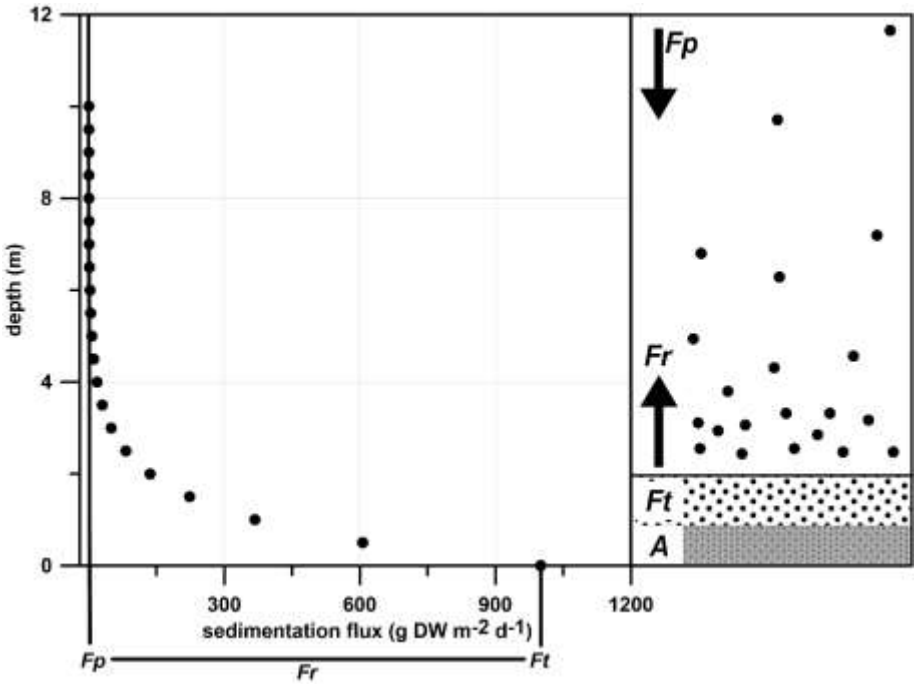

Fig.3.1 Sketch of sedimentary processes where resuspension (*Fr*) and settling flux (*Fp*) contribute to total sedimentary flux (*Ft*). The balance of sedimentary processes beneath the benthic mixing layer determine the accumulation rate (*A*).

Resuspension process is induced by wind-induced surface waves (Lesht et al., 1980; Aalderlink et al., 1984; Sanford, 1994), internal waves (Cachione & Southard, 1974) or currents (Kenney, 1985; Sanford et al., 1991). Resuspension in coastal areas is mainly caused by surface waves and tides, while in deep sea resuspension is primarily due to currents.

The total downward flux (*Ft*) is the sum of *Fp* and *Fr*, and gross deposition rate is defined as *Ft* at the sediment surface. The accumulation rate (*A*) is the amount of sediment permanently deposited beneath the benthic mixing layer. The dynamic of inorganic fraction of particle sedimentation flux into the sea is mainly driven by energetic regime of water flows while the depositional processes of organic fraction are more complexes and variables.

Part of the organic matter flux is mineralized after deposition. The knowledge on the mineralisation of organic matter in coastal sediments is important for the understanding of carbon cycle. Organic matter mineralisation causes an exchange of nutrients that may affect the biological productivity in the water column. Mineralisation rate depends on many factor among which physical forcing governing exchange processes between the sediment and the water mass.

The resuspension play an important role in the mineralisation process enhancing the mineralisation rates, for example by the exposure of a larger surface area of recently settled organic material to microbial attack. Laboratory tests demonstrated the ability of resuspension in doubling, or more, the mineralisation rates compared to sediments not subjected to water turbulence (Stahlberg et al., 2006).

Mediterranean littoral *P. oceanica* meadows are important sites of net organic carbon burial, derived from biological activity of seagrass meadows, sedimented sestonic particles and seagrass detritus (Gacia et al., 2002). Seagrass meadows tend to produce an excess of organic carbon over community requirements (Gattuso et al. 1998) and are believed to store an important fraction of the excess carbon they produce in the sediments (Duarte and Cebrian, 1996). The land derived organic carbon contribute to sustains net heterotrophic planktonic metabolism in the coastal areas.

The deposition of organic matter within seagrass meadows must also be associated to a significant input of nutrients, which may play an important role in their nutrient budget. The deposition of organic matter is likely to be particularly important within the meadows of the Mediterranean *P. oceanica*, which develops communities with particularly high biomass (Duarte and Chiscano 1999) and the tissues of which decompose very slowly (Romero et al. 1992; Mateo and Romero 1997).

3.1.2. Analysis of human pressure on sediment fluxes

The world's coastal area is a long-narrowed feature of mainland, island and adjacent seas denoting a zone of transition between land and ocean. If we consider a world coastal band 20 km wide, we can compute that this area represents nearly 4 % of total Earth surface. Nearly 30% of people in the world live in this relatively small but highly valued and highly dynamic area. Humans have lived in the coastal area for millennia utilising its many and rich resources for their survival and socio-economic benefit. Sediment fluxes are driven by different factors, such as proximal (climate/ glaciation, land cover, topography), distal (base level) and local controls (human activity). The principal influences on sediment flux during the Holocene are driven primarily by geography (temperature, runoff, biogeography and pedology), geomorphology (basin area and relief), geology (tectonic, lithology) and climate change (sea level change, flooding, storms, length of the season and El Nino events or Asian monsoon) (Jones and Frostick 2002). Over the Anthropocene which spreads over the last three centuries, however, large-scale human activities like dam, jetty and seawall construction challenge natural processes like changing sea level and major storms have influences on the shoreline position (Pilkey and Dixon 1996). Quick land cover changes over wide areas into watershed also impact water and sediment fluxes. From a quantitative point of view, the impact of watershed management by humans has first led to an increase in natural sediment supply to the ocean due to soil erosion (+2.3 +/-0.6 billion tonnes/year) and now leads to a decrease (1.4 +/-0.3 billion tonnes/year) due to sediment trapping in dams (about 30 % of the sediment flux coming from inland) (Syvitski et al. 2005; Vorosmarty et al. 2003). At this decrease overlap subsidence processes in the majority of large muddy deltas (Syvistki et al. 2009). Finally, on an annual decadal time scale, human activities, such as dredging, spoil disposals and beach replenishment, along with storm-generated waves, are probably

the most important factors in shaping the coast (Hill et al., 2004). Quantitative assessment of the relative importance of these processes and prediction of future beach behaviour remain important problems for coastal geologists and engineers (Thieler et al., 2000). Large amounts of sediment have been consumed on Earth for beach nourishment, land reclamation and construction. Hence coastal and marine sediments are limited in quantity and should be managed sustainably.

The alteration of sediment flux which is felt in a generalized way is thus the result of a well-known convergence of the following factors with different temporal and spatial scale (Fig.3.2):

- Climatic changes: increase of the marine level, modification of the modes weather-sailors (winds, swell);
- Reduction in the sedimentary contributions of the rivers because of the extractions of sands and gravels or the stopping, and the progressive unpacking, of the basins slopes;
- Reduction in sand stocks available on the spot because of urbanization;
- Disturbances of the sedimentary transit by harbour works or protections which can defer the problem on the close sectors.

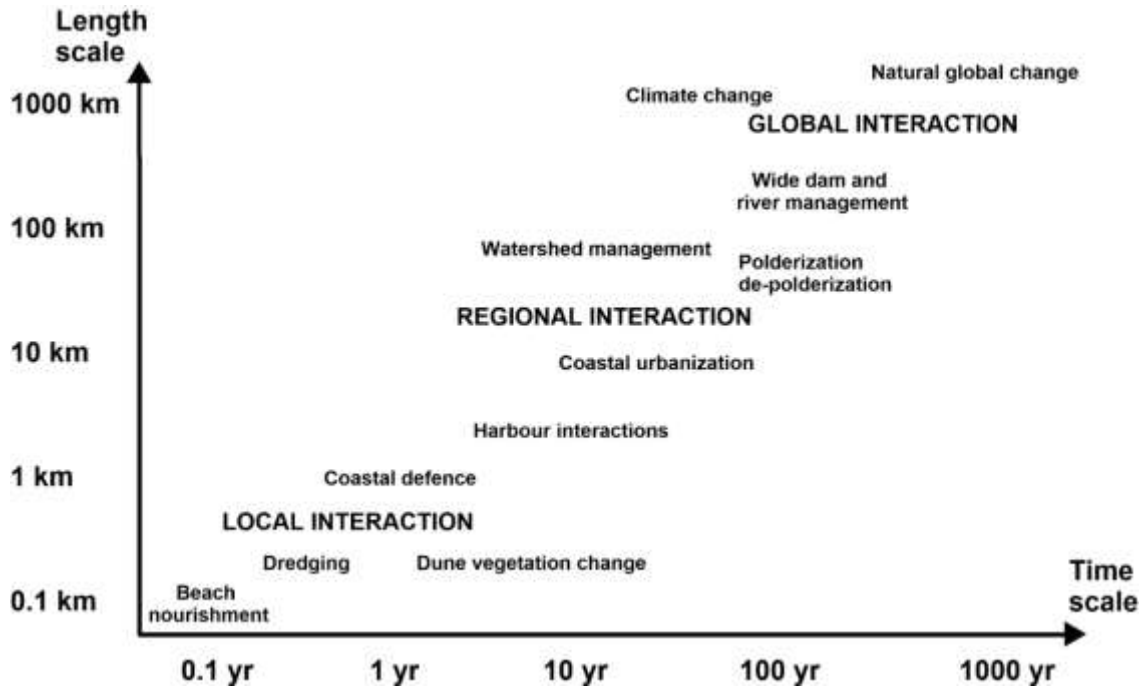

Fig.3.2 Examples of human interaction with sediment fluxes in coastal area at various spatial and temporal scales

Several studies gathering a wide and synthesized knowledge have been published concerning sedimentary fluxes at different spatial and temporal levels and different scientific issues. Jones and Frostick (2002) present a current perspective on controls and constraints on sediment supply, a model and empirically based driven understanding of sediment fluxes and the interaction of geomorphology,

landscape evolution and sedimentary geology to provide a more complete picture of the Earth system. Crossland et al. (2007) addressed key elements of material flux between land, sea and atmosphere through the coastal zone and indications of:

- Change in land use, climate, sea level and human activities alter the fluxes in the coastal zone, and affect coastal quality and morphodynamic;
- Change in coastal systems, including responses to varying terrestrial and oceanic inputs, will affect the global carbon cycle and the trace gas composition of the atmosphere with an assessment of the influence of human society, before looking at future needs for targeted research and management actions in the coastal zone;

3.1.3. Quali-, quantitative alteration of sediment flux on the study area

Like most of the Italian coasts in the study area, human activities have a great pressure on coastal ecosystems. Several towns, land use, fishery and industry, in the past and present intensely exploit and affect marine resource. In this context, a frame of about the whole potential impacts of human activities on the coastal area need to be considered.

Analysis about trace metal contamination in coastal sediments show a high enrichment and contamination levels of *As* and *Mn* located especially in two coastal hot spots as a result of an overlap between intense human activities with high natural levels of these elements. The natural high level is due to naturally enrichment of *As* and *Mn* in the Mignone River (Spadoni et al, 2005) and the Marangone Stream as well, while the human contribution is linked to the intense human activity in the area including the largest energy production site in Europe (Torrevaldaliga Nord coal-fired power plant) and the port of Civitavecchia for cruise traffic in the Mediterranean Sea (Piazzolla et al., 2015). The Marangone stream basin, located on the study area has abandoned pyrite, marcasite, and galena mines as well as marcasite mine waste deposits and galena small pits (Kreidie et al. 2011). This contamination is testified also by the high accumulation in *Paracentrodus lividus* as a consequence of bioaccumulation process (Scanu et al., 2015).

Recently large human activities regard works due to Civitavecchia harbour expansion (Table3.1), but also important use of soil (Table3.2) and river regimentation occurred in last decades.

In the coastal area of Civitavecchia, more than 7,500,000 m^3 of sediment were handled from 1995 to 2012. The 90% of this volume of sediment is linked to harbour expansion works while other 10% are of concern beach nourishment.

Municipality	Location	Project	Years	Type of intervention	Volume (m^3)
Civitavecchia	Civitavecchia harbour	Service and ferries docks	2012	Dredging and new docks construction	725983
Civitavecchia	Civitavecchia harbour	Colombo embankment extension	2012	Dredging and new docks construction	449530
Civitavecchia	Civitavecchia harbour	Dredging for harbour entrance	2010	Dredging activities	960000
Civitavecchia	Civitavecchia harbour	Completion of terminal containers	2009	Dredging and new docks construction	493000
Civitavecchia	Torre Valdaliga power plant	Coal pier construction	2008	Dredging activities	1223872
Tarquinia	Porto Clementino	Defence of reconstruction of shoreline	2004	Nourishment	570000
Civitavecchia	Civitavecchia harbour	Terminal containers	2001	Dredging and new docks construction	1100000
Tarquinia	Porto Clementino	Works of urgency	2001	Nourishment	11000
Civitavecchia	Civitavecchia harbour	Dredging for harbour entrance	1999	Dredging activities	1120000
Tarquinia	Porto Clementino	General project for the rebalance of the beach of Tarquinia	1999	Nourishment	22000
Civitavecchia	Civitavecchia harbour	Construction of commercial docks	1998	Dredging and new docks construction	902050
Tarquinia	Porto Clementino	General project for the rebalance of the beach of Tarquinia	1996-1998	Nourishment	59000
Tarquinia	Porto Clementino	General project for the rebalance of the beach of Tarquinia	1990-1995	Nourishment	49000
Future works					

Civitavecchia	Civitavecchia harbour	Construction of Large Masses Docks (DEGM)	2017	Dredging and new docks construction	5430000
Civitavecchia	Civitavecchia harbour	Construction of 2nd functional lot (2FL)	2018	Dredging and new docks construction	70000

Table3.1 List of works regarding harbour expansion

With the new Port Regulating Plan, the port of Civitavecchia has increased its commercial traffic and cruise passenger flow. Future enlargements to the harbour (i.e., the embankment extension and the realization of ferries and services docks (Decision 140/2007, 2008) will involve the handling of significant quantities of sediments (5,500,000 m^3) as observed in Table 3.1. The great human alteration of sedimentary fluxes in coastal area, makes the sedimentary dynamic, an important theme for the conservation of coastal natural ecosystems. In this context, the C-CEMS observation system has been operating since 2005 in the coastal area of Civitavecchia (Bonamano et al., 2016) in order to monitor the effects of human activities on the coastal ecosystems.

The future dredging and building activities for DEGM and 2nd FL realization directly interest surrounding coastal ecosystems including *P. oceanica* meadows object of the study (Fig.3.3).

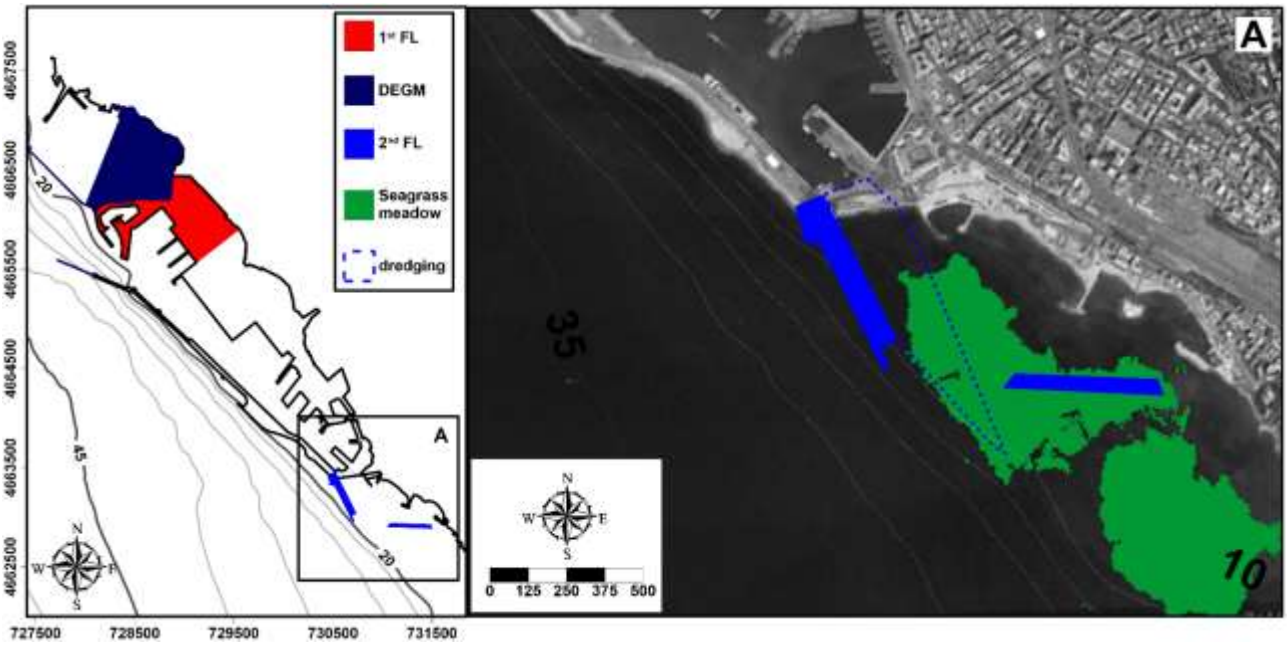

Fig.3.3 Harbor expansion works (left) and focus on 2nd FL that direct interest a portion of *Posidonia oceanica* meadow.

Furthermore, is provided an example of sedimentation flux alteration due to anthropogenic impact on the river basins of northern Latium (Scanu et al., 2015) coast. The hydrographic basins of northern Latium (Italy) between Sant'Agostino and Monte Argentario showed a general increase of artificial soil (6-10%) occurred in last decades with the exception of Marta basin where already in 1990, the natural soil use was less than 20% (Table 3.2).

River basin	**Soil use**	**% Coverage**		
		1990	**2000**	**2006**
Fiora	Artificial soil	54.94	54.94	65.29
	Natural soil	45.05	45.05	34.7
Marta	Artificial soil	83.24	85.4	83.06
	Natural soil	16.75	14.59	16.94
Mignone	Artificial soil	56.18	53.44	59.88
	Natural soil	43.81	46.55	40.11

Table3.2 Use of soil on river basins

The role of river regimentations for agricultural purpose linked to change in use of soil on the texture of continental shelf sediments on the northern Latium region was demonstrated by Scanu et al., 2015 placing in relation the changes on mass accumulation rate and texture of sediment core together to use of soil, river flow, rainfall and anthropic interventions on watercourse, last summarized in Table 3.3.

Anthropic impact on river basin			
Hydrographic basin	use	number	Flow (ls^{-1})
Fiora	Irrigation	55	1360.9
	Zootechnical	1	1
	Hydroelectric	3	2300
	Drinkable	9	2830
	Individual	4	25
	Fish farm	1	10
	Other use	2	10.6
Marta	Flow rate regulation	1	0
	Hydroelectric	5	11126
	Irrigation	1	2850
	Hydromechanic	1	2143
Mignone	Thermal	1	3750
	Irrigation	1	95
	Irrigation	1	30

Table3.3. Anthropic impact on river basins

Over the period considered, 1975-2011, the synergistic action of several factors has produced variations in the textural ratios of materials in the offshore area of the Fiora delta where is observed a dramatic decrease in the sandy fraction, which declined from 30% to about 7% over 36 years, with a total decrease of 400% (Fig.3.4). The qualitative and quantitative changes observed through the analysis of sediment core are consistent with the previously reported data that indicated a regressive trend in the coastline, which is still ongoing and particularly strong along the coast of Montalto di Castro and Tarquinia (Berriolo and Sirito 1985). Human interventions that lead to changes in the water flow have an indirect consequence on the transport of solid materials because reduction in the liquid flow will decrease the sustainability of the river (Vörösmarty 1997, Meybeck et al. 2005).

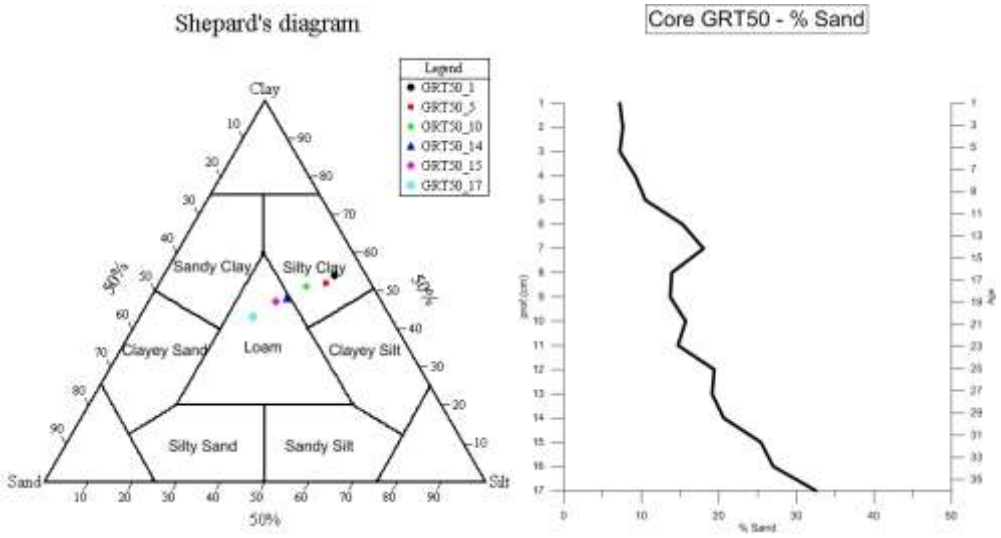

Fig.3.4 Shepard Diagram (left) and sand content evolution (right) in considered core sections

In general, an increase in the fine fraction is related to changes in the soil use (Brush 1989, Appleby and Oldfield 1983, Engstrom and Wright 1985) with a subsequent increase in the runoff (Brush and Davis1984). A likely influence on the average river flow could be reflected in a progressive decrease in the annual rainfall, which was particularly apparent in the Fiora basin. Even though the average flow of the Fiora River has decreased, the flood regime remained unaffected over the past 30 years justifying the mass accumulation rate (Fig.3.5).

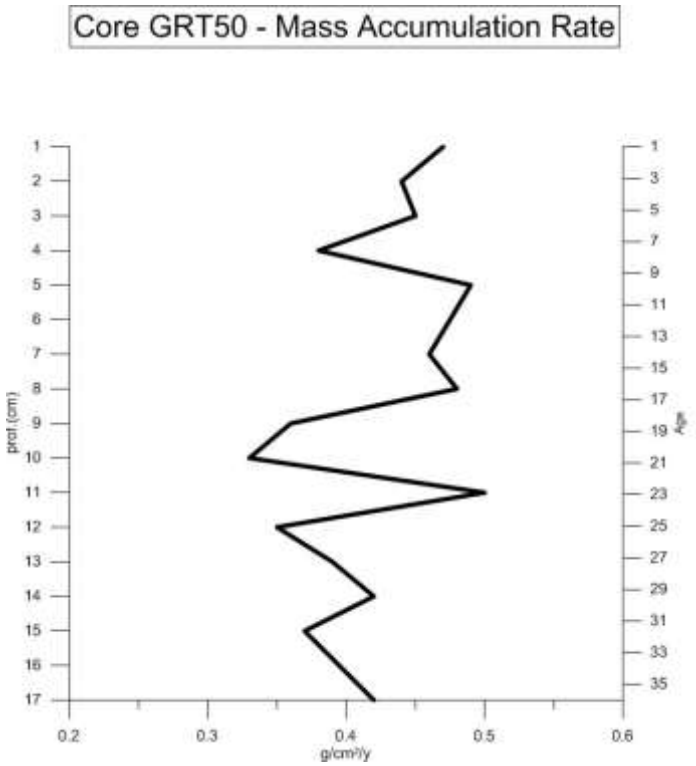

Fig.3.5 Mass accumulation rate of Mignone Core

In a broader context, it is known that precipitation in the Western Mediterranean is strongly influenced by cyclones and global atmospheric patterns, in particular during winter, by the North Atlantic Oscillation (NAO) (Hurrell 1995, Dai et al. 1997). The negative NAO state is responsible for positive precipitation anomalies over most land areas in the Mediterranean Region and the association between the structural characteristics of cyclones and NAO was demonstrated by Trigo et al. (2000). As observed by Maheras et al. (2001) and Trigo et al. (2000), the cyclones have decreased in the Western Mediterranean Sea and in the same way, the Mediterranean average winter precipitation has decreased during the last fifty years by about 20% with the decrease occurring mostly during the period 1970-1990 (Mariotti and Struglia 2002; Reale and Lionello 2013).

The rainfall analysis shows a negative trend in the Fiora and Marta basins, while in the Mignone basin, this trend is not significant. The data are therefore consistent with the general trend observed in the Western Mediterranean area. In this context, the anthropogenic impact may not be the only driving factor of the observed textural variations, although the strong impact of human activities (more than 60% of the artificial soil use) observed in the river basins and the relative variations over the last 16 years (Table3.2) added to the history of human intervention directly in the riverbeds (Table 3.3), could have produced the textural variation observed on the core samples. However, the acquired data suggest a progressive change in the quality of sediments arriving in the coastal area, with a clear trend for an increase in the pelitic percentage over the sandy fractions.

3.2. Coastal benthic ecosystem

3.2.1. Zonation of benthic communities

Conspicuous zonation patterns and strong environmental gradients have long attracted ecologists and physiologists to rocky shores (Benson, 2002). The topic of zonation occupied much of early marine ecology, and essentially involved the description of pattern and species occurrences along perceived gradients. Temperature, light, moisture, wave exposure and pressure are usually considered as mayor factors determining zonation patterns. Pérès (1982) described vertical zones as the "*depth interval of the benthic domain where the ecological conditions related to the main environmental factors are homogeneous…where the boundary between two adjacent vertical zones corresponds to a sharp change in the living assemblage composition*". With regard to the subdivisions inside the infralittoral, Riedl (1966) assigned a primary role to the quali-quantitative variations of the water movement along a bathymetrical gradient. According to these variations, different water masses may be recognised: they are well distinct and relatively homogeneous (zones) and are separated by discontinuities (critical depths). The zones recognised are five and the critical depths three (Fig.3.6).

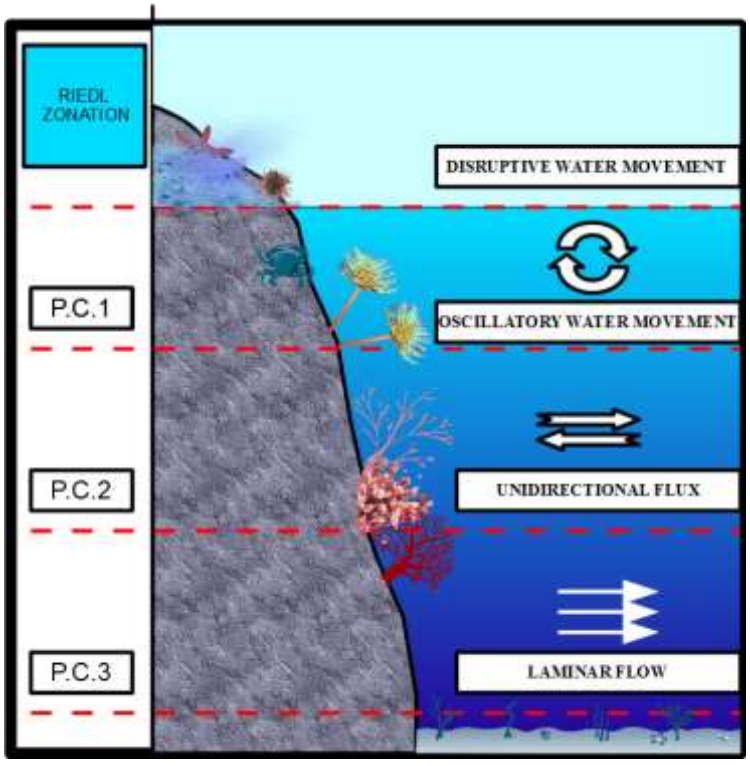

Fig.3.6. Riedl zonation sketch

The different zone of Riedl classification are:

- Zone of disruptive or lacerating water movement (+ 0.3 > 0 > - 0.3 m, with zero being defined as the "level of calm waters").

- Zone of water's edge, (-0.3 m and -1.4 m depth) with water movement multidirectional or multidimensional.
- Critical depth 1 (-1.4m /-15m): Zone of oscillatory water movement, in which the movements are both pendular and orbital;
- Critical depth 2 (-15m /-40m): Zone of uni-dimensional flow water movement, along the littoral slope.
- Critical depth 3 (-40m / -80m): Zone of bi-dimensional flow (laminar) water movement, corresponding to the continental plain;

Only the first and, usually, the second critical depth are in the infralittoral zone, while the third already belongs to the circalittoral zone. The extension of the hydrodynamic zones may be exactly calculated from wave parameters (length and height of the wave), even if influenced also by local topographic factors; in particular, the first critical depth is situated at a depth equivalent to two and half times the wave height, the second one at a depth equivalent to half a wave length. Since organisms respond to this hydrodynamic gradient, the different zones are distinguishable by biological criteria (Fresi and Cinelli, 1982; Boero et al., 1985). The direct action of water movement on the organisms is mediated by the granulometric sorting on soft bottoms (Fresi et al., 1983) and by the biotic conditioning of the substrate on hard bottoms (Abbiati et al., 1987).
The benthic organisms live close and strictly linked to seabed at least in one stage of the life cycle. Benthic communities, play a crucial role in the characterization and functionality of coastal marine ecosystems, since, for their persistence characteristics, are real biological memories that integrate separate events in time.
The biocenosis represent the grouping of living organisms (animal and plant), characterised by composition, number of species and individuals, that indicate stably average conditions of a given environment. Inside the biocenosis there are three kind of species: characteristics, companions and accidentals. The characteristic species can be exclusive and preferential and the companions can be indicators of environmental factors and ubiquitous. The critical depth 1 of Riedl zonation corresponds to Infralittoral zone of Pérès zonation where the main biocenosis are:
- Surface fine sand;
- Well sorted fine sand;
- Muddy sand of calm environment;
- Coarse and fine sand;
- Coarse sand and fine gravel affected by waves
- Corse sand affected by bottom currents;

- Gravel and pebble;
- Hard substrata: algae and *P. oceanica*;

Considering the depth and sedimentological features of the study site, placed between 5 and 10 meter depth, it can be theoretical referred to two kind of biocenosis: Biocenosis of coarse sand and fine gravel affected by waves (SGBV) (Fig.3.7) and Biocenosis of coarse sand and fine gravel affected by bottom currents (SGCF) (Fig.3.8).
The SGBV biocenosis is located in small bays, rocky coasts, moderate and high exposed to waves with sediment thickness of few decimetres.

Fig.3.7 Illustration of biocenosis "Coarse sand and fine gravel affected by waves" (SGBV)

This biocenosis is characterised by Archianellide *Saccocirrus papillocercus* and by *Nemerteo Lineus lacteus*, which populations are subjected to strong fluctuation induced by variation of environmental factors, in detail the local hydrodynamic. Together to these species there are Nemertini such as *Cephalothrix bipunctata, C. linearis, C. rufifrons*. There are also, *Spatangus purpureus* and *Donax variegatus* and Polichaete *Microphthalmus fragilis*; in addition, it was detected the presence of Nemertino *Linneus sanguinens*, which is not a characteristic organism of this biocenosis. This habitat is sensitive to mud concentration and water quality.
The biocenosis SGCF, in Mediterranean Sea is present between 3-4 m and 20-25 m depth, but locally can be found until -70m; thus, this biocenosis can be found also to Circalittoral zone. This biocenosis

is frequent in channel between island, area subjected to strong current and often in sand channels inside a *Posidonia oceanica* meadow. This habitat is strictly linked to intense currents, may changes during calm period and due to natural or anthropogenic changes. In this condition, can be presented quali-, quantitative variations in populations. The seasonal variations consist in abundance and replacement of the species. The sediment is characterised by coarse sand and fine gravels.

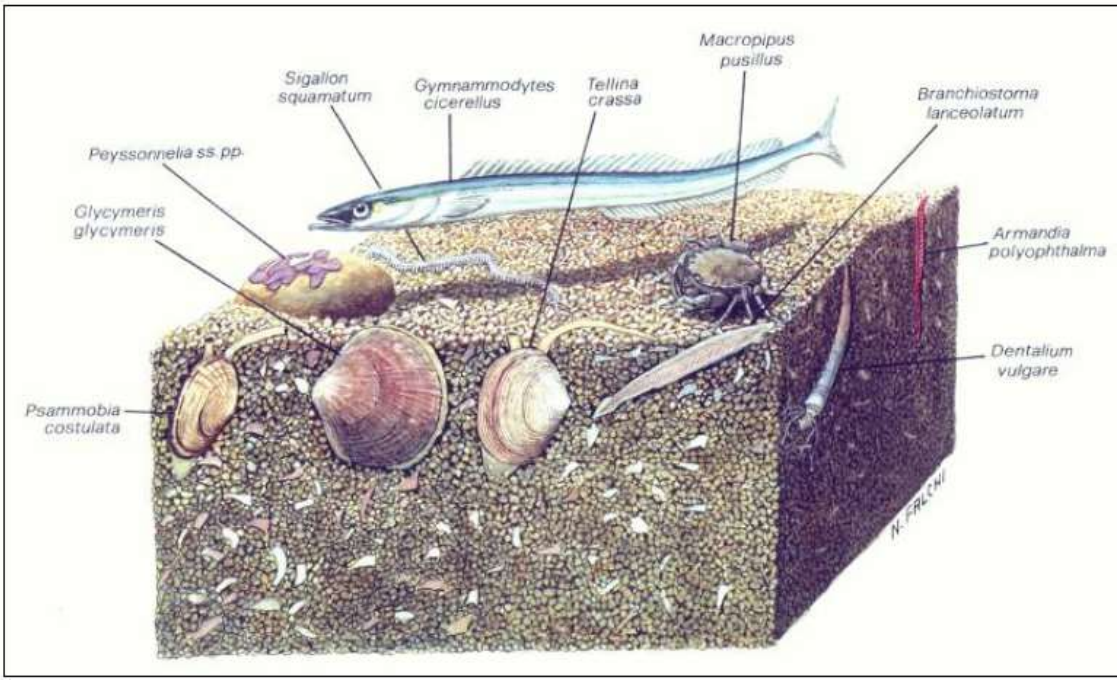

Fig.3.8. Illustration of biocenosis "Coarse sand and fine gravel affected by bottom currents" (SGCF).

The characteristic species are:

- Anellidae Polychaetes: *Sigalion squamatum, Armandia polyophthalma, Euthalanessa occulta (= Dendrolepis)*;
- Bivalve shellfish: *Venus casina, Glycimeris glycimeris, Laevicardium crassum, Donax variegatus, Dosinia exoleta;*
- Echinodermata: *Ophiopsila annulosa, Spatangus purpureus*;
- Crustacea: *Cirolana gallica, Anapagurus breviaculeatus, Thia polita*;
- Cephalocordata: *Amphioxus lanceolatus*;

This habitat is characterised by the presence of Anfiosso (*A. lanceolatus*), rare species in Mediterranean Sea. This habitat is sensitive to mud concentration in sediment and water quality especially regarding to suspended solid matter.

3.2.2. *Posidonia oceanica* meadow structure and role on hydro-, sedimentary dynamic processes

P. oceanica meadows are usually recorded from near the surface to 40 m depth (Boudouresque and Meinesz, 1982; Gobert et al., 2006; Boudouresque et al., 2012), but living plants have been found as deep as 48 m in particularly clear waters (Boudouresque et al., 2012). *P. oceanica* meadow architecture can exhibit continuous cover of the seabed or be organized in patches of various shapes, including strips parallel to the shoreline or cordons perpendicular to the shoreline (Borg et al., 2005; Boudouresque et al., 2012). Depth and nature of the upper (landward) and lower (seaward) limits are other important parameters characterizing meadow architecture (Montefalcone, 2009). Limit typology allows the limiting factors to be inferred: light attenuation causes a shaded limit, change in substratum characteristics (e.g. from sand to mud) a sharp limit, occurrence of bottom currents an eroded limit. The linkage between seagrass meadow development and sedimentary features of the seafloor has been the focus of several studies (e.g. Fonseca, 1996; Madsen et al., 2001; De Falco et al., 2003; Boudouresque et al., 2012). However, recent investigations have demonstrated that sedimentary features alone are poor determinants of marine species distribution (Hemer, 2006; Post et al., 2006; Ryan et al., 2007). In shallow underwater environments, local geomorphology, currents and wave exposure play a very significant role in controlling habitat distribution, particularly for seagrass meadows (Short et al., 2002; Koch et al., 2006; Ryan et al., 2007).

The growth dynamics of *P. oceanica* meadows and sedimentary processes are linked by complex feedback relationships (de Boer, 2007), which have been qualitatively observed since the 1980s (Boudouresque and Jeudy de Grissac, 1983). The plant is capable of adapting its growth rate and inclination of its rhizome branches to the rate of sediment deposition.

Rhizomes can grow either vertically or horizontally, thus showing erect (orthotropic) or prostrate (plagiotropic). The orthotropic rhizomes mainly develop in crowded situations, whereas the plagiotropic rhizomes are more typical of areas undergoing colonization (for instance, at the borders of clearings). Progressive silting and the alternation of the two types of rhizome growth result in a typical terraced formation called ‘matte’, consisting of interlaced remnants of roots, rhizomes and entangled sediment (Giovannetti et al., 2008). More than an analogue of terrestrial soil vegetation, the matte may also be considered a form of bioconstruction (Bianchi, 2001). The sediments accumulating inside meadows generally show a high percentage of biogenic carbonate particles produced by the biota associated with the seagrass ecosystem, such as coralline algae, foraminifers, gastropods, bivalves, serpulid polychaetes, bryozoans, and echinoids (Fornós and Ahr, 1997). The carbonate sediments associated with *P. oceanica* can be transported inshore, thus affecting the composition of adjacent beach sediments. This was observed in the Balearic Islands (Gómez-Pujol et al., 2013), in western Sardinia (De Falco et al., 2003), and in pocket beaches of southern Corse. In

this respect, current trends in seawater acidification (Bianchi et al., 2012) probably represent a threat to these processes in the Mediterranean Sea. In comparison with other Mediterranean coastal benthic ecosystems, carbonate production in meadows, evaluated by sampling leaf epiphytes only, is low (69–157 g CaCO3 m^{-2} a^{-1}; e.g. Canals and Ballesteros, 1997). Estimates based on the rhizome growth rate of meadows located in the northern sector of the Gulf of Oristano (western Sardinia, Italy) indicate that carbonate production is in the range of 390 to 1147 g CaCO3 m^{-2} a^{-1} (De Falco et al., 2008a). These values are amongst the highest for seagrass ecosystems (Gacia et al., 2003) and lay within the range calculated for coral reefs (Bianchi, 2001). *P. oceanica* meadows also colonize sediments of terrestrial origin (see for instance Cavazza et al., 2000; De Falco et al., 2008a) and rocky substrates (De Falco et al., 2003). The sedimentary depositional environment seems influenced by the spatial distribution of wave energy. For instance, biogenic carbonate reefs associated with *P. oceanica* meadows develop in sheltered areas characterized by low wave amplitude. In the exposed locations, meadows colonize relict siliciclastic sediments or rocky substrate, with a lower rate of carbonate particle deposition (De Falco et al., 2008a, 2011) and an absence of thick matte development.

P. oceanica meadows usually occur within the most dynamic region of the seafloor (Boudouresque et al., 2012), strongly influenced by waves and currents. Referring to low energy beaches, Basterretxea et al. (2004) suggested that meadows influence the relative stability of the beach by controlling the local morphodynamic domain (i.e. the distinctive type of beach produced by the topography, wave climate and sediment composition) and by constraining sediment transport. Only during episodic storm events, when nearshore energy is increased, is energy supply sufficient to promote significant alongshore and/or cross-shore transport. Experimental evidences (Stratigaki et al., 2011; Infantes et al., 2012; Manca et al., 2012) have confirmed that meadows are effective at reducing wave energy, especially for waves with low energy and small amplitude influencing bottom roughness and flow drag. Under these conditions, meadows are able to enhance sediment stabilization relative to unvegetated patches of the seafloor. However, under high energy/large amplitude wave conditions, *P. oceanica* is less efficient at reducing wave energy, and thus does not offer significant beach protection against erosion during storms (Manca et al., 2012). Recognizing the influence of seagrass meadows on nearshore hydrodynamics, recent research has also demonstrated a strong control of nearshore hydrodynamics on the morphology and bathymetrical distribution of seagrass meadows themselves (Infantes et al., 2009; Vacchi et al., 2010, 2012, 2014b). The position of the landward, or upper, limit of *P. oceanica* meadows is a response to wave energy showing that an increase in wave energy is related to a decrease in *P. oceanica* cover, and that above a threshold wave energy, no seagrass is present.

3.2.2.1. *Posidonia oceanica* leaf litter

Seagrass beach-cast leaf litter deposits, called 'banquette' in Mediterranean Sea, (i.e. beached necromass sensu Boudouresque et al., 2015) are common in many coastal areas around the world (De Falco et al., 2008b; Mossbauer et al., 2012; Gómez-Pujol et al., 2013). This organic material can occur in large amounts and can play a role in the geomorphic evolution of beaches under normal wave conditions (i.e. not under storm conditions), in particular on low energy beaches (Jackson et al., 2002). Formation of seagrass berm deposits depends on the availability of leaf litter on the upper shoreface (Simeone and De Falco, 2012; Gómez-Pujol et al., 2013). *P. oceanica* sheds leaves mostly in late summer and autumn (Mateo and Romero, 1996), and beach-cast leaf litter is part of the material exchanged among submerged beach section, the emerged beach and dunes. Banquettes are wedge-shaped structures, which range from a few centimetres to several metres thick. Similarly to sediment berms, banquettes can be considered features resulting from the accumulation of seagrass necromass (leaves and rhizomes) and sediments at the extreme landward point of wave influence (Simeone and De Falco, 2012). On sheltered beaches (Fig. 3.9a), the presence of leaf litter on submerged beaches is related to the proximity of *P. oceanica* meadows to the shoreline, as for other seagrasses and terrestrial plant species colonizing the foreshore (Jackson et al., 2002; Simeone and De Falco, 2012). On exposed beaches (Fig. 3b), leaf litter can be transported as floating material during storms and can be deposited, when the storm decreases in energy, far from the meadow from which the leaf litter originates (Simeone and De Falco, 2012). On embayed beaches, leaf litter deposited on the seafloor can remain enclosed by headlands for a long period of time (from days to seasons), and this can promote repeated cycles of deposition and erosion of seagrass berms on this beach typology (Simeone et al., 2013a, 2013b). In addition, leaves and fragments of *P. oceanica* transported inland by winds and trapped by pioneer plants can enhance sand moisture content, favour nutrient uptake by plants (Cardona and Garcia, 2008; Del Vecchio et al., 2013), and thereby can have a positive effect on the accretion of the foredune.

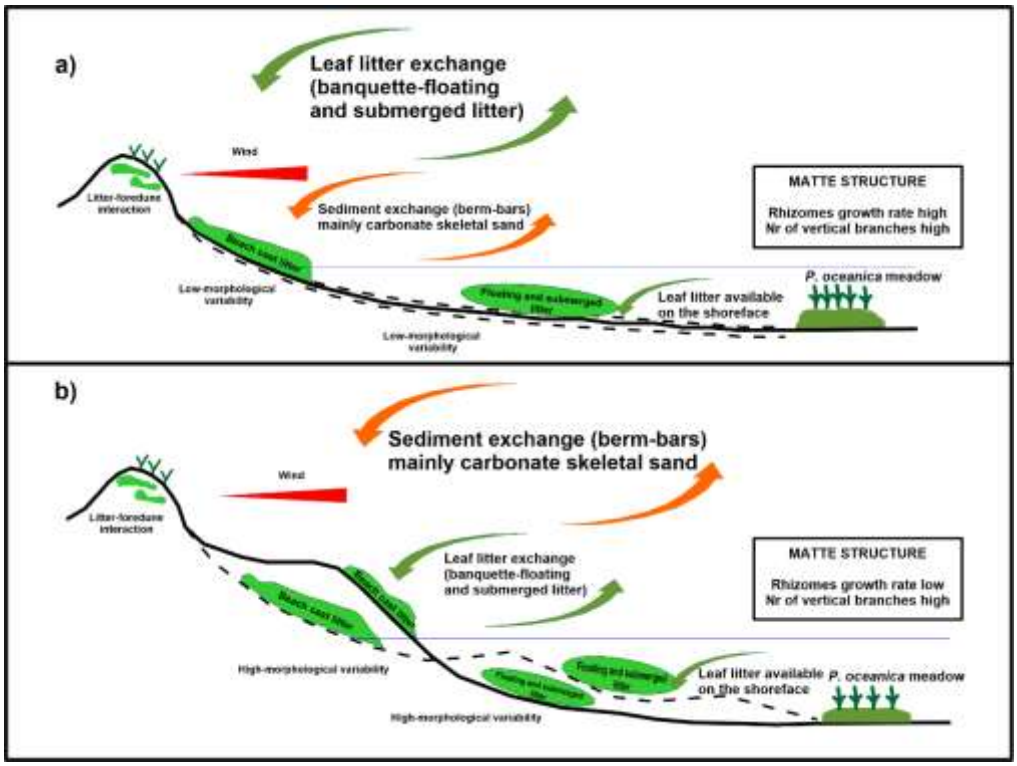

Fig.3.9. Relationship between *P. oceanica* leaf litter, sediment exchanges and beach morphology in (a) sheltered and (b) wave exposed environments.

Although banquettes are often suggested to play a role in beach protection from erosion (Boudouresque and Jeudy De Grissac, 1983; Mateo et al., 2003), very few studies have been published on this issue. On low energy and short fetch beaches, beach-cast leaf litter can resist waves and be effective in suppressing wave run-up and limiting beach change (Nordstrom and Jackson, 2012). In contrast, Gómez-Pujol et al. (2013) found that seagrass berms were eroded during swell conditions between two consecutive storms on a semi enclosed beach in the Balearic Islands. Under such conditions, the capacity of these features to protect beach from erosion during storms is thought to be negligible, because no interaction between waves and beach-cast leaf litter can occur. In other Mediterranean regions, the residence time of seagrass berms on beaches is higher than the time interval between storms (Simeone and De Falco, 2012; Simeone et al., 2013a). In these cases, some proportion of storm energy may be dissipated by the destruction of the banquettes.

3.2.3 Fauna assemblage and trophic role of *Posidonia oceanica*

P. oceanica is a vascular marine plant that supports highly complex and productive ecological systems (Den Hartog, 1977; Pergent and Pergent-Martini, 1991) considered a “mayor carbonate factory” of the Mediterranean inner shelf (Canals and Ballesteros, 1997; Fornos and Ahr, 1997, 2006; De Falco et al., 2008, 2011; Mateu-Vicens et al., 2012).

It was studied the architectural role of the seagrass canopy in the structuring of rich faunal assemblages (Bell and Westoby, 1987; Klumpp et al., 1992), and it has been widely demonstrated that animal abundance in vegetated habitats is greater than in unvegetated areas, especially when compared with bare soft bottoms (Stoner, 1980; Young and Young, 1982; Hicks, 1986). This pattern has been due to both increased food supply and reduced predation risks (Heck et al., 1989; Ferrell and Bell, 1991; Stoner, 1980; Heck and Orth, 1980; Lewis and Stoner, 1983; Bell and Westoby, 1986 a, 1986 b; Hall and Bell, 1988) and to the effect of the "structural complexity" of the seagrass canopy and plant "architecture" or configuration (Orth et al., 1984; Virnestein and Howard, 1987; Stoner and Lewis, 1985). Plants provide additional microhabitats and structural and functional descriptors of seagrasses (shoot density, or leaf surface and biomass), strongly affects the composition and abundance of the fauna associated with seagrasses. Many relationship were found between the meadow structure and the associated organisms, more evident for epifauna associated to the leaf stratum, than for the infauna, which are more or less buried in the sediment (Howard et al., 1989). The role of the *P. oceanica* on sedimentation processes by trapping suspended particles and limiting sediment resuspension, have an effect also on larval emigration to other sites (Eckmann, 1987) favouring larval settlement within the meadow. The vertical gradient of shoots coupled to the vertical change of plant features correspond to a variation of fauna assemblages and trophic characteristics. On the basis of the work of Mazzella et al., 1992 a general conceptual model of the vertical structure of *P. oceanica* assemblage is shown in Fig.3.10.

Along the leaf there is a zonation of epiphytic communities according to the blade-age gradient. In the basal portion of leaf (meristematic area or young leaf tissue) bacterial and diatom coverage is dominant. In the median part (age up to 100 days) encrusting macroalgae red and brown dominate and in the apical portion (300 days) macroalgal layer and earlier assemblages are present (Wittman et al., 1981; Novak, 1984; Buia et al., 1989). The compositional sequence of environmental parameters may influence the community structure. At regard of algal flora, the *Corallinaceae* family and brown alga *Myrionema orbicularis* are the most frequent. The infaunal communities of both living and dead *Posidonia* "matte" are determined by a mosaic nature of substrate, supporting species with different ecological requirements (Harmelin, 1964; Willsie, 1983). The fauna assemblage is dominated by polychaetes as to both species richness and biomass. Rhizome epifauna is exposed to a less stressful and variable environment than that of leaf stratum (Pansini and Pronzato, 1985; Gambi et al., 1989), while the great abundance of microhabitats again supports forms with different ecological requirements. The detrital litter, produced by dead *Posidonia* leaves is deposed at rhizome level and allows the development of rich fauna dominated by echinoderms which *holothurians* play a central role in reworking surface sediment. Epifauna of leaf stratum is dominated by *hydroids* and

bryozoans which show a clear zonation and succession in growth form related to depth and position along the leaf (Boero, 1981; Fresi et al., 1982; Balduzzi et al., 1983; Casola et al., 1987).
Communities of vagile fauna of the leaf stratum show several patterns linked to environmental factors such as water motion and temperature. Vagile leaf macrofauna is dominated by plant feeders mainly represented by micro- and meso-grazers (Hay et al., 1987). The herbivore group are influenced by patterns of algal ephiphytes. *Posidonia* beds host a diversified fish population where more than half is composed by resident species (Bell and Harmelin-Vivien 1982). *Labridae* is the most common family that populate prairie which are carnivores, mainly on crustaceans (Bell and Harmelin-Vivien 1982; Khoury, 1984). Moreover, the herbivore *Sarpa salpa* can be an important component of total fish biomass (Velimirov, 1984; Verlaque, 1985; Francour, 1990).

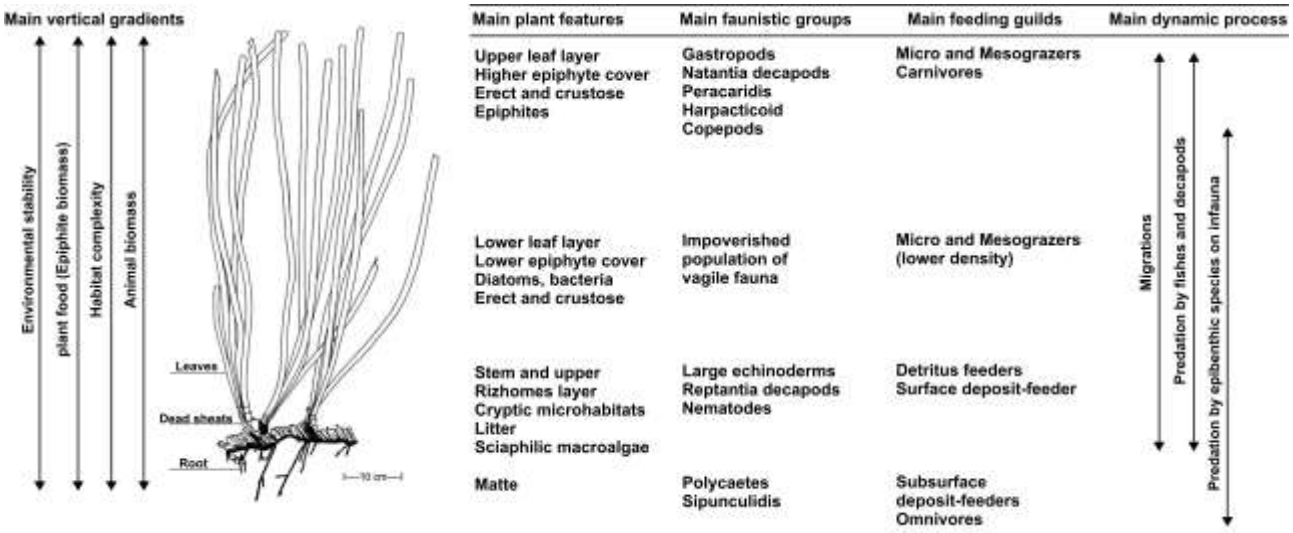

Fig.3.10 Conceptual scheme of *P. oceanica* ecosystem vertical structure (Mazzella et al., 1992)

"The most striking feature of the *P. oceanica* ecosystem appear to be the "conservative" role of the plant itself with respect to the other components. Its high energy and biomass are only minimally available for direct trophic interactions, although they become of mayor importance for stabilizing the system" (Mazzella et al., 1992). The trophic role of *P. oceanica* is performed by vegetal epiphitic communities on seagrass leaves which supports most of the faunal seagrass community. Although *P. oceanica* is utilised by consumers via grazing, mainly as a consequence of its poor nutritional value and high lignocellulose content (Ott and Maurer, 1977). Only few species of consumers are able to exploit the photosynthetic leaves (e.g. *Idotea baltica, Paracentrotus lividus, Sarpa salpa* and some decapod species) (Ott and Maurer, 1977; Mazzella et al., 1992). In contrast, it was demonstrated that the main transfer route of seagrass organic matter is the detrital pathway. *P. oceanica* detritus may be exploited as a carbon source by small detritivore invertebrates, and above all seems to be exploited

as a nitrogen reservoir by both bottom and water column consumers determining benthic–pelagic coupling (Vizzini et al., 2002). The food web structure of *P. oceanica* analyised at Stagnone di Marsala, by Vizzini et al., 2002, (Fig.3.11) gives a clear evidence about the key role of sedimentary process of organic matter at the basis of the ecosystem structure and also on its evolution.

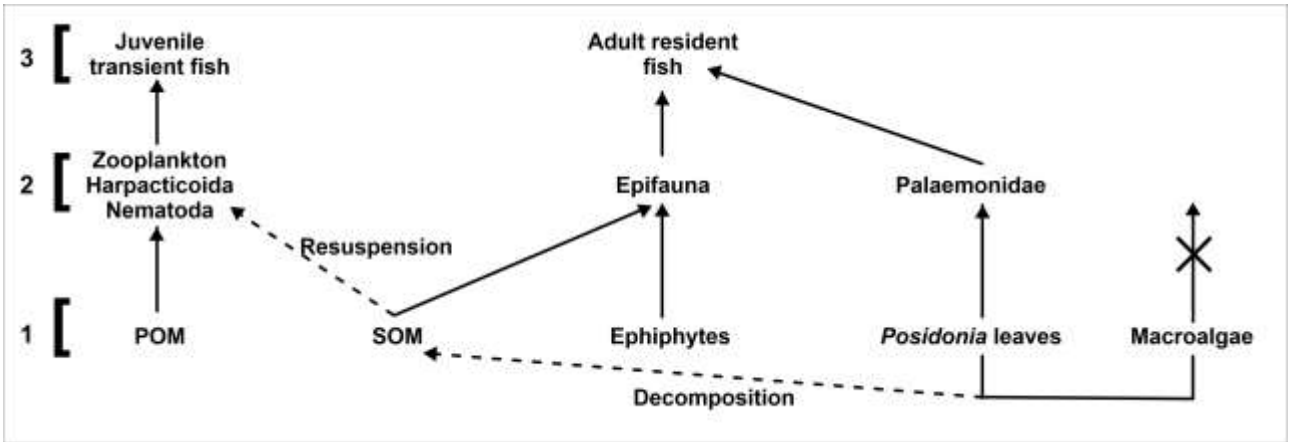

Fig.3.11 Food web structure in a *P. oceanica* meadow of the Stagnone di Marsala as revealed by δ13C and δ15N analysis. Dot Arrow: physical or chemical events. Solid arrow: organic matter fluxes. SOM: sedimentary organic matter. POM: (Vizzini et al.,2002).

4. Experimental evidence of the effect of a *Posidonia oceanica* meadow on particle resuspension and deposition in coastal shallow water and the relationship between particle sedimentary dynamics and fauna assemblage

4.1. Introduction

The study of vertical sedimentation flux over a *P. oceanica* meadow is herein presented as the result of an investigation on the role of seagrass in deposition and resuspension processes in a shallow-water coastal area. In addition, we study the relationship between the sedimentary dynamics of organic and inorganic matter and the seasonal variation of fauna assemblage structure associated to the seagrass.

4.2. Study site

The study was conducted along a coastal stretch located in the centre of the Gulf of Civitavecchia between the port breakwater in the north and the Pecoraro jetty in the south (Fig.4.1b); data was collected at a depth of 7 m in front of Lega Navale (LN) (Fig4.1c). The study area is located in the northern Latium coast (Italy) of Central Tyrrhenian Sea, which is characterized by a spring tidal range of 0.3 m and is exposed to waves mainly from the SW and to southerly and northerly winds. The wave intensity exhibits a seasonal fluctuation with a maximum during the winter and autumn and a minimum in the summer. Most of the wave energy is constrained in a wave power range of 5 – 40 kWm-1 that corresponds to waves with a significant wave height (*Hs*) of about 1.5 – 3 m and a peak period (*Tp*) of 6 – 9 s (Paladini de Mendoza et al., 2016). On the basis of rainfall records of the last 12 years (2003-2016) retrieved from the Hydrographic Service of Latium Region (http://www.idrografico.roma.it/), the average annual precipitation in Civitavecchia is 481±163 mm and is subjected to seasonality with a maximum intensity in the autumn (225±45 mm) and a minimum intensity in the summer (59±34 mm).

The coastal morphology is characterized by a dominance of terraces where the irregular seabed is composed by rocky outcrops and natural depression covered by sediments. Along the coast, there are only several minor streams that originate from the nearby Tolfa Mountains, while the largest river (i.e., the Mignone river) is located 11 km north of the study site. The sediment contribution from the Mignone river does not influence the study site because sediment transport along the shore is oriented northward (Anselmi et al. 1976, Berriolo and Sirito 1985, Noli et al. 1996). In the examined coastal site (Fig.4.1b), the coverage of *P. oceanica* consists of two wide areas (Special Area of Conservation, SAC, according to EU Habitats Directive) that extend from approximately 10 m to 30 m in depth. In the experimental sites (Fig.4.1c), the *P. oceanica* meadow appears from a depth of 3 m, and the

architecture exhibits a nearly continuous cover with the presence inside the meadow of several sand patches of various dimensions. Moving from northwest to southeast parallel to the shore, the meadow is interrupted by a wide sand channel, which is a transitional zone between the rocky outcrops and the meadow (Fig.4.1c).

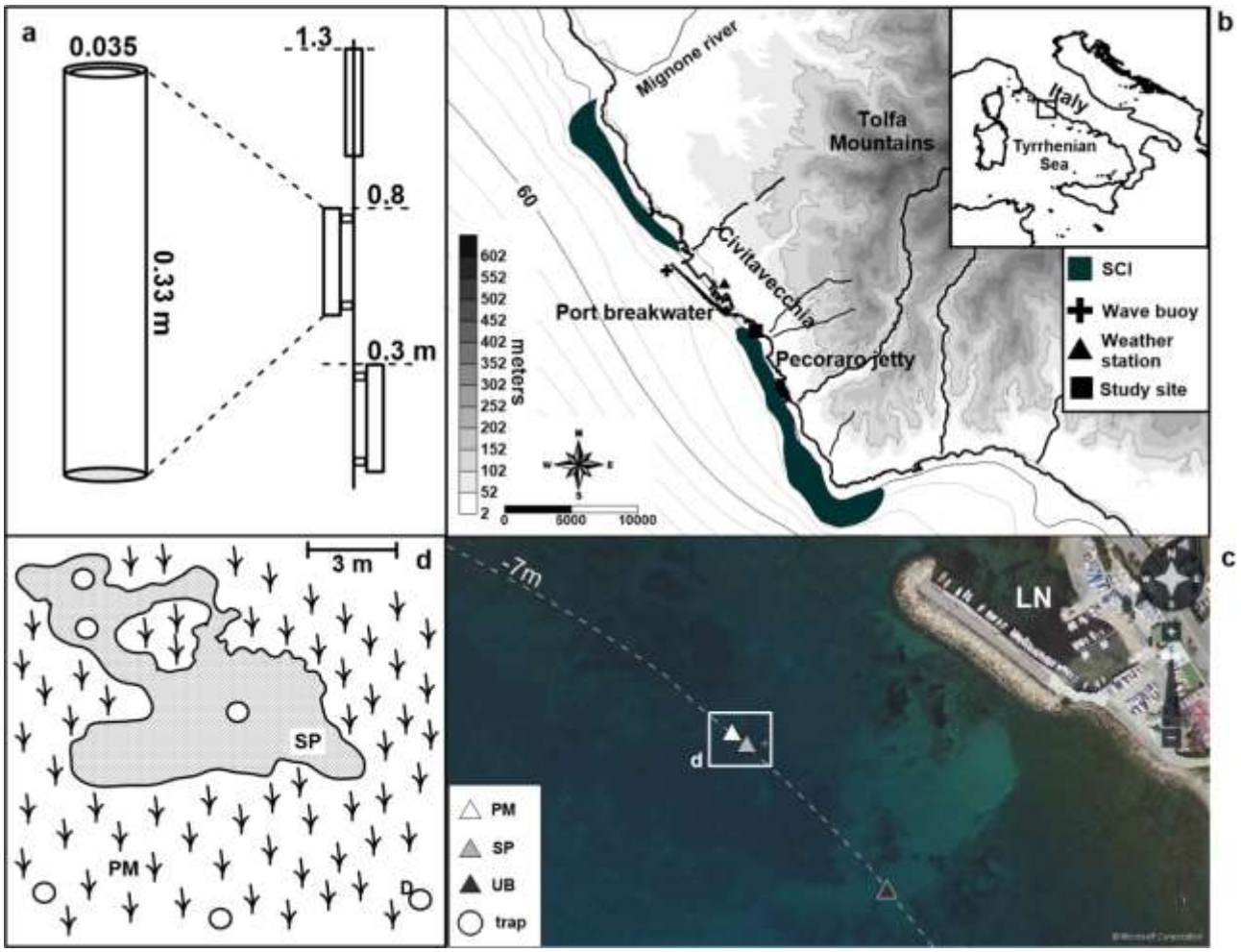

Fig.4.1 a) Sketch of traps and geometry of their deployment; b) extended study area showing the location of the Site of Community Importance (SCI), wave buoy, weather station and study site. The mainland topography is the result of Digital Elevation Model (DEM) of Tarquini et al. 2012. c) Aerial view of study site with the position of the stations; LN is the Lega Navale building. d) Sketch of sand patch configuration, position and distance of the steel rods where traps were mounted.

4.3. Methods

4.3.1. Experimental design and analysis of particle sedimentation flux

Three measuring stations (Fig.4.1c,d) were located at three different sites, respectively, on the *Posidonia* meadow (PM), on the sand patch inside a meadow (SP) and on the unvegetated sandy bottom (UB). The distance between the stations are 15 meters between PM and SP, whereas UB is approximately 150 meters further away from the others.

The total sedimentary flux was monitored in PM, SP and UB using sediment traps from October 2015 to December 2016. The traps were constructed using polyethylene cylindrical tubes with an opening diameter of 0.035 m and a length of 0.33 m; this provided an aspect ratio of 9.4, which is near the optimal aspect ratio suggested for minimizing the over- and under-trapping (Gardner 1980; Hargrave and Burns 1979). The traps were mounted on a steel rod at three elevations from the seabed (i.e., 0.3 m, 0.8 m and 1.3 m) (Fig.4.1a) in three replicate units located within a radius of approximately 3-6 meters. Considering previous studies (Gacia and Duarte 2001), at the same distance from the bottom, different frames could be considered as replicate units.

Before the installation, the traps were filled with surface water; then, they were covered with caps, which scuba divers removed at the start of survey.

The experiment involved 11 surveys extended over a year; the surveys were planned on the basis of weather conditions and seasonality as well (Table 4.1). Each survey lasted for a period ranging between 2 and 17 days. Bed sediments were sampled seasonally at the PM and SP stations using a 0.20-m diameter corer during October and December 2015 and March and July 2016.

The contents of the sediment traps were collected in two ways depending on the amount of the trapped material: for trapped content lower than 1 g, the material was collected by filtration onto pre-combusted 47-mm GF/F filters; for trap content greater than 1 g, the wet sediment was placed into a pre-weighed aluminium tray. In both cases, the collected material were inspected for active swimmers that were removed if present (Michaels et al. 1990) and dried in an oven for a minimum of 24 hours at 60 °C until a constant weight was obtained (precision of 1 mg). Grain-size analyses were carried out on the bed-sediments samples and on trap samples recovered after surveys characterized by storms (this was the only condition that permitted the trapping of enough material for determination). The grain-size analyses were carried out using a Malvern Mastersizer 2000 laser diffraction particle size analyzer. Sediments were sieved using a 2-mm mesh in order to separate the gravel biogenic component from the sand and mud. Only the latter fractions (> 2 mm) were analysed. Grain-size data are represented using the Krumbein's φ notation, and the main components were computed following the Udden-Wentworth scale. The statistical parameters of the grain size—that is, mean size (*Mz*), sorting (*s*) and skewness (*Sk*)—were calculated following Folk and Ward (1957).

The load of the traps was converted in flux (g $m^{-2}d^{-1}$) considering the geometry of the traps and the duration of the survey. According to Pejrup et al. (1996), the total sedimentary flux at the bottom (*Dr*) is the sum of resuspended material and the natural settling material (primary). Following the methodology of the same authors, the resuspension flux (*Fr*) can be fitted by an exponential function where the load declines exponentially with increasing height above the sediment source. Fr can be estimated as the intercepts at the sediment surface of the fitted exponential relationship between the

downward depositional flux and the height of the sediment traps above the bottom. As a general rule, primary flux can be obtained by considering the vertical asymptotic value of the exponential function. The availability of the method is ensured when resuspended flux does not involve the upper trap. Otherwise, when resuspension is the dominant effect on the sea-bottom, as it may occur during extreme storms, the contribution of the primary flux on the total sedimentary flux can be considered to be negligible.

Survey	Date	Cumulative rainfall (mm)	Wind max speed (ms^{-1})	Wind direction	Max wave power (kWm^{-1})	Wave direction	Site
1	25-30/10/15	34	12.53	SE	6.39	SE-SW	SP PM
2	16/11-3/12/15	8.6	22.39	S-NE	93.77	SW	SP PM
3	11-20/03/16	2.3	17.43	N-NE	4.79	SE	SP PM
4	21/04-5/5/16	24.8	20.46	N-SE	26.25	S-SE	SP PM
5	8-10/6/16	34.5	9.46	SE	0.93	S-SW	SP PM
6	1-4/7/16	0.1	9.38	SE	6.29	S-SW	SP PM
7	20-22/7/16	0	10.41	SE	0.41	N-S	SP PM UB
8	30/8-1/09/16	7	7	N	0.13	N-S	SP PM
9	12-20/9/16	50.2	16.8	SW	13.87	S-SW	SP PM UB
10	17-19/10/16	0.7	12.21	SE-SW	0.39	S-SW	SP PM UB
11	1-4/12/16	0	8.6	SE	1.01	SW	SP PM UB

Table 4.1 Timeline and characteristics of surveys

The *P. oceanica* meadow was analysed at the depth where the traps were placed by defining the percentage of cover of seagrass and other type of substrata as well as seagrass density and biometry of leaves.

For percentage cover, we used the *LITs* methodology (Line Intercept Transects) of Bianchi et al., 2004 and Montefalcone et al., 2007. During May 2016, three sampling stations were chosen and in each station, four transects, each of 10-m length (Marcos-Diego et al., 2000), were positioned; transects extended radially in opposite directions from a fixed point in the middle of the sampling station. This analysis was carried out at the PM station and at two points respectively positioned 50-m north and south from the PM station and always at the same depth (i.e., 7 m). Plant and substrate cover were assessed along each transect. A centimetre-marked line was laid on the bottom along

which a scuba diver recorded the occurrence of live *P. oceanica* and the nature of the substrate (i.e., sand, rock or dead matte). The percentage cover was obtained by dividing the length of each substrata by the total length in order to provide information of the amounts of different substrata and live *P. oceanica* that covered the sea bed.

The biometry of leaving leaves (foliar shoots) was determined seasonally on 10 shoots according to Giraud (1977); the Leaf Area Index (*LAI*, leaf surface area per shoot, m^2m^{-2}) was also calculated. The shoot density was evaluated at the PM station by counting the number of shoots using 0.4×0.4 m^2 standard quadrates (10 runs). In addition, we collected photographs and measurements of the dimensions of the sand patch in order to record its evolution throughout the year.

Meteorological data during sampling periods were recorded by a weather station (i.e., wind speed, direction and precipitation) and a wave buoy (i.e., significant wave height, peak period and direction). The wave buoy and weather station were located in proximity of the study site (Fig.4.1b). The wave buoy data were used to determine the bed shear stress and predict the theoretical transport capacity of waves useful for the interpretation of trap results. The formulations used for bed shear stress come from Komar and Miller (1973), where, following linear wave theory, the maximum horizontal velocity at the bottom produced by waves associated with elliptical motion of orbits is

$$U_x = \frac{\pi H}{T \sinh(2\pi d / L)} \quad (1)$$

where H is the wave height, T is the wave period, d is the depth and L is the wave length.

The bed shear stress (τ_0) is given by:

$$t_0 = 0.5 C_f r U x^2 \quad (2)$$

where Cf is the dimensionless drag coefficient (0.004, according to Jonsson, 1966), and ρ is the water density.

The bed shear stress was computed on the time series recorded by the wave buoy, we subsequently was imposed a threshold of motion considering the value proposed by Berenbrock and Tranmer (2008) for fine silt that is, the finest significant grain-size class featuring the local sediments. The transport capacity (Ct) of waves during each survey was determined using a filtered time series (by threshold) through the following equation:

$$Ct = \int_{t_0}^{t_{0+1}} \tau_0 dt \quad (3)$$

where t_0 is the start time of the filtered time series and t_{0+1} is the end time of the filtered time series. Pearson correlation coefficient were determined to define correlations between meteorological forcing and sedimentation flux. The temporal changes of the *P. oceanica* meadow descriptors were analysed using ANOVA for repeated measurements. The statistical significance on differences about depositional rates and bed sediment composition over the time and between stations was defined by non-parametric tests, includign the Wilcoxon Signed Ranked test and the Kruskal-Wallis test (Hollander and Wolfe 1999).

4.3.1.1. Organic matter determination

Organic matter content was determined from the traps and bed-sediment samples using a mass-loss technique referred to as loss on ignition (LOI). The samples were ignited at 550 °C for 4 h, left to cool inside the furnace, then placed in the dessicator and weighed. The mass of the dried and ignited sediment was recorded with a precision of 1 mg using an analytical balance. The loss on ignition of the dry mass of the sample is expressed as a percentage calculated from the dry mass of sediment, the mass of crucible and the mass of the residue of ignition. The weight loss should then be proportional to the amount of organic carbon contained in the sample; Dean (1974) showed a strong correlation between LOI at 550 °C and organic carbon content determined chromatographically. Organic matter flux was compared with the total sedimentation flux using Pearson's correlation; this statistical test was also applied to define the role of weather forcing on organic matter concentration and flux. The Wilcoxon Signed Rank and Kruskall-Wallis tests were applied to compare the sedimentation flux of organic matter at different stations.

4.3.2. Estimation of water movement on the benthic boundary layer

The flow as a proximity of the bottom interacts with the seabed roughness that causes a drag force that reduces the flow. Aquatic flow with submerged vegetation can be patterned on a mixing layer rather than a boundary layer. It was demonstrated that the drag force on the vegetation produce a vortex that dominates the vertical transport of momentum and produce the waving of vegetation which was called "*monami*" by Akerman and Okubo (1993). This vertical transport in the generated mixing layer is more efficient than in boundary layers (Ghisalberti and Nepf, 2002). The interaction between the flow and vegetation is complex, and with respect to the unvegetated seabed, the processes

in presence of vegetation are not simply a passive reflection of the flow structure (Ghisalberti and Nepf, 2002).

Exposure to water movement has been measured in different ways by submarine benthonologists; in the present research, we used the method of "plaster dissolution" described by Muus (1968) and Doty (1971) and used by various authors (Russo, 1977; Bailey-Brock, 1979; Pansini and Pronzato, 1982; Boero and Fresi, 1986). The plaster dissolution method measures weight loss during field exposure of plaster balls or cubes (Muus, 1969; Doty, 1971). The plaster is lost mostly by diffusion, and the water movement enhances the weight loss. Although not accurate, this method is useful for a first approach to obtain estimates for future, more precise measurements. To make the plaster balls, we followed the method proposed by Gambi et al., 1989 that used "*Scagliola*" as a substitute for Plaster of Paris (used by Doty and Muus), which is not readily available in Italy. The *Scagliola* is a di-hydrate sulfate ($CaSO_4$ $2H_2O$) that is crushed to a very fine powder. The *Scagliola* was mixed with fresh water in a proportion 50 gr x 45 cc. Plaster balls were formed from a tennis ball mould. Before the plaster hardened, a thin steel bar was placed inside each ball. We placed two steel bars in the opposite sides of the tennis ball, and when the plaster was hardened, the ball was cut in two parts. After removal from the mould, the semi-balls were dried for 3 days or longer on a laboratory bench, and the bottoms were sanded until the semi-balls had uniform weight within a batch (within 1.5 g). Balls each had a diameter of 5.4 cm and an average weight of 25.5 +/- 1.07 gr. The balls had to be calibrated to evaluate the normal plaster diffusion, and considering that the salinity in the range of 20–40% did not greatly affect dissolution (Thompson, 1994), the calibration was performed by placing plaster balls (4 runs each experiment) in a seawater tank at different temperatures (10–15–20–25°C) for different times of exposure in a range of 6–89 hours. K1 (calibration coefficient) was then calculated using the following equation:

$$K_1 = Mc\frac{Te}{Tc} \tag{4}$$

where *Mc* is the weight loss during the calibration time (*Tc*) and *Te* is the time of field exposure. Also, the calibration coefficient (K_1) changes with temperature and the Diffusion Factor (*DF*) is obtained by the following equation:

$$DF = \frac{Me}{K_1} \tag{5}$$

where *Me* is the weight loss during field exposure.

The *DF* is the measure of plaster dissolution enhanced only by water movements (Doty, 1971; Bailey-Brock, 1979). The *DF* is required to convert the plaster consumption into "water speed equivalents" according to Bailey-Brock function (1979):

$$V = 3.65(DF - 1) \quad (6)$$

where V is the equivalent water speed expressed in cm s^{-1}.

Because water movement in the sub-tidal zone is a complex of unsteady non-uniform flow, the water speed calculated is an average water speed. These speeds do not provide any information about direction and fluctuation of intensity during field exposure.

The plaster balls were held in the field for 48–72 h and were mounted at 4 different elevations (i.e., 0.1, 0.4, 0.7 and 1 m) from the seabed inside and outside the meadow in order to observe the vertical variability into the benthic boundary layer composed by a vegetated and unvegetated bottom. During the first survey, the plaster balls were only placed inside a meadow (PM station) at four elevations (maximum was 0.7 m). During the third survey, plaster balls were placed at three stations: PM, SP and UB. At station UB, the plaster balls were placed at two elevations (i.e., 0.1 m and 1 m) from the seabed.

Except during two surveys, 4 runs for each elevation were carried out in order to estimate the variability of the measures. Care was taken to place the balls so that there was no contact between them and any plants in order to avoid the effect of abrasion. Information about sea water temperature was retrieved from a water-monitoring station deployed near the study site; information about the sea-weather condition was obtained from the wave buoy and weather station (Fig.4.1a).

4.3.2.1 Energy contributions of dynamic forcing on sediment dynamic processes

In shallow, micro-tidal environments the disturbance of bottom sediments by surface gravity waves is a primary mechanism for bottom sediment resuspension. In addiction wind-induced resuspension is an important physical processes for sediment transport in coastal environments (Drake and Cacchione, 1985, 1986; Cacchione et al., 1987; Roberts et al., 1988; Moeller et al., 1993) and can be the dominant physical process in shallow, micro-tidal coastal environments (Ward, 1980; Solis and Powell, 1999). In this study, only the mechanical energy generation term and the buoyancy term are considered while the radiative transfer can safely be neglected under the present conditions. The mechanical energy is assumed to be transferred to the water from the wind; following Kullemberg (1977) the energy input per unit time and area by the wind is generally expressed through the following equations:

$$Ew = k\rho_a CdW_{10}^3 \quad (7)$$

where k = 0.018 (Kullemberg, 1977);

ρ_a = 1.025 kg m^{-3} density of air

Cd = 1.1 x 10^{-3} drag coefficient

The energy at depth z is the difference between Ew and the amount of energy consumed per unit time and area.

$$E(z) = Ew - Pe(z) \quad (8)$$

The amount of energy consumed per unit time and area from the surface to a depth is:

$$Pe(z) = \int_{-z}^{0} \rho K N^2 dz \quad (9)$$

where ρ = 1020 kgm^{-3} density of water

K = vertical mixing coefficient

N^2 = Brunt-Vaisala frequency

z = depth (m)

Information about K and N^2 were computed from the SST profiles carried out at the measuring station. Since there were no evidences about water column stratification at a depth of 7 m depth, K and N^2 may be treated as approximately constant, implying that the integral may be evaluated by using average values of K and N^2 over the water column.

The available energy at depth z is the sum of the potential and kinetic energy:

$$E(z) = \rho g z + \frac{1}{2}\rho U^2 \quad (10)$$

This relation can be used to determine flow velocity (U) at depth z from which current bed shear stress (τ_0) is calculated through the following equation:

$$\tau_0 = C_f \rho U^2 \quad (11)$$

We described the wave energy propagation over the water column using linear wave theory. Surface waves produce an oscillatory motion in the water and the water particles following circular or

elliptical paths depending on the water depth. Near the bottom, itself, the elliptical motion is reduced to only horizontal motion. The orbital diameter (d_0) is given by:

$$d_0 = \frac{H}{\sinh(2\pi z / L)} \tag{12}$$

where: H = wave height

L = wave length

The maximum horizontal velocity associated with this motion at the bottom is:

$$Ux = \frac{\pi d_0}{T} \tag{13}$$

The bed shear stress (τ_w) is given by:

$$\tau_w = 0.5 Cf\, \rho Ux^2 \tag{14}$$

where Cf is the dimensionless drag coefficient (0.004; Jonsson, 1966), and ρ is the water density.
We use the drag coefficient for a sandy bottom without considering the presence of vegetation.
The bed shear stress induced by wind and waves considering a flat benthic boundary layer were evaluated on the waves and winds records retrieved from the buoy and weather stations. The comparison of bed shear stress induced by wind and waves allows us to define the role of physical stressors on hydrodynamic and sedimentary processes.

4.3.3. Analysis of fauna assemblage of *Posidonia oceanica*

The fauna assemblage of *P. oceanica* were studied at the PM station during 2015-2016 at four time intervals (25/10/15; 20/03/16; 22/06/16; 01/09/16). The sampling methods follow those proposed by Gambi et al., 1998. The sampling was carried out on leaves and rhizomes. The fauna on *P. oceanica* leaves were collected by means of a hand net (0.4 mm mesh size) that was towed over the seagrass canopy; this method used a standardized technique with a series of strokes (60) to shake the leaves (Russo et al., 1985). In addition, forty rhizomes were collected in two sub-areas of the sampling station.

Diversity indexes (*H* Shannon and Weaver, 1949; *D* Simpson 1949; *DMg*, Margalef, 1958) were calculated to give a quantitative measure of population structure that reflects how many different species are in a community and simultaneously takes into account how evenly individuals are distributed among those species. Species evenness (*J*, Pielou, 1969) was determined to define the closeness (in number) of each species in an environment. The trophic role about organisms was mined from the literature for each individual species wherever possible; if the feeding behaviour of a

particular species was unknown, it was assumed to feed in a similar manner to congeneric or confamiliar species or to species within the same major group. The trophic behaviour is represented by a coding system; for each organism, the following information was recorded: Detritus feeder (ingests or particular matter only, without sediment, or sediment, *Dt*), Suspension/Filter feeder (strains particles from the water, *Su*), Predator (eats live animals and carrion, *Pr*), Suctorial parasite (*Sp*), Chemosynthetic (with symbiotic bacteria, *Ch*), Herbivorous and grazers (eats leaves and algae and feeds by scraping, either on algae or sessile animals, *Gr*), and Browsing (feeds by tearing or gathering particular items, *Br*). The seasonal variation of structural parameters of the population and frequency of trophic categories of organisms were analyzed with respect to the sedimentary dynamic processes of total particles, organic matter concentration and seasonal evolution of *P. oceanica*. For this purpose, multivariate analysis of Canonical Correspondence (Legendre & Legendre 1998) was applied in order to define correspondence between environmental variables and species abundance. In addition, inside the pool of species, we selected some sea bed indicator organisms that are able to suggest specific perturbations or environmental factors. For example, we have observed the presence and abundance of Amphipoda, *Ericthonius punctatus* and *Leptocheirus guttatus* as indicators of good *Posidonia* quality (Zakhama-Sraieb et al., 2006) as well as the variation of abundance of Polychaeta *Su* and *Dt* as indicators of sedimentary dynamic regime.

5. Results

5.1. Sedimentary processes

5.1.1. Meteorological conditions

Meteorological conditions from 10/2015 to 12/2017 were characterized by a total rainfall of about 670 mm maximum in October 2016 (136 mm) and a minimum in July (0.6 mm). The cumulative rainfall observed during the surveys ranged from 0-50.2 mm (Table5.1), and the maximum occurred in September 2016 during survey 9. The prevailing wave directions and the intensity occurred during sampling periods are inside the variability of the study area according to the local wave climate with a wave power between 0.13 and 93.7 kWm^{-1} (Table 1). The maximum wind speed shows a magnitude between 7 and 22 ms^{-1} with a prevailing wind direction from SE. Three severe storms (H_s > 1.8 m) occurred during surveys 2, 4 and 9, corresponding to maximum wave power of 93.77, 26.26, 13.87 kWm^{-1}, respectively. Two less intense storms of comparable maximum wave power (6.39 and 6.29 kWm^{-1}) occurred during surveys 1 and 6.

The meteorological conditions from the total surveys were compared to available records (Fig.5.2) in order to observe the agreement between the variability of meteorological conditions that occurred during samplings and typical meteorological conditions of the study area.

The wave climate (Fig.5.2a) of the surveys shows that the prevailing directions of waves were from the southern sector (SW – SE) and consisted of a maximum wave intensity at a height of 5 m. This corresponds with the wave buoy records as well. The two main wind directions were from the NE and SE with a maximum intensity of 23 ms-1 coming from NE. The time-series data during 2009-2016 indicate two prevailing directions (NE – SE) of wind and a maximum intensity of 25 ms-1 from NE. The pluviometric regime observed during the year highlights a maximum rain intensity during autumn (especially in October) and a minimum during the summer period (especially in July). The extended time series (2009-2016) of the weather station indicates a seasonal oscillation of rain intensity with a maximum intensity in autumn (November) and a minimum in summer (August).

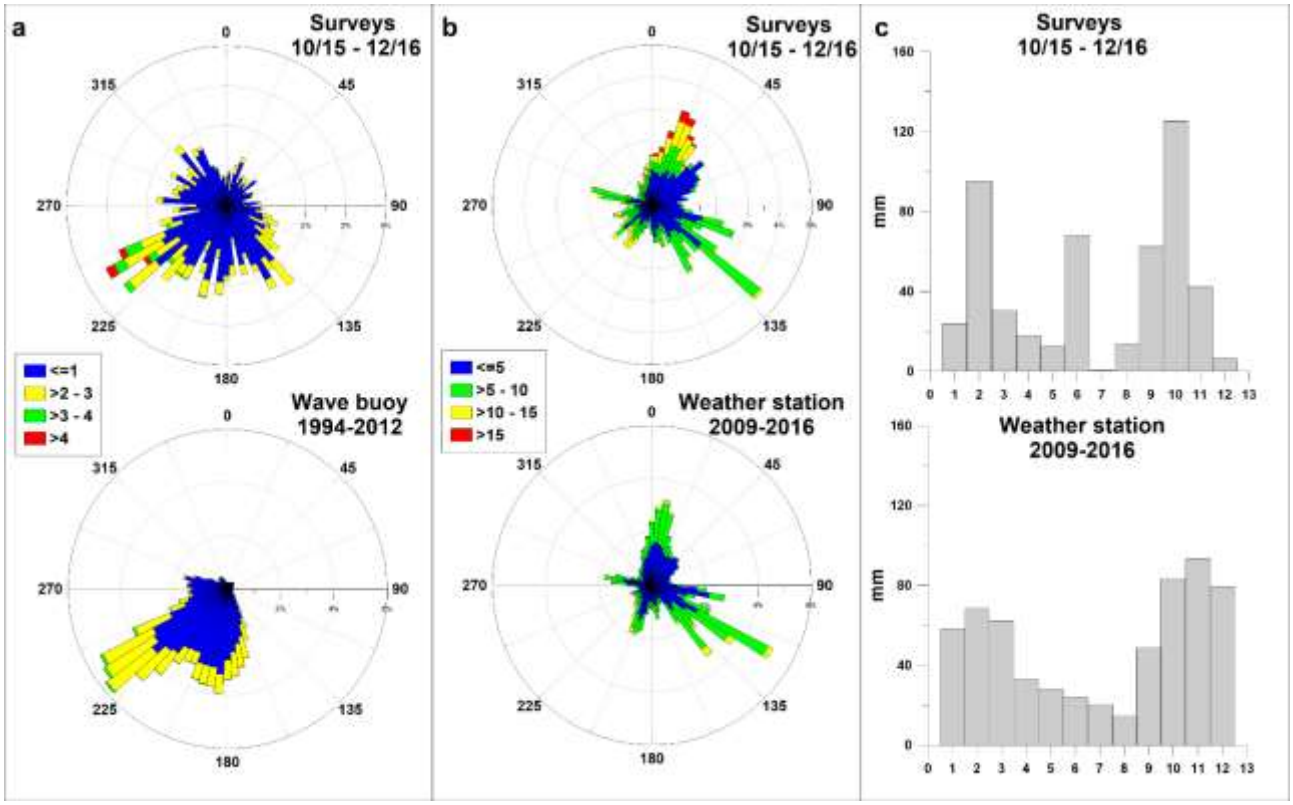

Fig.5.2. Meteorological conditions occurred during samplings and available long time records. a) wave records, colour scale in meters; b) wind conditions, colour scale in ms^{-1}; c) rain.

Figure 5.3. shows the wind and wave conditions of each sampling. For each one, there are three separated plots concerning the wind and wave intensity, wind and wave direction and bed shear stress induced by wind and waves. Regarding the bed shear stress, the black and grey bars represent, respectively, the contribution of waves and wind on the total bed shear stress. The calculation of the

bed shear stress induced by wind and waves in each survey (Fig.5.3) highlights the greater contribution of waves on the total shear at the seabed. Especially during storms, the waves produce bed shear stress that is sufficient to generate the resuspension of sediment particles. We chose the threshold of 7φ particles because this corresponds to the peak of the secondary mode of the grain-size sediment distribution. The contribution of wind to the total bed shear stress is generally lower except in some cases characterised by a calm sea. The critical shear stress of grains (7φ) is exceeded in the presence of waves greater than 1.2 m (Hm0) and 4 sec (Tp), while during other conditions, the shear produced by wind and waves does not seem strong enough to generate resuspension of grains.

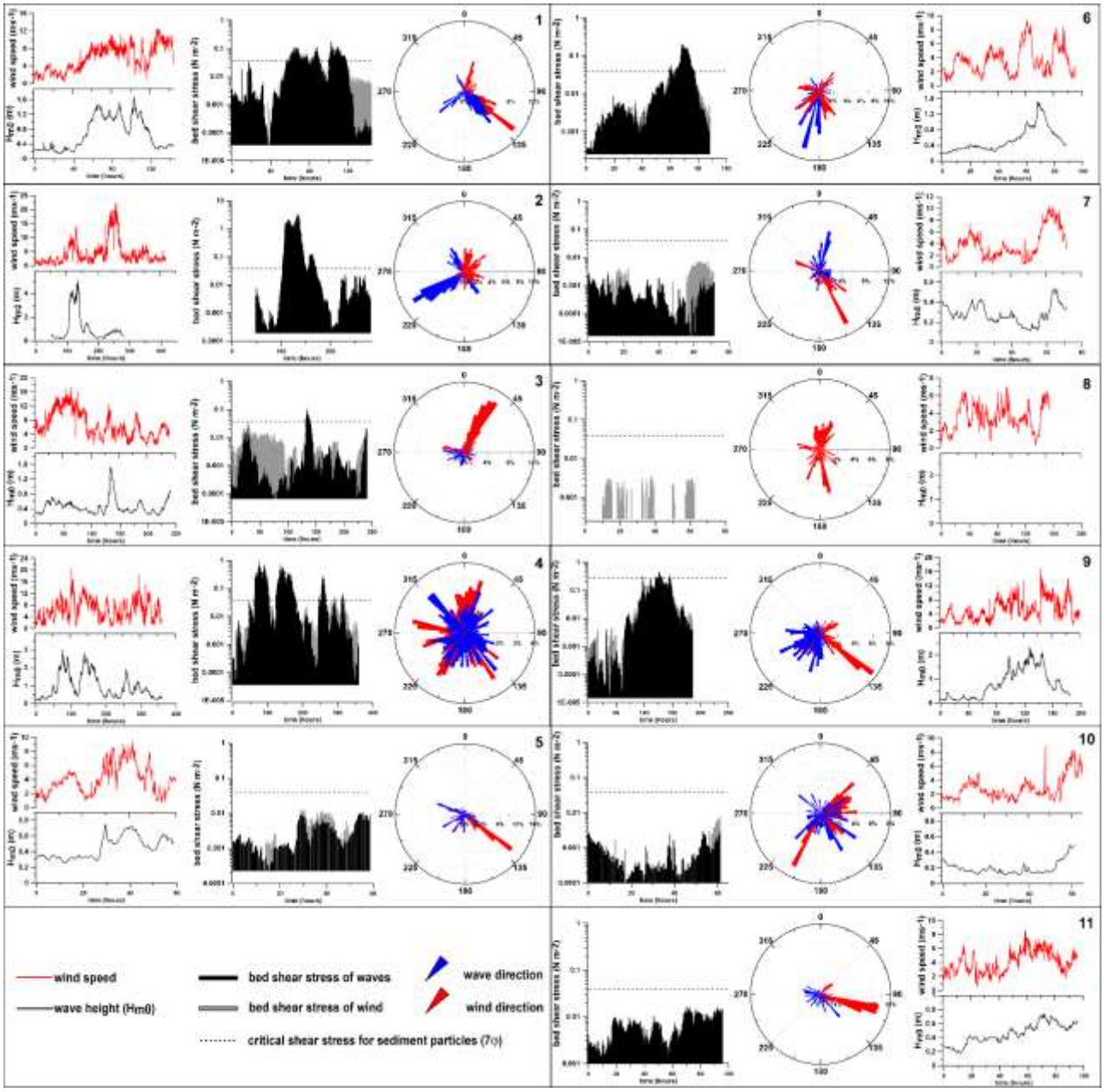

Fig. 5.3. Wind and wave conditions occurred during different surveys (red and black lines), bed shear stress induced by waves and wind (black and grey bars), polar plot of wave and wind direction (blue and red). The dotted line indicates critical shear stress of 7 φ sediment particles. The number of each subpanel refers to survey number as reported in Table 4.1.

5.1.2. Seasonal changes of the characteristics of *Posidonia oceanica* meadow

The total percentage of cover of the different substrata assessed by the *LITs* methodology provides information regarding the amounts of different substrata and live *P. oceanica* covering the sea bed. Live *P. oceanica* cover 69% of the seabed, 17% is covered by sand and 14% consists of mixed rocks and sandy bottom.

The unvegetated areas are mostly represented by sand patch with circular shape and various dimensions, ranging from 1 to 6 meters. The average densities sampled in different stations (Fig.5.4b) range between 227 and 380 shoot m^{-2} and do not show significant differences (ANOVA p = 0.8).

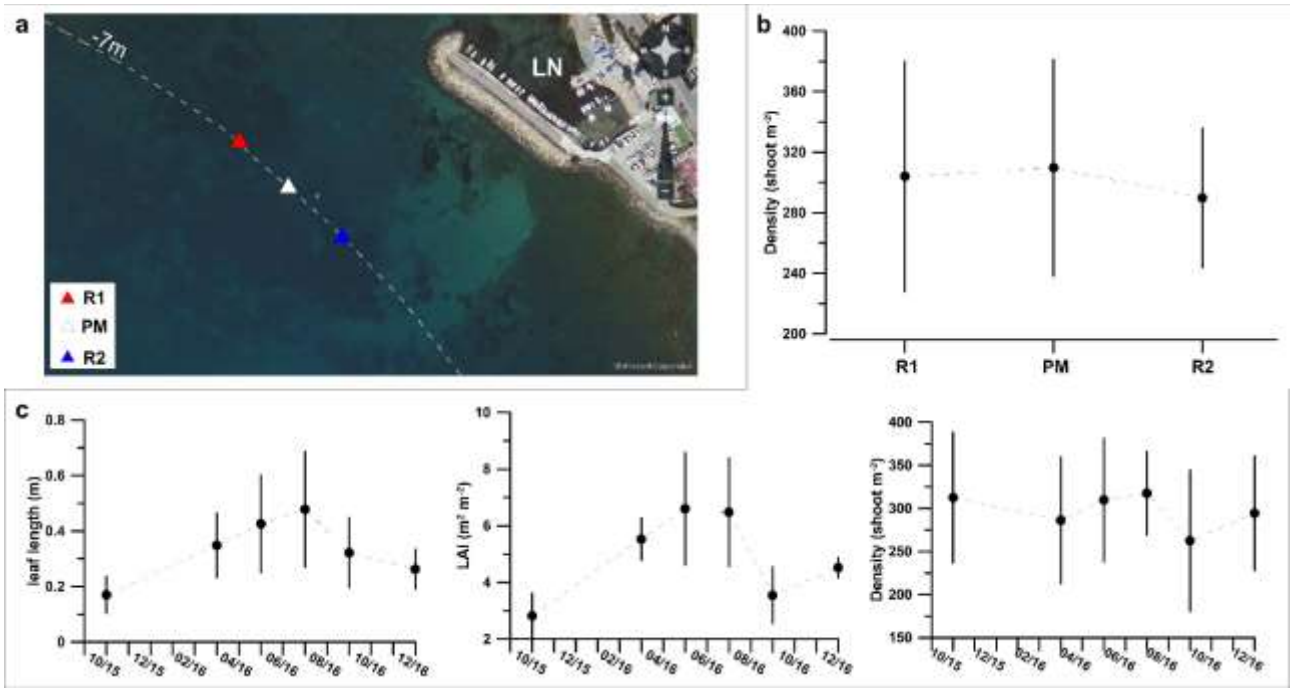

Fig.5.4 a) Sampling stations used for the determination of coverage and density; b*) P. oceanica* density in each station; c) Variation of *P. oceanica* descriptors over the year. From left to right: Leaf Length, LAI and Density on PM station.

The PM station is sampled over the year and on PM station the length of leaves shows a significant variation over the seasons (ANOVA $p < 0.001$); the minimum is in the Autumn (October), with an average value of 0.17±0.06 m, and the maximum is in the summer (July), with an average value of 0.47±0.20 m (Fig. 5.4c). The growth of leaves also influences the *LAI*, which shows the same trend of leaf length reaching its maximum value in May (6.6±1.99 m^2m^{-2}) and minimum value in October (2.82±0.8 m^2m^{-2}). Density does not show a significant variation over the year (ANOVA $p = 0.9$); its remains quite constant in the range of 260-312 shoots m^{-2} (Fig.5.4c).

The sand patch at the SP station shows large changes between the seasons (Fig.5.5). In Autumn, the sand patch presented, apparently, the maximum extension, as reported in Fig.5.5a, while during the summer, the growth of seagrass leaves halved the bare surface (Fig.5.5c). During strong Autumn and

Winter storms, the bed of the SP station shows erosive features, such as large ripple marks and outcropping of bedrock (Fig.5.5b). In the late summer, *P. oceanica* started to shed leaves, which progressively covered the seafloor with leaf litter (Fig.5.3d). The leaf litter remained on the seafloor until the first storm, at the end of which it was largely transported away.

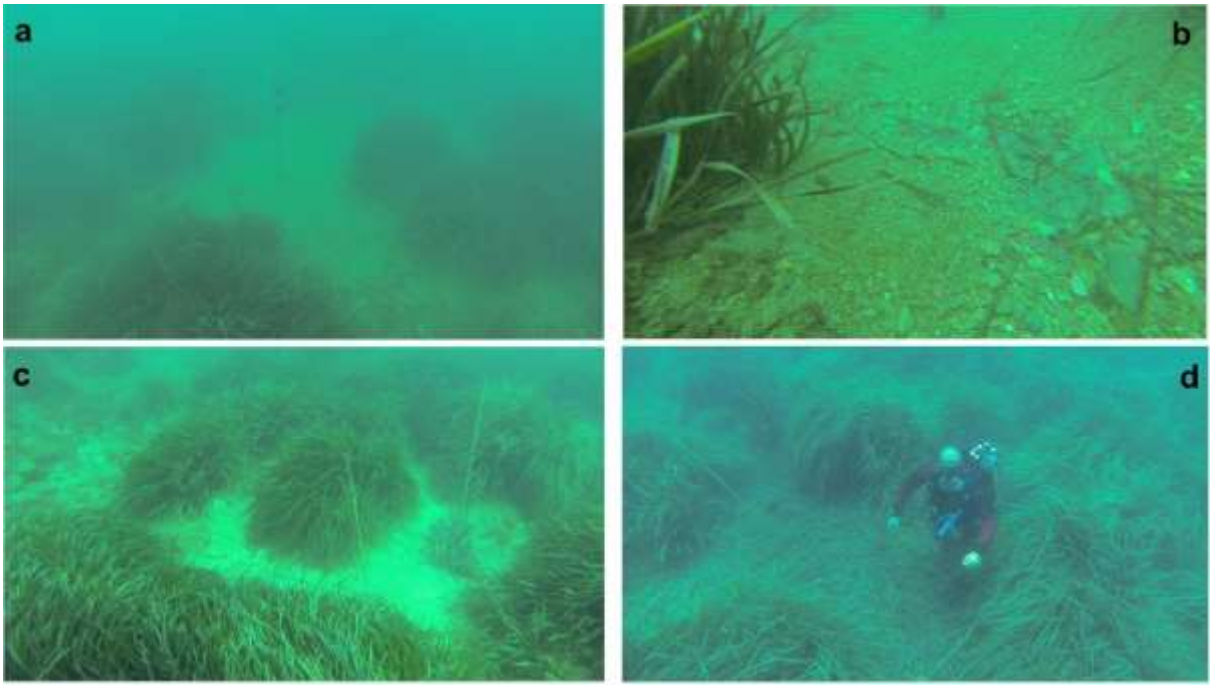

Fig.5.5 Sand patch evolution during the year. a) Autumn phase, b) detail of the bedrock outcropping after an extreme event, c) Summer phase, d) late Summer phase

5.1.3. Bed sediment composition

The bed sediments were collected seasonally at the PM and SP stations. In Fig.5.6, the cumulative distribution curves and textural bar plots show the general coarse nature of bed sediment. Gravel accounts for more than 40% in SP station and 10% in PM station. The cumulative distributions of grain size each show a bimodal shape with a change in slope around 3φ, which indicates the presence of two populations of grains. The grain mode 1 can be attributable to a tractive transport, while the grain mode 2 can be attributable to a suspended transport. The biogenic component in the bed sediment is dominant and is produced by biological activity of organisms living in the *P. oceanica* ecosystem and in the surrounding substrate (infralittoral and mesolittoral rocks). The gravel fraction is totally formed by bioclasts composed of shells and skeletal fragments. Comparing PM and SP cumulative distributions (Fig.5.6a), it is evident that there is a generally finer composition of PM sediment compared to SP; this is also apparent from the mean size (*Mz*) and the 95th percentile (*D95*) (Fig.5.6c). During the year, there are some changes in textural composition of bed sediments (Fig.5.6b), which are slight for the SP samples and marked for the PM samples. In particular, in the PM samples, a large variation occurs over the seasons (Kruskal-Wallis test $p < 0.05$), especially from Winter to Summer, where there is a great increase of sand and mud fractions in the composition of bed sediment (Fig.5.6b). During the year, the PM station is more variable than the SP station, suggesting the influence of vegetation on sedimentation processes. The bivariate relationships between grain-size statistical parameters permits us to further distinguish PM from SP, as data are plotted in two distinct fields (Fig.5.6c). Only the PM sample collected in Winter falls within the SP sample area, featuring the coarsest mean size and highly positive skewness. During Winter, the energy and frequency of storms are large, whereas during Spring and Summer, the storms become less frequent and less intense.

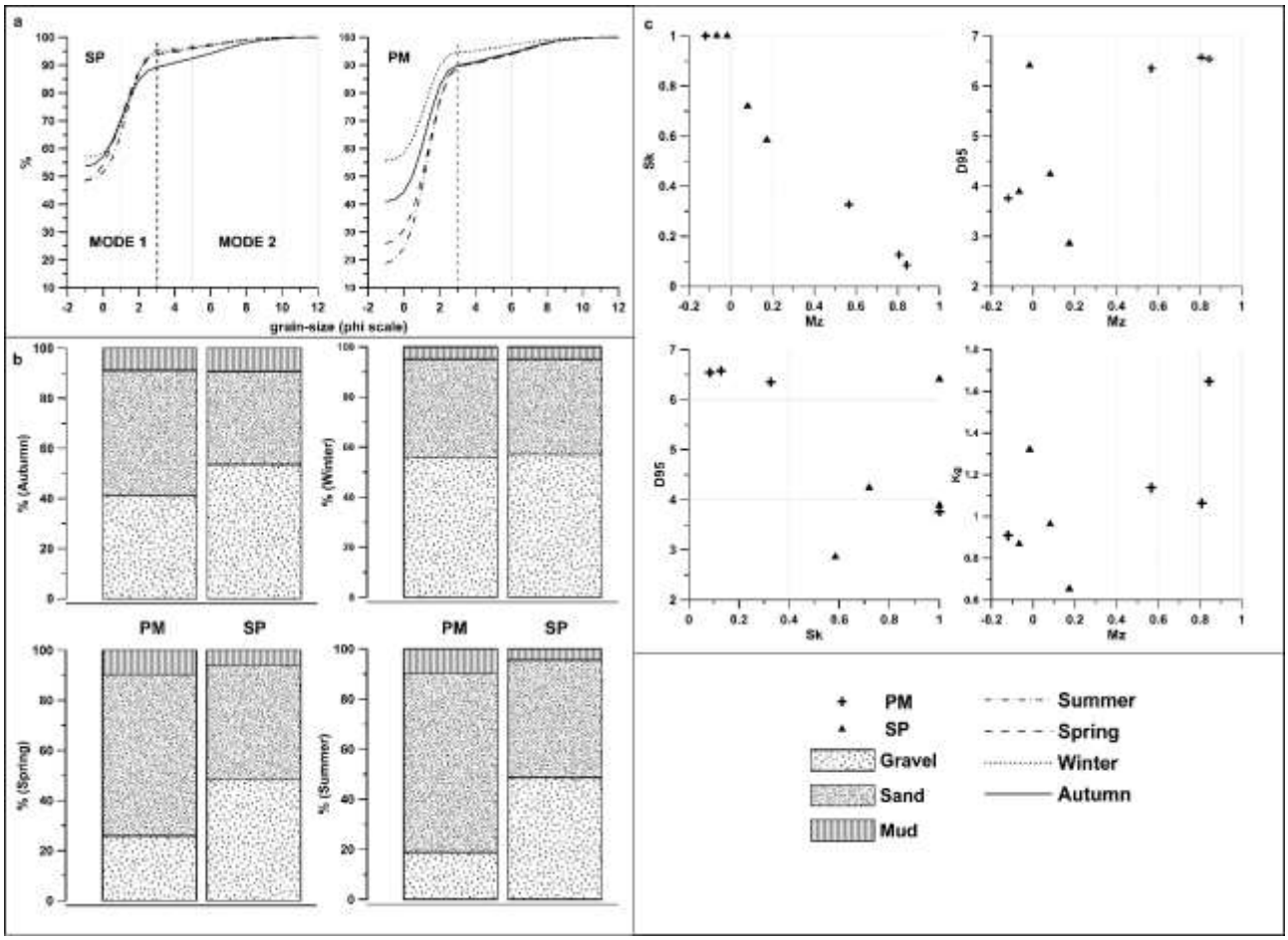

Fig.5.6 Results of sedimentological analysis of bed sediment samples; a) cumulative distributions; b) textural composition; c) bivariate plots between some grain-size statistical parameters.

5.1.4. Particulate sedimentation flux

The vertical sedimentation flux at different elevations from the seabed was evaluated seasonally and during different weather conditions (Fig.5.7, 5.8). During the year, the maximum depositional rate was recorded in November 2015 with 9640 ± 2848 g DW $m^{-2}d^{-1}$, while the minimum was recorded in October 2016 with 3.89±0.28 g DW $m^{-2}d^{-1}$. Along the vertical profile the total sedimentary flux generally increase toward the seabed showing larger values during the autumn and winter seasons (Fig.5.7). In particular, sedimentary flux has a substantial increase when rainfall is larger than 20 mm and mostly in the presence of wave power greater than 5 kWm^{-1}. Slight rainfall and calm sea determine sedimentary flux values less than 66 g $DWm^{-2}d^{-1}$ in bare sand stations and less than 12 g DW $m^{-2}d^{-1}$ over the seagrass. The sedimentary flux at the bottom is generally larger at the bare-sand stations (SP and UB) with the exception of three cases where the total sedimentary flux at the bottom in PM is larger than SP.

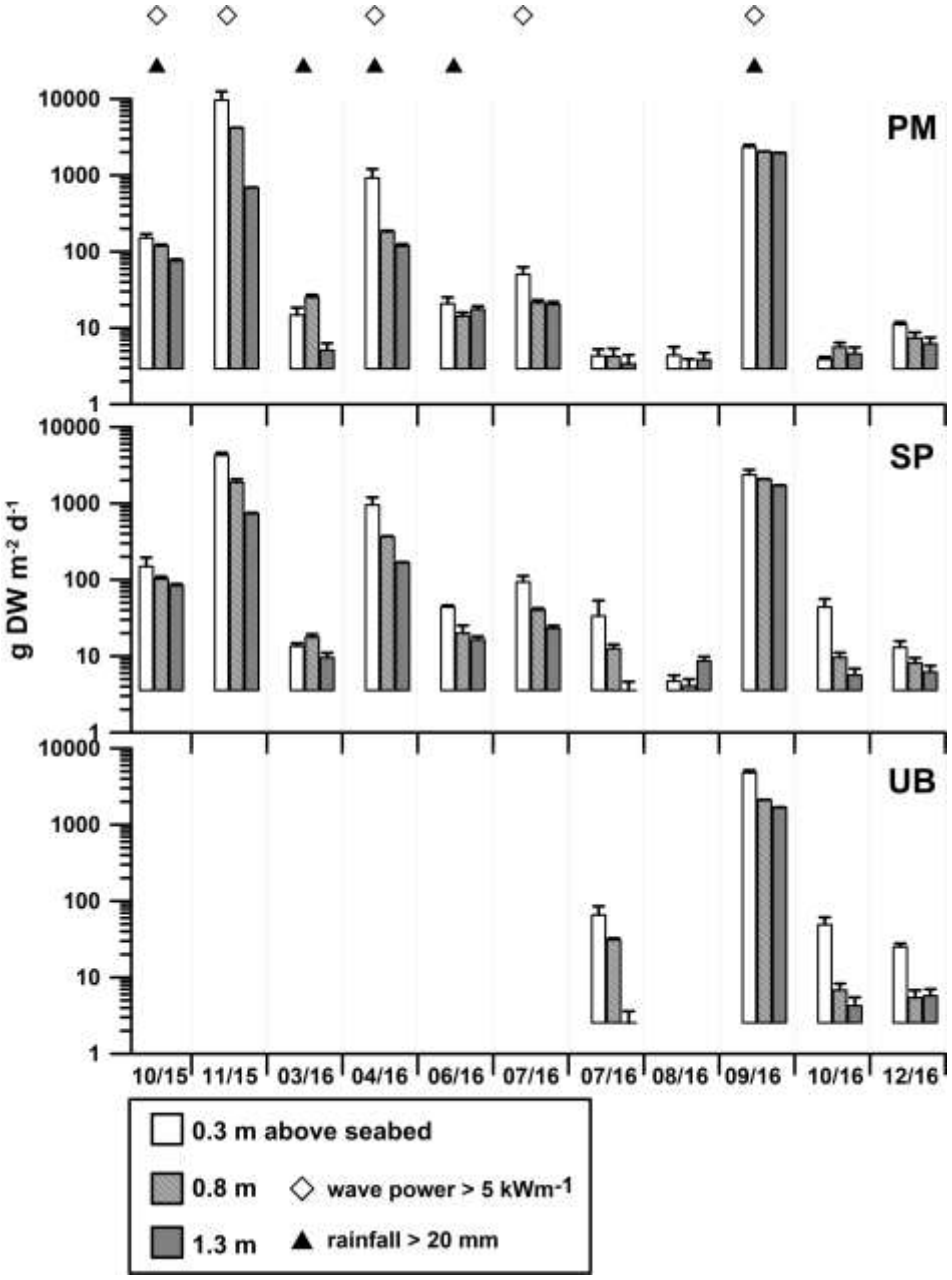

Fig.5.7 Measured sedimentation flux at different elevations over the seabed and in the different stations.

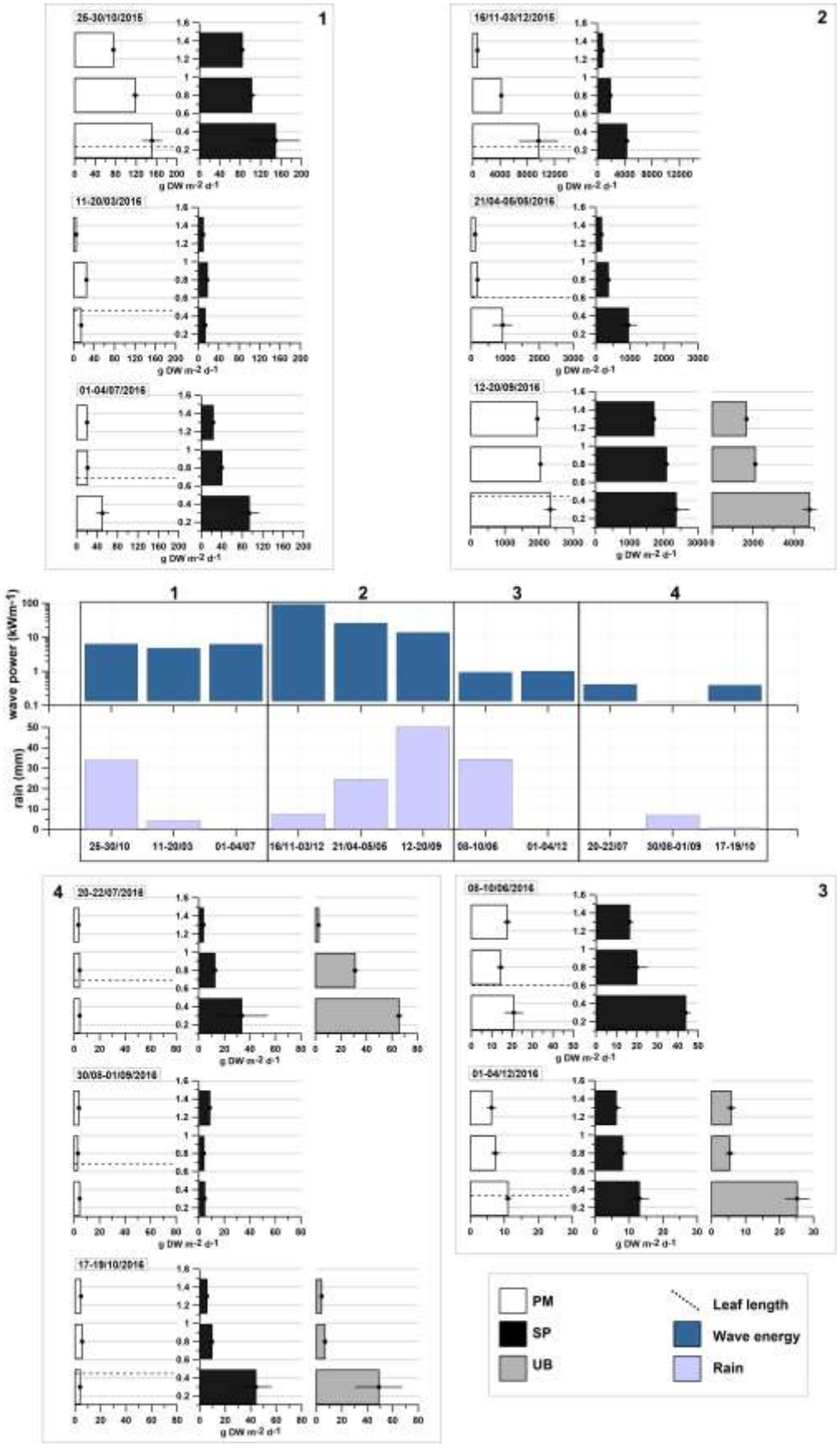

Fig.5.8 Vertical profile flux measured at progressive distances from the seabed within *Posidonia oceanica* (PM), sand patch (SP) and unvegetated bottom (UB) from October 2015 to December 2016. The symbols indicate the mean, while the bars indicate the standard deviations of the runs. The dotted line indicates the shoot length (mean + standard deviation) of *Posidonia oceanica*.

The depositional rates at 1.3 m over the sediment surface were highly correlated and not significantly different ($R > 0.95$; $p < 0.0001$; Kruskal-Wallis test $p = 0.37$) in different stations and over time, while depositional rates at the bottom (0.3 m) and at the intermediate level (0.8 m) show significant variations (Kruskal-Wallis test $p < 0.05$) among stations, suggesting a possible role of vegetation in constraining the sedimentary process within a boundary layer almost 0.8 m thick.

The vertical profiles of sedimentary flux (Fig.5.8) show the dominance of an increasing trend of sedimentary flux towards the seabed especially in the SP and UB stations.

Table 5.2 reports data on sedimentary flux distinguished between the resuspension (*Fr*) and the primary settling (*Fp*) components (Table 5.2). The best-fit statistics are reported in the form of R^2, according to the exponential function proposed by Pejrup et al. (1996) and significant fitting indicate the presence of a resuspension process.

The exponential trend due to resuspension best fits in the 81% of the measurements at the SP station while at the PM station, resuspension is less frequent, occurring in 54% of the cases (Table 5.2). In the unvegetated sandy bottom (UB) during all surveys vertical profiles are characterised by resuspension.

Others vertical profile patterns show nearly uniform depositional flux without evidence of resuspension, found especially at the PM station.

The comparison among stations highlights the general trend of larger *Fr* at the SP station compared to the PM station. The average contribution of resuspended material to the total depositional rate amounts to 94% in UB, 81% in SP and 72% in PM.

Information on the effect of leaf growth as a possible constraint in the resuspension processes, can be obtained by comparing the sedimentary fluxes and gradients recorded in PM during different vegetation phases and comparable wave intensities (Fig5.8). Fig 5.8 shows the modification of the vertical profile in presence of vegetation, which is particularly evident during calm sea conditions.

In these conditions, the sedimentation profiles are characterised by resuspension on unvegetated stations, while inside the meadow records show a homogeneous trend along the vertical profiles. In presence of strong and moderate storms, the resuspension process always occurs inside vegetation, but its magnitude is governed by the length of leaves.

The 1st class of wave intensity (Fig.5.8) shows a slight effect of vegetation in presence of short leaves, but there is a reduction of resuspended flux (*Fr*) of about 70% with the lengthening of leaves at the PM station. The 3rd class shows the neglection of resuspended flux in the summer when the leaves are long. During calm sea conditions (4th class: wave intensity less than 1 kWm^{-1}) resuspended component of flux is always absent in the PM. In all of the cases mentioned above, measurements at

the unvegetated sandy station (UB) show the constant presence and greater magnitude of resuspension.

During strong storms (10kWm^{-1}), the resuspended flux seems to be larger or very similar inside the vegetation (PM) compared to the sand patch (SP). On these samples, comparison with an unvegetated sandy area (UB) and sedimentological analysis better describe the sedimentary process.

Class	*Survey*	*Date*	*Fr*	*Fp*	*Dr*	*%Fr*	*%Fp*	R^2	*Site*
1	1	25-30/10/15	187	70.8	257.8	72.5	27.5	0.65	PM
			176	70.7	246.7	71.3	28.7	0.8	SP
	3	11-20/03/16	0	14.7	14.7	0	100	0.16	PM
			0	13.4	13.4	0	100	0.17	SP
	6	1-4/7/16	57	12	69	82.9	17.1	0.75	PM
			133.1	14.6	147.7	90.1	9.9	0.91	SP
2	2	16/11-3/12/15	17508	-	17508	100	-	0.84	PM
			7112	-	7112	100	-	0.98	SP
	4	21/4-5/5/16	2164	28	2192	98.7	1.3	0.85	PM
			1554	103.3	1657.3	93.8	6.2	0.89	SP
	9	12-20/9/16	584.8	1850.3	2435.2	24	76	0.75	PM
			985.3	1635.8	2621.1	37.6	62.4	0.62	SP
			5786.6	1033.4	6820	84.8	15.2	0.93	UB
3	5	8-10/6/16	0	15	16	0	100	0.15	PM
			50.9	10.2	61.1	83.2	16.8	0.89	SP
	11	1-4/12/16	7.8	5.1	12.9	60.4	39.6	0.78	PM
			12	5.1	17.1	70.2	29.8	0.71	SP
			49.4	1.4	50.8	97.2	2.8	0.88	UB
4	7	20-22/7/16	0	3.3	3.3	0	100	0.15	PM
			59.6	2.8	62.4	95.5	4.5	0.64	SP
			111.7	6.6	118.4	94.4	5.6	0.95	UB
	8	30/08-1/9/16	0	3	3	0	100	0.29	PM
			0	9.6	9.6	0	100	0.63	SP
	10	17-19/10/16	0	5.1	5.16	0	100	0.08	PM
			98.4	1.6	100	98.4	1.6	0.88	SP
			147.2	0.6	147.8	99.6	0.4	0.84	UB

Table 5.2 Results of separation between resuspended *Fr* and primary *Fp* fluxes; the depositional rate at the bed (*Dr*) is also reported as well as the contribution of resuspended *(%Fr*) and settled *(%Fp*) material on the total depositional rate are also reported. R^2 refers to the significance of exponential function that best-fit with measured values. The fitting is significant ($p < 0.05$) with $R^2 > 0.61$. In survey 2 the *Fp* was not determined because all the traps have been involved in resuspension.

The evaluation of the relationships among transport capacity (*Ct*) of wave induced bed shear stress, precipitation and sedimentation flux was made using Pearson's correlation coefficients (Table 5.3). Correlation with cumulative rainfall was made considering the sedimentation flux of the only suspended sediment fraction (> 3φ) represented by the secondary mode of bed sediment grain-size distribution, linked mainly to mainland run-off. This fraction is directly determined on trap samples analysed for grain-size, whereas for those samples with very scarce trapped material, the sediment texture was reasonably considered entirely larger than 3φ.

Station	*Trap elevation (m)*	*Ct*		*Rainfall*	
		R	*p-val*	*R*	*p-val*
PM	0.3	0.85	<0.001	0.36	0.27
	0.8	0.83	0.001	0.51	0.09
	1.3	0.31	0.32	0.65	0.02
SP	0.3	0.86	<0.001	0.56	0.06
	0.8	0.67	0.02	0.63	0.04
	1.3	0.38	0.22	0.65	0.02

Table 5.3 Pearson correlation coefficients and related probabilities of the relationships between sedimentary flux measured at different elevation vs transport capacity (*Ct*) and rainfall

The results, reported in Table 5.3, show significant correlation in both stations between transport capacity (*Ct*) and total sedimentation flux, which loses significance in the highest traps (1.3 m).
Correlation of *Ct* and *Fr*, which is driven only by wave effect on the bottom, indicates larger correlation in SP station ($R = 0.95$; $p < 0.001$) than PM ($R = 0.91$; $p < 0.001$).
The correlation with rainfall (Table 5.3) in both stations is significant only in traps placed at 1.3m above the seabed while only in SP the significance occurs also at the intermediate level (0.8 m). Moreover, in both stations over time, the Signed Rank Test, applied to *Fp* and sedimentation flux of fraction > 3φ at 1.3m traps, shows no statistical differences ($p > 0.83$).
Grain-size determination was performed on samples recovered after four storms (surveys 1, 2, 4 and 9).

Station	**Elevation**	**Survey 1**			**Survey 2**			**Survey 4**			**Survey 9**		
		Gravel	**Sand**	**Mud**	**Gravel**	**Sand**	**Mud**	**Gravel**	**Sand**	**Mud**	**Gravel**	**Sand**	**Mud**
PM	0.3	0	38	62	25.75	58.1	16.15	0	77.47	22.53	0	51.57	48.43
	0.8	0	35.3	64.7	18.01	65.16	16.83	0	49.98	50.02	0	47.3	52.7
	1.3	0	28.7	71.3	1.33	71.3	27.46	0	49.5	50.5	0	48	52
SP	0.3	0	31.5	68.5	15.67	67.33	17	10.49	53.47	36.04	0	42.81	57.19
	0.8	0	29.7	70.3	10.55	67.14	22.3	0	59.41	40.59	0	45.18	54.82
	1.3	0	26.9	73.1	2.22	65.25	32.51	0	48.65	51.35	0	37.9	62.1
UB	0.3	-	-	-	-	-	-	-	-	-	1	58.83	40.17
	0.8	-	-	-	-	-	-	-	-	-	0	45.27	54.73
	1.3	-	-	-	-	-	-	-	-	-	0	44.13	55.87

Table 5.4 Frequency of gravel, sand and mud fractions of trap samples

In Table 5.4 shows the frequency of main sediment classes (gravel, sand and mud) are shown, while in Fig.5.7 represents the grain-size distributions (sand+mud) are represented in a synoptic scheme for comparison with bed shear stress, rainfall, sedimentary fluxes and seagrass characteristics. During survey 1, the bed shear stress induced by waves exceeds the threshold of 5φ grain size which

corresponds to the peak of sediment distribution, further enhanced by rain contribution (34 mm in 24 hours). The shape of the frequency distribution does not change along the vertical profile; slight inflections are only visible in the bottom trap (0.3 m) of both stations around 2φ, which is attributable to the weak resuspension of the coarse sediment fraction. The sand concentration at the different levels above the sea bed decreases 10% upward at the PM station, while at the SP station, the decrease is about 5%. The absence of a marked variation in the distributions of stations PM and SP is also apparent from survey 2. In both surveys 1 and 2, *P. oceanica* was in the period of a short-shoot-length phase, which is typical of Autumn. During survey 2, the huge shear stress induced by storm waves was able to move the coarse fraction, which was trapped at all elevations, indicating that resuspended particles moved at least up to 1.3 m. Moreover, strong currents were developed during storms, digging the seabed and causing the outcropping of bedrock in SP as previously observed in fig.5.5.

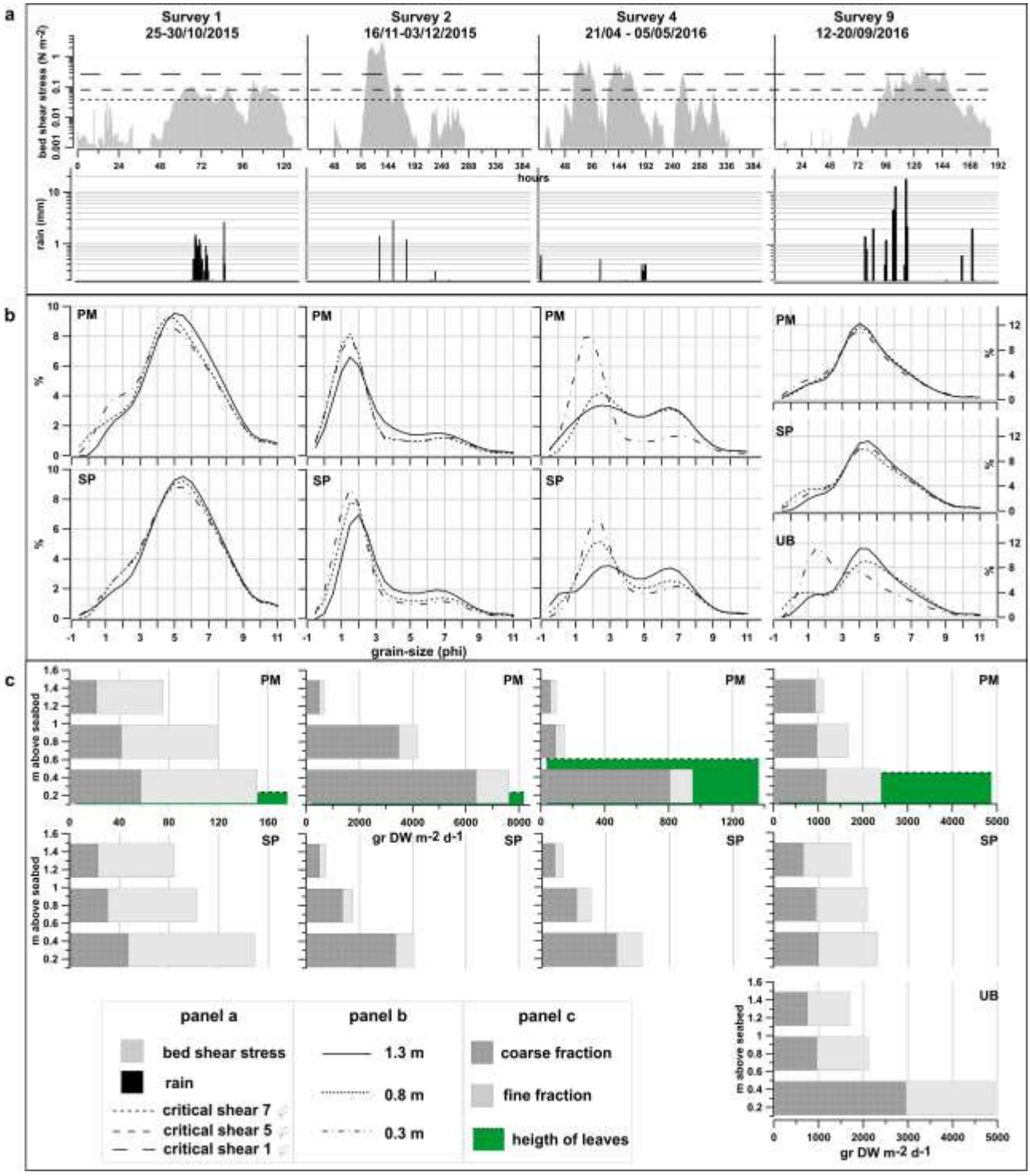

Fig.5.9 Summary diagram of the results. a) in the top the wave-induced bed shear stress and threshold of motion for different grain-size; down, precipitations occurred during sampling period. b) grain-size distributions of trap samples; c) sedimentation flux and its coarse and fine components; in the station PM the green area represent the height raised by the leaves.

Grain-size distributions feature a sudden fall in the peak at the PM station compared to the gradual lowering found in the SP station. Moreover, the gravel fraction shows a larger decrease along the vertical profile in PM (24%) than the 13% observed in SP, where a greater amount of gravel was also found in the trap.

Survey 4 was carried out during a long-leaves phase (Fig.5.9c): the storm that occurred during the survey induced a bed shear stress that was able to trigger resuspension of the coarse component as highlighted by the highest modal peak of the grain-size distribution of bottom traps in both the PM and SP stations. Considering that the gravel component (Table 5.4) was collected only at the SP station, we can infer a different energetic regime between stations. The coarse mode at the SP station gradually decreases along the vertical profile, while at the PM station, it undergoes a sudden decay, leading to the balance with the fine mode already at the intermediate elevation (0.8 m). Furthermore, along the vertical profile, the sandy fraction has a larger decrease in PM (28%) than SP (4.8%) (Table 5.4).

Despite that during survey 9 the bed shear stress triggered by the storm exceeded the threshold of the coarsest component, the coarse mode was significantly captured only in the bottom trap of UB station, which was also characterised by gravel traces (1%) (Table 5.4). In the highest traps, the coarse component is clearly subordinate, although it is still observable as a secondary mode at -0.8 m and as an inflection at -1.3 m (Fig.5.7). In stations SP and PM, the grain mode is placed around 5.5 phi, while a coarser secondary component emerges just as a slight inflection on the bottom trap of the SP station (Fig.5.9b). This survey was affected by two further fundamental factors as a significant precipitation of 50 mm of rainfall in 24 hours and leaf litter covering the seabed (Fig.5.5d), which probably further constrained the sedimentary dynamics.

5.2. Water movement on the benthic boundary layer

The normal diffusion of plaster induced by temperature and time of exposure was experimentally determined in a tank. The results highlight a linear trend following the equation $y = ax+b$. The regression model was applied on the dissolution of plaster over time at different temperatures (Figure 5.10A, B). The slope and intercept parameters obtained from the linear regression are given in Table 5.5.

T (°C)	***n***	***a***	***b***	***R^2***	***Time (hr)***	***n***	***a***	***b***	***R^2***
10	14	0.0402	0.164	0.98	6	14	0.0445	0.16	0.83
15	16	0.0453	0.379	0.97	24	12	0.0618	0.709	0.81
20	16	0.0456	0.598	0.97	48	8	0.0282	2.416	0.72
25	16	0.0463	0.867	0.98	66	12	0.0593	2.444	0.72

Table 5.5. Slopes (a), intercepts (b), number of observations (n) and coefficient of determination (R^2) of linear regression model of plaster balls dissolution as a function of temperature (T) and time.

The results obtained by the linear regression models were interpolated using "*kriging*" technique in order to define the parameter *k* of different surveys. The results of calibration show the acceleration of plaster dissolution with the increase of temperature and time.

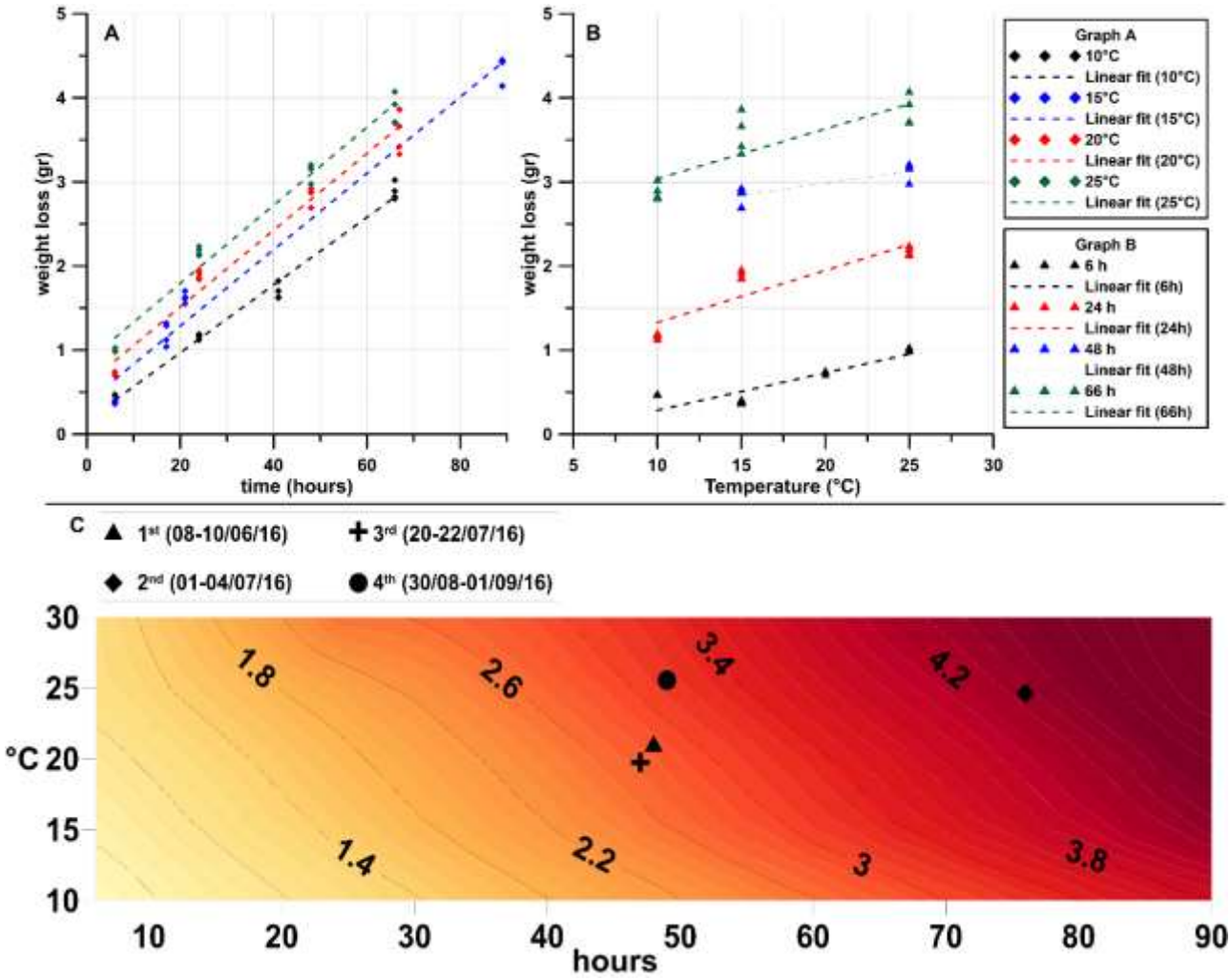

Fig.5.10 Linear regressions and contour plot of the normal dissolution of plaster balls calculated from the calibration test results. A) Dissolution over time at different temperature; B) Dissolution over temperature at different times; C) Contour plot of the dissolution of the plaster balls as a function of time and temperature; the different symbols on the contour map indicate the different surveys.

The results obtained with plaster balls in the field (Fig. 5.11) highlight a general decrease of speed proceeding toward the bottom. During surveys of 08/10/2016 and 30/08-01/09/2016 an increase of speed corresponding to the leaf boundary occurred. Comparing the results between the vegetated and unvegetated stations, a larger decrease of speed occurs inside the vegetation. During the survey of 01-04/07/16, a storm occurred and, in this case, measurements inside the vegetation cannot be considered valid due to the likely abrasion of plaster balls by the motion of leaves. At the unvegetated station (SP) the results indicate a mean velocity of 0.05 ms^{-1} which is in agreement with predicted mean velocity of 0.07 ms^{-1} empirically obtained.

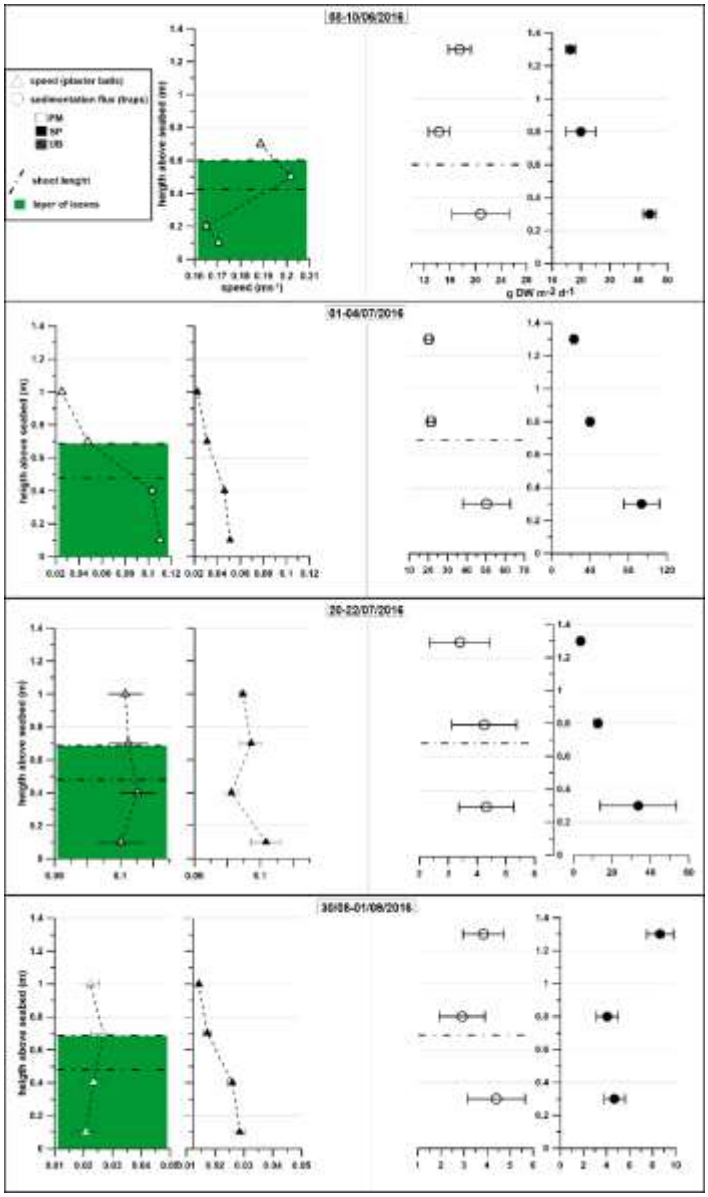

Fig.5.11 Results of surveys with plaster balls; on the left, there are the vertical profiles of the flow speed; on the right the vertical profiles of sedimentation flux measured by the traps.

Along the vertical profile of plaster inside vegetation, a flow speed reduction was observed in a range of 2.6 – 9.6%; between stations (PM-SP), there was a greater decrease of flow inside the canopy ranging from 3 – 27%, confirming the role of vegetation in flow attenuation.

5.3. Sedimentation processes of organic matter

5.3.1. Bed sediments

Organic matter in bed sediments fluctuate from 2% to 3.5% in the stations inside the meadow (PM and SP), while in samples from the UB station, the concentration of organic matter is always lower than 1.5%. Bed sediments from stations PM and SP are characterized by seasonal variations without significant differences between them (Signed Rank Test $p > 0.3$). The maximum concentration of organic matter in sediment occurs in April, while the minimum is observed in December.

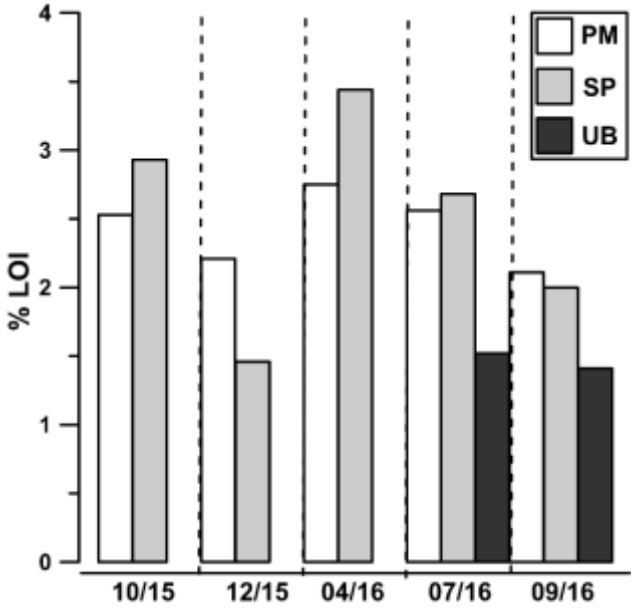

Fig.5.12 Percentage of organic matter in bed sediments

5.3.2. Sedimentation flux of organic matter

The fraction of organic matter (LOI) within the total particulate flux varies from 2 to 40% at the PM station, and in a range of 3 - 71.5% at the SP station. At the UB station, LOI is always less than 20%. Along the vertical profile of traps (Fig.5.13a), the organic matter concentration decreases toward the bottom in all stations. At the bottom (0.3m), the organic matter concentration increases toward spring and summer.

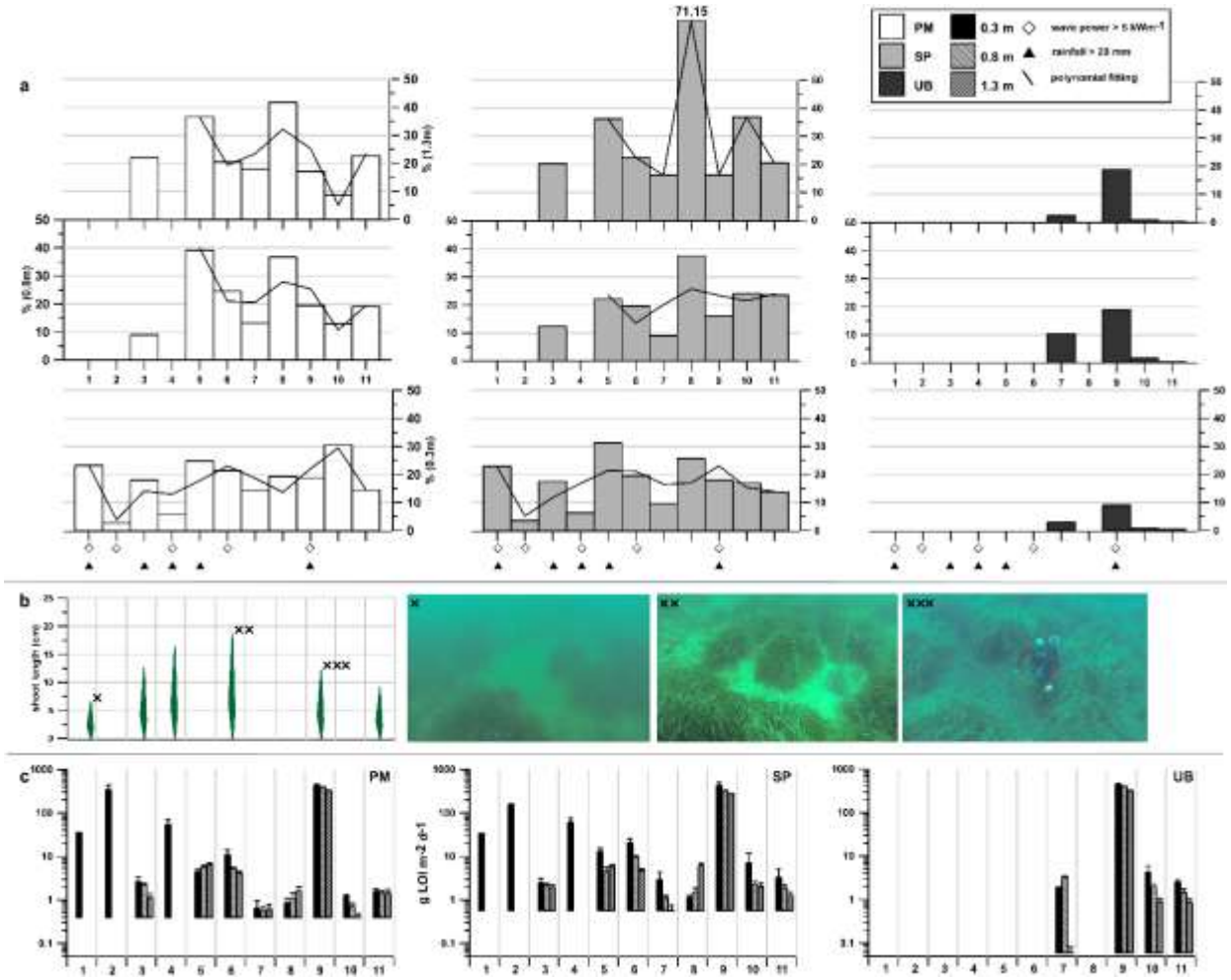

Fig.5.13. a) Organic matter percentage (LOI %) at different elevations of different stations (PM, SP, UB), the black line indicates polynomial fitting of data; b) shoot length of *Posidonia oceanica* and sand patch evolution during the sampling period; the crosses indicate the time corresponding to the photos; c) sedimentation flux of organic matter at different elevations at stations PM, SP and UB.

During the year, the maximum depositional rate of organic matter is recorded in September 2016 with 435 ± 29 g LOI $m^{-2}d^{-1}$, while the minimum is recorded in July 2016 with 0.64 ± 0.3 g DW $m^{-2}d^{-1}$. The organic flux, estimated by LOI, is compared with the total sedimentary flux, and there is a significant correlation. Higher correlation occurs at the UB station (R = 0.92; p < 0.0001) compared to the SP and PM stations (respectively R = 0.76 and 0.7 and p < 0.01). Organic matter flux increases in the presence of intense rainfall and waves (Fig.5.11c).

No significant differences occur at high traps (1.3 m) between stations (Kruskal-Wallis test p = 0.48); in contrast to the total sedimentation flux, organic matter compounds, at the bed, does not show significant differences between stations PM and SP (Wilcoxon Signed Rank Test; p = 0.13).

Pearson's correlation is significant between organic matter flux and rainfall at stations PM and SP; the best fit is found in the higher traps, and the *R* value decreases while moving toward the bed (Table 5.7) and it becomes insignificant at 0.3m at the PM station.

	PM		**SP**	
Elevation	***R***	***p-val***	***R***	***p-val***
0.3	0.5	0.1	0.65	0.02
0.8	0.79	0.03	0.79	0.03
1.3	0.8	0.03	0.8	0.03

Table 5.7. Pearson's correlation of organic matter flux at different elevation with rainfall

Organic matter concentration has a significant inverse relationship with the capacity transport of waves (*Ct*) only at the bottom in both stations (PM and P) where the correlation coefficients (R) are respectively -0.7 and -0.8 ($p\text{-}val < 0.01$).

5.4. Fauna assemblage and relationship with dynamic processes

During the sampling period, there is evident variation of fauna assemblage living in *P. oceanica*. Generally, the most abundant groups are represented by Amphipoda (39%) and Polychaeta (24%) and by less frequent groups composed of Anisopoda (4.4%), Chitons (3.1%), Mollusca Bivalvia (3.5%) and Gastropoda (8.1%), Decapoda (7.1%), Echinodermata (3.9%), Sipuncula (1%) and Isopoda (4.4%). The population of rhizomes is more abundant than leaves (Fig.5.14). On the leaves, in October and March, species are constrained to two taxonomic groups (i.e., Decapoda and Gastropoda), while in June and September, there is a substantial increase in the number of taxonomic groups. The most abundant species of rhizomes are Polychaeta and Amphipoda. Since Polychaeta are quite constant during the samplings, Amphipoda increase in June and September (Fig.5.14).

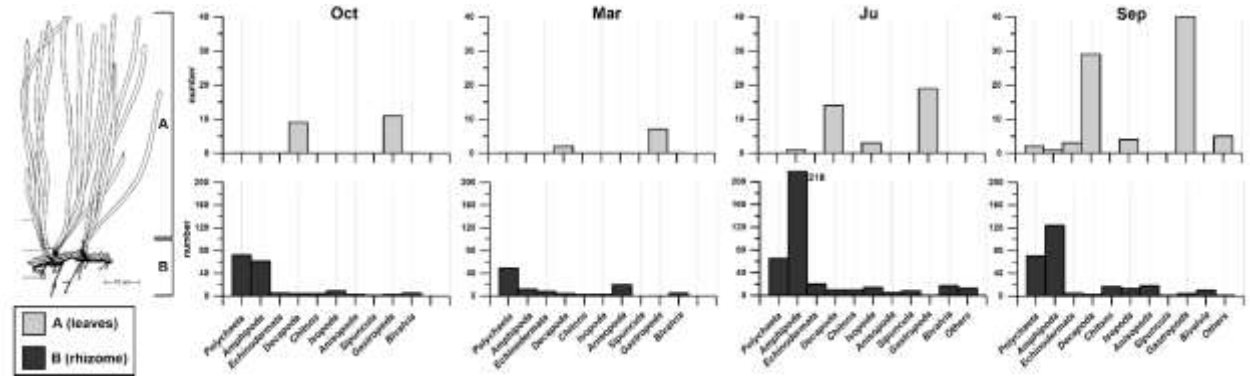

Fig. 5.14 Number of individuals for each species at both levels of shoot (A, leaves and B, rhizome) observed during different surveys in October (Oct), March (Mar), June (Ju) and September (Sep).

In October, the total number of species are 65 with 187 individuals where there are 167 individuals of 59 species of rhizomes and 20 individuals of 6 species from the hand-net samples. The most frequent species was Polychaeta *Polyophthalmus pictus*, (16 individuals in the rhizome samples) and Gastropoda *Alvania discors* (7 individuals from the hand-net samples).

In March, the total number of species are 50 with 112 individuals separated in: 103 individuals of 46 species of rhizomes, and 9 individuals of 4 species from hand-net samples. The most frequent species of rhizomes was Anisopoda *Chondrochelia savignyi* with 20 individuals while the largest taxonomic group is represented by Polychaeta where *Megalomma messapicum* is the most numerous (7 individuals). The Gastropoda *Rissoa sp.* is the most abundant from the hand-net samples with 3 individuals.

In June, the total number of species was 105 with 413 individuals, 376 individuals of 94 species come from rhizomes, and 37 individuals of 11 species were found from hand-net samples. The most frequent species in rhizomes was Amphipoda *Ericthonius punctatus* with 74 individuals and in the same way the largest group was represented by Amphipoda. The Gastropoda *Rissoa sp*. was the most abundant species (13 individuals) in the hand net samples.

At the end of the summer, (September) the total number of species was 102 with 355 individuals where 267 individuals of 83 species were collected on rhizomes and 87 individuals of 19 species from hand-net samples. The most frequent species was Amphipoda *Ericthonius punctatus* (23 individuals in the rhizome samples) and Decapoda *Hippolyte inermis*, (26 individuals from the hand-net samples).

The frequencies of different taxonomic groups (Fig. 5.15) show the dominance of Polychaeta in October and March, in terms of the number of individuals and species. Though Amphipoda grows significantly in terms of the number of organisms in June (56.3%) and September (37.2%), the Polychaeta group always shows the largest number of species (35.11-38.2%). During sampling in

September, the Gastropoda group undergoes to an evident increase of more than 7% in terms of number of individuals.

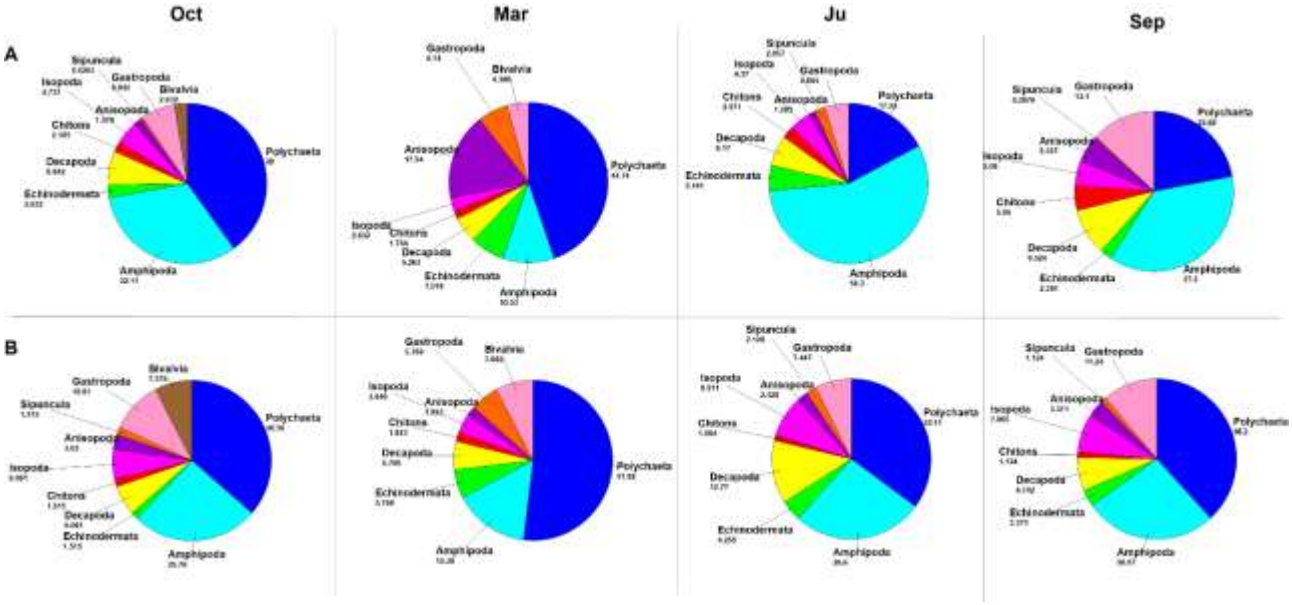

Fig. 5.15 Pie charts of taxonomic groups found in each sampling. A) Individuals; B) Species

The analysis of structural parameters of the population (Table 5.8) sampled in *P. oceanica* during 2015-2016 highlights a large number of taxa in June sampling (105) and a minimum in March (50). The same trend is followed by the number of individuals with a great increase in June (413). Indexes regarding diversity and evenness do not show marked changes through the sampling period; this suggests that communities with many taxa are equally present and each have few individuals and no dominant species.

Variable	October	March	June	September
Taxa	65	50	105	102
Individuals	187	112	413	355
Simpson (D)	0.96	0.94	0.94	0.97
Shannon (H)	3.73	3.51	3.73	4.06
Margalef (DMg)	11.33	10.38	17.11	17.2
Pielou (J)	0.91	0.89	0.80	0.87

Table 5.8 Structural parameters of population sampled in *Posidonia oceanica* that define abundance, diversity and evenness.

The trophic analysis of organisms shows that, in general, the largest frequency is comprised of *Dt* (Detritus feeders), followed by *Su* (Suspension feeders), *Pr* (Predators) and *Gr* (Grazers) (Fig.5.16).

In October, the trophic group of *Dt* (34%) is characterised by the largest abundance of organisms followed by *Pr* (28%), *Su* (17%) and *Gr* (16%). In March, the trend does not change except for a slight variation of the frequencies that involve the increase of *Su* organisms (*Dt* = 37%; *Pr* = 24%; *Su* = 22%; *Gr* = 14%) which became dominant in June (51%). In September, the frequency of Su decreased to 16.56% together with an increase of Pr (24.7%) and Gr (30.9%). Regarding the number of species, belonging to different trophic categories, it is noteworthy that the dominance of the *Dt* and *Su* species that rose more than 50%. A fluctuation of the number of species of different trophic categories from October to September is evident, especially for *Pr* and *Dt.* The number of species of suspended feeders increase from October to June and decrease in September. Grazers species are quite constant from October to June (14.8-17.4%) and undergo an evident increase in September (32.2%).

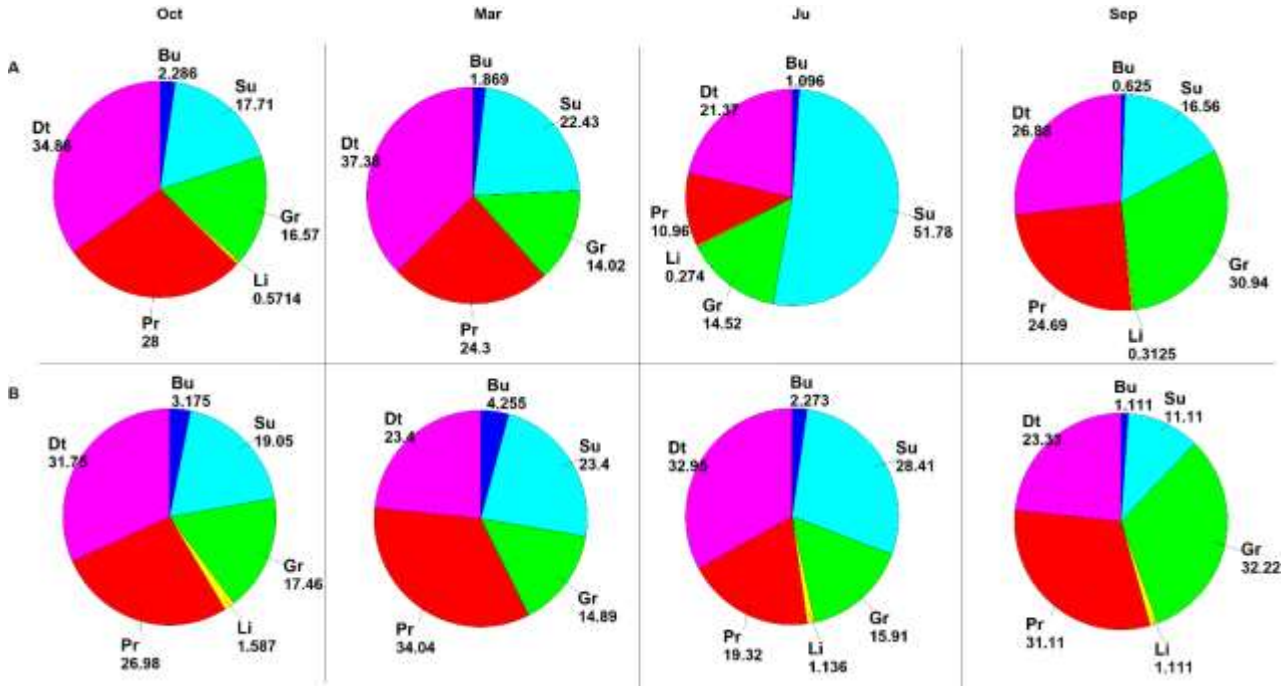

Fig. 5.16 Pie chart of trophic categories found in each sampling. A) Individuals; B) Species

From each sampling list, the 5 most-abundant species were selected and are reported in Table 5.9. In October, the most abundant species live in both levels of *Posidonia* shoot (rhizome and leaves) and cover a wide range of trophic categories. The trophic group *Dt* is associated with the most abundant species (*Polyophthalmus pictus*). In March, the dominant species only lives in rhizomes, and suspension feeders represent the most frequent trophic categories, which are also associated to the most numerous organism (*Chondrochelia savignyi*). In June, the most abundant species lives in both levels of the shoot, and there is a massive abundance of Amphipoda *Ericthonius punctatus* (76

individuals) and *Leptocheirus guttatus* (26). The dominant species belong to several trophic groups, and there is a great abundance of suspension feeders. In September, the most abundant species lives in both levels of the shoot with a similar abundance (17-26 individuals). The most abundant species belong to different trophic categories with a greater presence of suspended feeders.

Organism	October	March	June	September	Trophic role	Sample
Nereis rava	9	-	-	-	Pr	Rhizome
Polyophthalmus pictus	16	-	-	-	Dt	Rhizome
Leptocheirus guttatus	9		26	19	Su	Rhizome
Alvania discors	7	-	-	-	Gr	Hand net
Hippolyte inermis	9	-	10	26	Pr	Hand net
Nereis sp.	-	4	-	-	Pr	Rhizome
Megalomma messapicum	-	7	-	-	Su	Rhizome
Branchiomma bombyx	-	5	-	-	Su	Rhizome
Chondrochelia savignyi	-	20	-	-	Su	Rhizome
Amphipholis squamata	-	6	16	-	Dt	Rhizome
Ericthonius punctatus	-	-	74	23	Su	Rhizome
Rissoa sp.	-	-	13	-	Gr	Hand net
Quadrimaera inaequipes	-	-	-	20	Dt	Rhizome
Callochiton septemvalvis	-	-	-	17	Gr	Rhizome

Table 5.9 Dominant species observed in different surveys, trophic role and sample where are found

On the basis of previous investigations regarding sedimentary processes, Fig. 5.17 shows a large amount of resuspension of sediment during the autumn and winter seasons due to the high magnitude and frequency of storms. The resuspended flux and organic matter percentage of Fig.5.17A is averaged over the months between benthic surveys. The percentage of organic matter within sedimentation flux raises the maximum value in June and September when the foliar growth of *P. oceanica* is large.

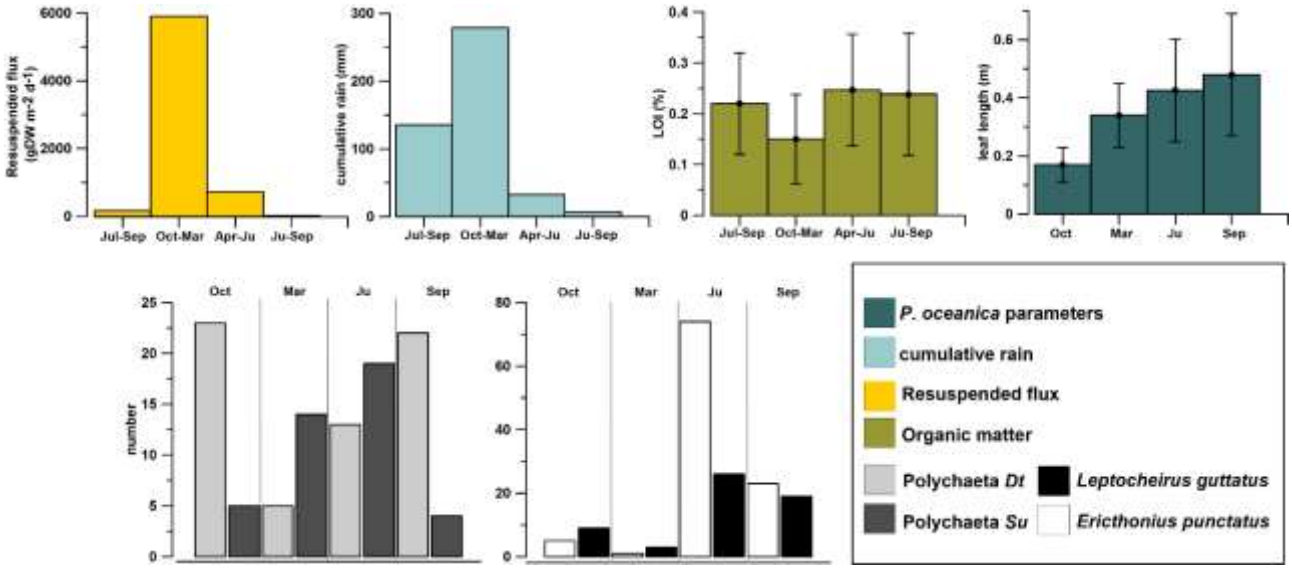

Fig. 5.17 Variation of resuspended flux, organic matter concentration in sedimentation flux and *Posidonia oceanica* parameters during different months of 2015-2016 as well as variation of trophic categories of Polychaetes and seabed indicators of *Posidonia oceanica* during the sampling period.

Together with a general increase of benthic population in June and enhanced by other ecological factors (i.e., temperature, light, nutrient availability), the Amphipodes (*Leptocheirus guttatus* and *Ericthonius punctatus*) greatly increased; this is directly linked to foliar stratum growth (Fig.5.17A). Furthermore, their presence is an indicator of the good quality of *P. oceanica* (Zakhama-Sraieb et al., 2006). The seasonal oscillation of the resuspension flux of sediment that reaches a maximum from October to March demonstrates the oscillation of the number of Polychaetes suspension feeders, which increases significantly in March. They experience further growth in June and undergo a sharp decline at the end of the summer. Conversely, Polychaetes *Dt* have a dramatic decay in March and then experience progressive growth until September. The oscillation of organic matter concentration of sedimentation flux corresponds with the dynamic of population of the detritus feeder group observed during the year (Fig.5.17).

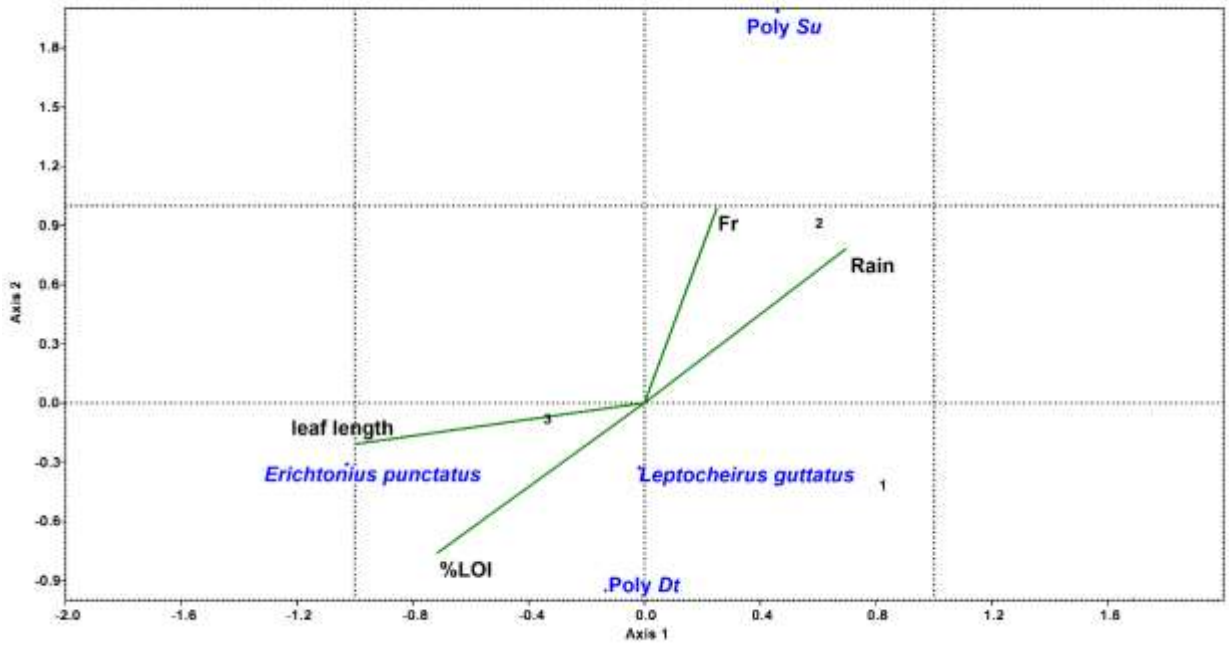

Fig. 5.18 Canonical correspondence analysis results

The canonical correspondence analysis reveals a statistical significance of correspondence between *Su* organisms and *Fr*, the abundance of Amphipoda *Leptocheirus guttatus* with leaf length and organic matter percentage with *Dt* abundance.

6. Discussion

The architecture of *Posidonia oceanica* meadow at the study site exhibits a cover of 69% with the presence of several sand patches of various dimensions. At a depth of 7 m, the variability of shoot density of *Posidonia* meadow is approximately constant throughout the study site. The canopy height of *P. oceanica* began to grow progressively from Winter to Summer, during which it reached its maximum extension. The growth of leaves involves both length and width, thus it also affected the leaf area index. On the contrary, *P. oceanica* sheds leaves from late Summer to Autumn, as observed in other Mediterranean coastal areas (Mateo and Romero 1996), causing the accumulation of leaf litter on the seabed, which also covers the adjacent unvegetated areas. The leaf litter remains on the seabed until the flow energy is not able to transport it away; after storms, they are usually deposited on the beachface with the formation of seagrass beach-cast leaf litter deposits, known as "*banquettes*" (Boudouresque et al. 2015) in Mediterranean Sea. The results show a seasonal relationship between the growth of leaves and the variation of the textural composition of bed sediments that result in the enrichment of sand and mud fractions during Spring and Summer. This result clearly indicates how the growth of leaves increases the effect of energy reduction at the bottom, favouring fine particle trapping. By comparing the depositional rates at different elevations from the seabed in the different stations and over the time, we observed a significant effect of different substrata on the vertical sedimentation flux. Moreover, the variations induced by presence and absence of seagrass occur inside a layer thickness of 0.8 m.

The measured depositional rates, in proximity to the bottom, were compared with others collected in previous studies (Table 5). The maximum value recorded in this study is reasonably larger than the others, considering the depth where the measurements were made. In shallow water, waves have a greater probability to induce sediment transport. In Table 4, we did not report flux data obtained during survey 2, when a huge storm occurred. During this survey, the maximum depositional rate was 9640±2848 g DW $m^{-2}d^{-1}$ in the PM station and 4275±335 g DW $m^{-2}d^{-1}$ in the SP station, highlighting a larger depositional rate inside the canopies.

Reference	*Max*	*Min*	*Depth*	*Bottom*
Burns et al. 1985	5.3	0.2	100	Water column
Monaco et al. 1990	181	2.7	10	Water column
Buscail et al. 1990	171(2379)	8.3	25	Water column
Bavestrello et al. 1995	17.5	2.5	15	Rock
Bavestrello et al. 1995	20	2.5	20	Rock
Bavestrello et al. 1995	20	2.5	25	Rock
Charles et al. 1995	107	0.6	18	Sand
Gremaire et al. 1997	318	0.6	18	Sand
Gacia and Duarte 2001	494	1.5	15	Sand
This study	5000	23.08	7	Sand
Dauby et al. 1995	10(40)	0.3	36	*Posidonia oceanica*
Gacia and Duarte 2001	215	2	15	*Posidonia oceanica*
This study	2520	3.58	7	*Posidonia oceanica*

Table 5 Summary of depositional rate ($gDWm^{-2}d^{-1}$) measured in the coastal environments of previous and present studies

The near-bed vertical sedimentation flux profiles show the dominance of the resuspension phenomena. The flux is mainly driven by shear stress induced by waves within a 0.8-m-thick boundary layer. Survey 2 was the only survey where a storm drove an intense winnowing of the seabed sediment, resuspending coarse material on the whole investigated sea layer. During the phases of the maximum growth of seagrass leaves, the concentration profiles clearly suggest the role of vegetation in the resuspension process attenuation. This effect can be further observed when comparing surveys with similar wave conditions (survey 1 vs. 6 and survey 5 vs. 11), during which the resuspended flux decreases by about 52% and 100%. Grain-size analyses reveal additional evidences about the trap effect induced by canopies: long leaves prevent the resuspension of the gravel bioclasts and induce a sharp decay of the coarse component peak along the vertical profile inside the vegetated station. The fine fraction of sediment, which is suspended during storms, undergoes deposition when the storm ends, while it is the dynamics of the coarse fraction during storm conditions that mark the variations of energy flux in the boundary layer.

The role of seagrass meadow on resuspension processes in shallow waters extends the previous finding in coastal areas at larger depths (Gacia and Duarte 2001). In our case, resuspension within vegetation occurs more frequently (54%) than previous results (33%), but it is always linked to high energy events and to a phase of short leaves. These experimental evidences in natural conditions are in agreement with results obtained by flume experiments: Stratigaki et al. (2011) and Manca et al. (2012) studied the wave attenuation induced by a seagrass bed with a density of artificial shoots within a range 180 – 360 shoot m^{-2}, which is comparable with the density of natural meadow of this study (260 – 312 shoot m^{-2}). Flume experiments have demonstrated the ability of meadows to reduce shear stress at the bottom, especially if caused by low energy waves—this corresponds with our results when during normal wave conditions the canopies produce clear attenuation or prevention of

resuspension process. The resuspension process seems to be frequent in shallow water and in the vegetated bottom due to the larger interaction of waves with the bottom and by the "*monami*" effect that enhances the penetration of turbulent stress into the canopy (Ghisalberti and Nepf 2002). However, the attenuation of resuspension induced by canopies is evident if PM is compared to the SP and UB stations, where the resuspension process occurs frequently (respectively, 81 and 100%).
Most of the wave-height decay occurred within the first few metres of the meadow, as observed in the flume experiment (Manca et al. 2012), and in natural shallow seagrass beds (Bradley and Houser 2009). Therefore, waves are also generally attenuated by vegetation when they travel over a sand patch inside the meadow rather than over an open unvegetated area. The sand patch shows intermediate features explained by local wave interaction caused by the sudden change in the bottom friction encountered by the waves. In the presence of resuspension, the intermediate response of the SP station is also visible when comparing the contribution of resuspended flux to the total depositional rate. The contribution amounts to 72% in the PM station, 81% in SP and 94% in UB. This value is less than that observed within the meadow of Fanal Point (85%) by Gacia and Duarte (2001); this is probably due to the different distances from the coastline, which could determine a greater influence of mainland run-off on sedimentary balance. In this study, the flux of the fine fraction component (grain mode 2) during storm events fluctuates between 20% and 60% of the total sedimentary flux at the bottom. At an elevation of 1.3 m from the bottom, the suspended component, which dominates the total sedimentation flux at this height, is correlated to the rainfall that directly governs mainland run-off in the study site. The settling flux of fine particles over the meadow fluctuates within a wide range of 2.48 – 1971 g DW $m^{-2}d^{-1}$, which is strictly dependent on the rain intensity. Once again, we stress the greater capacity of the vegetated bottom in the retention of fine particles, which enhances the primary flux that largely contributes to the depositional rate (i.e., 60%). Deposition of the fine primary flux is on the average subordinate (27%) in SP and scarce (6%) in UB.
This study found that the trap effect induced by canopies might act in two ways depending on the hydrodynamic regime near the bed. During weak hydrodynamic conditions, the dominant process is the attenuation of resuspension induced by canopies, while over a threshold of transport capacity of waves, the trap effect of canopies translates into an increment of depositional rate fed by the advection of coarse material, which is resuspended from the adjacent unvegetated patches.
This thesis is supported either by grain-size signatures of sediment collected in the traps either by the erosive features observed in the sand patch; this suggests the presence of a higher energetic regime in SP than PM. This result is in agreement with previous studies, which demonstrates the role of seagrass in the enhancement of deposition (Scoffin 1970; Short and Short 1984; Walker et al. 1996), but it also gives further confirmation regarding the complexity and variability of the particle-trapping

process (Gacia and Duarte 2001). The greater resuspension always observed in the UB station provides further proof that wide, bare sand is more susceptible to winnowing than seagrass and that seagrass plays a major role in sediment retention, buffering resuspension. A very similar consideration concerns the late-Summer period when leaf litter widely covers the seabed. Both the PM and SP stations are affected by a significant attenuation of the wave-induced bed shear stress, which is evident by the prevention of the coarse fraction resuspension. As a control, the same component is found in the UB station free from leaf litter. Similar to "*banquettes*", which are constituted by accumulation of seagrass necromass (leaves and rhizome), they are able to dissipate some portion of storm energy (Simeone and De Falco 2012) and to suppress wave run-up and to limit beach change on the low-energy condition (Nordstrom and Jackson 2012), the leaf litter deposed on the seafloor buffers sediment particle, thus acting as a temporary armouring that prevents resuspension. This feature could be added to the biogeomorphology of *Posidonia oceanica* summarized by Vacchi et al. (2016).

Regarding organic matter, the results indicate a similar trend of organic matter percentage within flux. The growth of *P. oceanica* rises from Autumn toward the summer together with a substantial increase of fauna in terms of abundance and diversity. The same trend of organic matter concentration is observed in the seabed samples, Table 6 reports previous results recorded in seabed samples collected in coastal areas of the Mediterranean Sea.

Reference	***Max (%)***	***Min (%)***	***Depth***	***Bottom***
Gadel, 1975	0.6	0.4	40-100	Circalittoral muddy deposit
Buscail, 1995	<0.3	-	0-10	Sand
	1.1	1.6	25-50	Prodelta deposit
	0.5	0.25	100-200	Fossil sand
Gambi et al., 1998	6	3	2-5	*Cymodocea nodosa*
Pusceddu et al., 1999	52.6	5.1	0.5-2	Lagoon deposit
Gacia et al., 2002	0.67	0.8	15	Sand
	1.47	0.71	15	*Posidonia oceanica*
This study	3.44	1.46	7	Sand
	2.75	2.11	7	*Posidonia oceanica*

Table 6 Summary of organic matter concentration (%) measured in coastal environment of previous and present studies

Organic matter flux depends on total particulate flux without significant differences between the stations inside the meadow and sand patch. This suggests that the intra-patch variability of sedimentary processes is constrained to inorganic matter linked to the flow's energy. The results also highlight the relationship between organic matter flux and the amount of rain that governs the

mainland run-off. This relationship disappears inside the canopy where several processes contribute to the sedimentation flux. An inverse relation is observed between the capacity transport of waves and the concentration of organic fraction within the total sedimentation flux. Previous studies (Gacia and Duarte 2002) in the western Mediterranean Sea demonstrated that organic carbon flux derives from sedimented sestonic particles and seagrass detritus; in particular, seagrass and its associated epiphytes contribute 29% of the sedimentary flux of organic carbon and represent 43% of the organic carbon present in the sediments. On this basis, our results suggest that the sedimentation probability of sestonic particles that come from the mainland is regulated by wave energy, and wave energy also regulates the probability of seagrass detritus to remain inside the canopy. Sestonic particles, biological activity of *P. oceanica* and its faunal assemblage are the major sources of organic matter, but wave energy regulates the organic matter concentration inside the canopy. Especially during the phase of maximum growth of the leaves, the capacity of seagrass to reduce resuspension enhances the particle trapping, favouring the settling of organic matter.

Structural parameters of the population suggest that the faunal assemblage of *P. oceanica* is composed by many equally present tax and that each have few individuals—that is, there is no dominant species, which is typical for shallow-water communities (Bedini et al., 2011). In particular, during sampling (2015-2016), the benthic communities associated with *P. oceanica* was composed by 1067 individuals belonging to 192 species, where the most abundant taxa were Amphipoda (417 individuals of 40 species); but, in terms of biodiversity, Polychaetes are represented by 60 species and 258 individuals. The Gastropoda group, which is one of the most representative taxa associated with *P. oceanica* (Gambi et al., 1992; Mazzella et al., 1992; Scipione et al., 1996; Bedini et al., 2011), is represented with 83 individuals of 18 species (7.8% of the whole community). The crustaceans group is the most abundant taxon and is represented by Amphipoda, which are strongly related to *P. oceanica* growth (Parker et al., 2001; Bedini et al., 2011); their maximum abundance was detected in June when environmental conditions (i.e., temperature, nutrient availability and light) favour the development of the population. In particular, the Amphipoda pool is represented by species *Erichtonius punctatus* and *Leptocheirus guttatus*, which are often typical of shallow-water populations and good quality *Posidonia* meadows (Zakhama-Sraieb et al., 2006; 2010). The Polychaeta community is represented by typical species associated with shallow-water *Posidonia* meadows (Gambi et al., 1992) and represent, in these samplings, the most abundant group in terms of number of biodiversity in rhizomes as observed by previous studies where this taxon dominates. The Polychaeta assemblage is often dominated by predator (*Platynereis dumerili*, *Syllis* spp.) and detritus feeder (*Polyophtalmus pictus*) species, but during Autumn and Winter, the population changes: there is an increase of suspension feeder species (*Megalomma messapicum, Branchiomma*

bombyx) linked to large resuspension of sediment due to storms as observed by trap records. The role of the sedimentary regime on the dynamic of the population is also elucidated by narrowing feeding categories toward suspension feeder species (i.e., Anisopoda *Chondrochelia savignyi*) that dominate the March sampling. The benthic community is largely represented by a detritus feeder group associated with detritus that settled in the rhizome stratum of *P. oceanica*; this community follows a seasonal oscillation of organic matter linked to biological activity of *P. oceanica* and its fauna. The observed capacity of a *P. oceanica* meadow to retain particles, especially during the maximum growth of leaves, favours the accumulation of organic matter and sediment that contribute to matte accretion (Gacia & Duarte, 2001; Gacia et al., 2002) and provide habitat and feed for benthic species that live in the rhizome-matte stratum (Polychaetes, Echinodermata and Bivalvia). Fauna associated with leaves increase together with foliar growth of *P. oceanica* and are represented by vagile suspension feeder and grazer species of Crustaceans (Amphipoda and Decapoda) and Gastropoda; the latter (*Gr*) has the maximum development at the end of summer.

6. Conclusions

This study expands current knowledge regarding the role of *P. oceanica* meadows on sedimentary processes thanks to a specific in-situ monitoring lasting more than one year. Moreover, the sedimentary dynamics of inorganic and organic matter are related to the variations of benthic communities. This multi-disciplinary approach uses the support of sedimentology and taxonomy to experimentally clarify the effect of coastal dynamics on the community structure throughout one year. The resuspension process generated by waves that mainly drives coastal dynamics is attenuated by vegetation by more than 50% during the maximum growth phase of leaves. The shallow-water dynamics are characterised by a frequent resuspension pattern. The waves that propagated over a vegetated field bottom are generally damped compared to an unvegetated bottom, and in a fragmented meadow, the local wave interaction caused by the sudden change in bottom friction encountered by the waves produce more resuspension in the sand patch. *P. oceanica* mainly buffers resuspension, but in the presence of high energetic regime of flow near the bottom, the canopies favour the deposition of particles transported from adjacent unvegetated areas. Further investigations are needed to further describe the dynamics of this process. In shallow waters, the meadow tends to enhance the capture of fine particles that derive from the primary flux, which is significantly linked to run-off. During late Summer, the leaf litter deposed on the unvegetated seafloor buffers seabed sediment particles, preventing resuspension at least for the duration of a storm able to induce drag forces that carry away all of the leaf litter. Organic matter flux is quantitatively linked to total sedimentation flux, which is driven by weather forcings. Sestonic particles, biological activity of *P. oceanica* and

its faunal assemblage are the major sources of organic matter, but wave energy regulates the organic matter concentration inside the canopy. Vagile fauna is strongly dependent to the growth of leaves, while the population of rhizomes is more susceptible both to sedimentary dynamic regime and organic matter compound that causes a shift of trophic categories. The capacity of a *P. oceanica* meadow to retain particles, especially during the maximum growth of leaves, favours the accumulation of organic matter and sediment that contribute to matte accretion and provide habitat and feed for benthic species that live in the rhizome-matte stratum.

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