Article

Silting Process and Loss of *Posidonia oceanica* Meadows in the Tyrrhenian Calabria Waters (Southern Italy)

Fabio Ietto[1], Gaetano Pellicone[2] and Nicola Cantasano[3*]

[1] Department of Biology, Ecology and Earth Sciences (DiBEST), University of study Calabria, Via P. Bucci, cubo 15b- 87036 Arcavacata di Rende (CS), Italy. e-mail: fabio.ietto@unical.it
[2] National Research Council, Institute for Agricultural and Forest Systems in the Mediterranean, Rende Research Unit, Rende, Cs., Italy. e-mail: gpellicone@gmail.com
[3] National Research Council, Institute for Agricultural and Forest Systems in the Mediterranean, Rende Research Unit, Rende, Cs., Italy, retired. e-mail: cantasano@tiscali.it.
* Correspondence: Corresponding author e-mail address: cantasano@tiscali.it

Abstract: In the Mediterranean Sea, there are two critical issues affecting marine benthic biocenosis: the sedimentation process and the increasing trend in marine biodiversity loss. These processes are very marked along the western side of Calabria coastline where siltation is one of the main reasons for the regression of Posidonia beds in the regional coastal waters.

This research aims to investigate the relationships between the geomorphological features of the debris source areas, represented by fluvial basins, and the distribution of Posidonia meadows. So, a geomorphological study of the Tyrrhenian fluvial basins with area greater than 200 km^2 and its correlation with the mapping of the meadows in the Calabria Tyrrhenian waters was carried out. Furthermore, in order to assess the increased level of burial in a *Posidonia oceanica* meadow and its health state over time, a program of Posidonia monitoring was undertaken between 2000 and 2010, in a test area located in the Marine Regional Park of Isca (Calabria, Southern Italy). The results of this survey highlighted that, at the beginning of the study period, for a silting rate of 4 - 5 cm/year, the meadow suffered a reduction of its photosynthetic ratio with a rate of mortality of 50%. In the following years, the siltation rate reach 12 cm/year in 2010 and the meadow began to disappear. Therefore, the marine pollution by sedimentation represents a serious factor for the regression of *Posidonia oceanica* meadows, enhancing the risk of a gradual loss in marine biodiversity.

Keywords: hydrographic network; *Posidonia oceanica* meadow; burial process; regression rate; Calabria region; Mediterranean Sea

1. Introduction

Around 60% of the world's population live in coastal regions despite only representing 10% of the Earth's surface (Parthasarathy and Natesan, 2015). The high demographic pressure could increase in the next decades, as urbanization is driving a growing movement of people towards the coast. A wide range of services are provided by coastal systems: fishing, harboring, commercial trade and coastal tourism. The littoral zone is a sensitive area where sea and land interact and play altogether an important role, integrating coastal water and its watershed in a whole system. However, the increasing urbanization of seaboard and river basin areas, the proliferation of harbors and the realization of artificial barriers, to protect sandy beaches from erosion, are contributing to a progressive deterioration of the coastal sedimentary balance. This trend could modify, in time, the structure of marine benthic ecosystems, causing a potential loss in marine biodiversity (Pimm and Raven, 2000). Amongst the main environmental problems in the Mediterranean Sea, two critical ones are: the process of sedimentation and the increasing trend in biodiversity loss, which has also been

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 25 May 2023 doi:10.20944/preprints202305.1751.v1

identified in other semi-enclosed basins as the Baltic and the Black Seas (Zaitsev 2006; Shadrin et al. 2012).

Seagrasses are one of the marine ecosystems most vulnerable in the Mediterranean (e.g., Jordà et al. 2012; Marbà et al. 2014) and they are often considered as biological sentinels because any change in their distribution or health state implies an environmental shift (Orth et al. 2006) due to natural or artificial causes. *Posidonia oceanica* L. (Delile) is the most common seagrass species in the Mediterranean Sea and nowadays it is undergoing a strong decline in its density and extension (Boudouresque et al. 2012; Marbà et al. 2014). Among the positive effects of Posidonia meadows, it includes effective traps for sediments, balancing the sensitive sedimentary budget of vegetated areas but also their role in contrasting erosion processes (Fonseca 1996; De Falco et al. 2000). Furthermore, during its biological evolution, *Posidonia oceanica* performed an important pivotal role in the development process of some endemic new species living on its leaves, especially amongst Bryozoan and Hydrozoan sessile species (Table 1) (Boero et al. 1985; Kocak and Aydin-Onen 2014; Lepoint et al. 2014).

Table 1. List of endemic sessile species recorded on Posidonia leaves. Legend: En=Encrusted; Er=Erected; In= Insinuating; Ma=Massive.

SPECIES	AUTHORS	PHYLA	CLASSES	ORDERS	HABIT
Agalophenia harpago	Schenk, 1965	Cnidaria	Hydrozoa	Leptothecata	Er
Campanularia asymmetrica	Stechow, 1919	Cnidaria	Hydrozoa	Leptothecata	In
Coryne epizoica	Stechow, 1921	Cnidaria	Hydrozoa	Antothecata	Er
Electra posidoniae	Gautier, 1954	Bryozoa	Gymnolaemata	Cheilostomatida	En
Fenestrulina joannae	Calvet, 1902	Bryozoa	Gymnolaemata	Cheilostomatida	En
Monotheca posidoniae	Picard, 1952	Cnidaria	Hydrozoa	Leptothecata	Er
Sertularia perpusilla	Stechow, 1919	Cnidaria	Hydrozoa	Leptothecata	Er
Tricolia speciosa	Von Mühlfeldt, 1894	Mollusca	Gasteropoda	Trochida	Ma

Thus, *Posidonia oceanica* meadow was protected by EU legislation (Habitat Directive 92/43) and inserted in the Red List of the International Union for Conservation of Nature (Borum et al. 2004; Pergent et al. 2010; Boudouresque et al. 2012; Holon et al., 2015).

Several authors (Boudouresque et al. 2012; Marbà et al. 2014; Roca et al. 2014) discussed the Posidonia decline topic, showing that the greatest suffer state was observed close to the urbanized coastal areas and mostly associated with various human activities such as: pollution, mining, engineering works, tourism and others. However, the effective influence of each of these potential causes on the overall decline of meadows remains unknown. Amongst the main causes, coastal sedimentation may lead to the complete burial of the meadows and subsequently their disappearance, hence it is considered amongst the main causes of Posidonia decline (Marbà and Duarte 1998). In fact, it is well known that, in conditions of coastal pollution by silting process, the rate of sedimentation at the base of meadows, can reach an annual rate of 15.0 cm/year, while the vertical growth of the orthotropic rhizomes of the plant is about 1.5 – 2.0 cm/year (Boudouresque and Meinesz 1982; Gacia et al. 2003). This large difference in the kinetic of the two processes can produce, in time, the reduction or, in extreme cases, the complete burial and the death of the meadows (Gacia and Duarte 2001). Therefore, the study of the silting process, the sedimentation rate and the geomorphological features of the sedimentary source areas, such as river basins, becomes of great interest for the international scientific community. These processes may lead, in time, to a potential deterioration of environmental conditions for marine ecosystems.

In Italian coastal waters, the marine pollution by siltation is one of the main reasons for the regression of Posidonia prairies (De Falco et al. 2000; Boudouresque et al. 2009). Italian coastal areas are considered one of the most densely urbanized and populated amongst the Mediterranean countries (W.W.F. 2014; Cantasano et al. 2017). Moreover, there are many littoral stretches exposed to an increasing environmental pollution caused by engineering works, industrial plants and factories that discharge their waste disposals into coastal waters. In Italy, also Calabria coastal region (southern Italy), with more than 800 km of coasts, is strongly altered by an unorganized urban development that, in the last century, produced a chaotic overbuilding of the littoral landscape and the destruction of several natural environments. (D'Alessandro et al. 2002; Ietto et al. 2018c). The chaotic urbanization, affecting both littoral areas and river basins, influences also the shallow-marine sedimentary processes (Ietto 2001; Ietto et al. 2018c). Furthermore, the geomorphological features of fluvial catchments place the region in a high state of landslide risk (Sorriso-Valvo and Sylvester 1993; Antronico et al. 2017a; Conforti and Ietto 2019, 2020), producing a great abundance of material that severely affects the survival of seagrass meadows. For these reasons, the Calabria Tyrrhenian coasts represent a favorable setting to study the resilience of *Posidonia oceanica* meadows to silting process due to river sedimentary load.

The aim of this paper is to evaluate the interaction between the state of health of a *Posidonia oceanica* meadow and the sedimentary pattern in a test area located in the Marine Regional Park of Isca in the western Calabria coast (southern Italy). At this regard, it has been planned a monitoring program, in the period 2000-2010, to assess the increasing level of burial on a *Posidonia oceanica* meadow located in the Marine Regional Park of Isca. For this scope, the research was based on the study of the sampled sediments, such as grain-size, composition and provenance, as well as on the assessment of silting rate to control the state of health of a *Posidonia oceanica* meadow.

2. Materials and methods

To reach the target of this study, regarding the complexity of coastal areas, it is necessary to identify the spatial distribution of hydrographic basins and, at the same time, to know in which context they are inserted. Furthermore, these data have been processed through Geographic Information System (Quantum GIS 17.0), overlapping all the cartographic elements with digital images released by Google Earth Maps on 2022 year.

2.1. Study area

The Calabria Tyrrhenian coast is characterized by a littoral area that extends mainly at foot slopes of uplifted mountains belt, having elevations higher than 1500 m. In Calabria, the high rates of uplift process (Ghisetti, 1981; Ietto and Bernasconi, 2005; Antonioli et al. 2009) have been responsible for reliefs with high erosional energy and continuous rejuvenation of the hydrographic network, causing a high erosion rate and rises widespread instability processes (Ietto et al. 2015; Antronico et al., 2017b). The mountain range, named "COASTAL CHAIN", lays at about 6 km from the coast crossed by rare fluvial plains. The main geological features of the area (Figure 1) are represented by rocky masses made up of dolostone, limestone and marble, from Anisian to Langhian in age (Scandone 1982; Ietto and Ietto 1998; Barca et al. 2010), which outcrop on the northern side of the region.

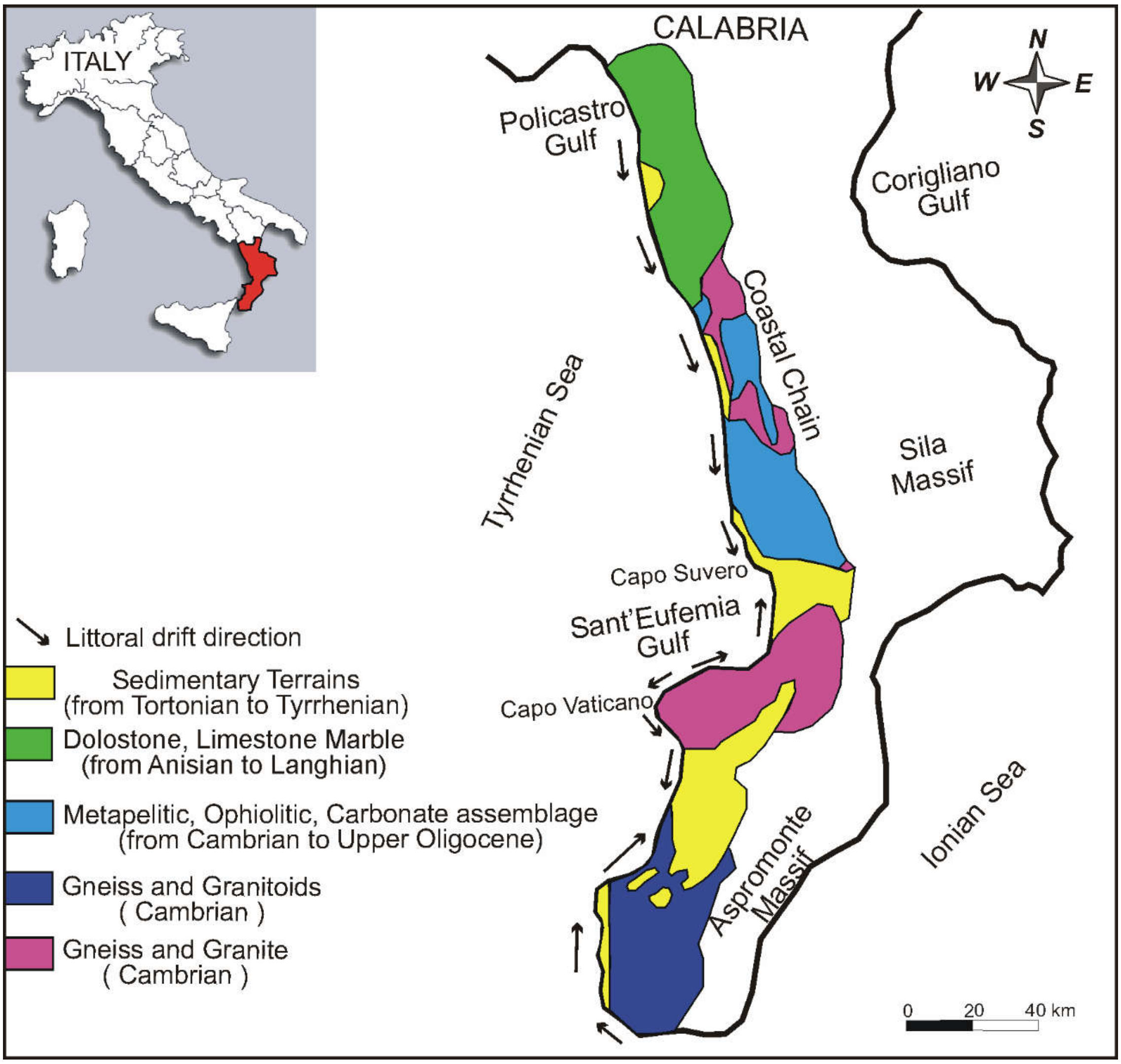

Figure 1. Geological map showing the main lithologies in the study area.

Cambrian to Upper Oligocene terranes, constituted by metapelitic-ophiolitic-carbonate assemblage, ranging from high- to middle- to low-grade metamorphic (e.g. Amodio-Morelli et al. 1976; Carrara and Zuffa 1976; Lorenzoni et al. 1983), occur on the central part of the Calabria coastal mountains. Cambrian gneiss and granite, which underwent intense weathering processes (Ietto and Ietto 2004; Perri et al. 2016; Borrelli et al. 2016; Ietto et al. 2018a), outcrop in the same area. Finally, in southern side, gneisses overlain by Cambrian granitoids constitute the Aspromonte massif (e.g., Bonardi et al. 1992; Graeßner and Schenk 1999), which represents the southernmost area of Calabria. Sedimentary terrains from Tortonian to Tyrrhenian ages, constituted by unconsolidated deposits or by marine arenitic sediments involved in weathering processes (e.g., Ietto et al. 2013, 2018b), discontinuously dominate the littoral areas on the southern side. The varying geology along the Calabria Tyrrhenian coast characterized by very narrow sandy beaches, interrupted by limited rocky spurs in the northern and central part of the region, while rocky cliffs with pocket beaches predominate in the southernmost side. Several researchers demonstrated that the beaches on the Calabria Tyrrhenian coast have suffered a strong erosional process in the last century, keeping erosion rate as a magnitude value i.e. 1 m/year, mostly close to river mouths (e.g. Ietto 2001; D'Alessandro et al. 2011; Ietto et al. 2012, 2018c; Cantasano et al. 2017). The same authors asserted that the human factor, such as the rough urbanization of littoral areas, represents the main cause of the severe erosion process affecting sandy beaches.

The continental shelf on the Calabria Tyrrhenian side has an average extension of 5 km, which reaches a width of 10 km, only along the western coastline of the region, in the littoral area of Capo

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 25 May 2023 doi:10.20944/preprints202305.1751.v1

Suvero surroundings (Mongardi et al. 2004). The continental shelf margin is shaped by widespread instability phenomena, testify by slide scars, gullies and canyons, covering 520 km^2 of seafloor (52% of the Calabria continental margin) (Chiocci and Casalbore 2017). In particular, more than 400 slide scars have been recognized in this area with a transport of about 1.4 km^3/year of sediments (Casas et al. 2016). Submarine canyons, indenting the continental shelf up to a very shallow depth and close to the coast, are also very common along the Tyrrhenian continental margins (Mongardi et al. 2004; Pierdomenico et al. 2016). These canyons act as major conduits for transport of sediment, water masses and organic matter to bathyal and abyssal depths (Shepard 1972; Canals et al. 2006). Furthermore, the subtidal profile of shallower water in the studied coast is characterized by steep gradient up to 10%, making the approach of sea waves to the coast more dynamic (e.g. Punzo et al. 2016; Ietto et al. 2018c).

The exposition of the coast to wind and to sea wave action is from North-West, West and South-West directions. In particular, the mean wave approaching the coast from north-west direction has a significant offshore height of 2-3 m. Besides, the height waves, with significant offshore height greater than 5 m, propagate from west-southwest, where the major geographic fetch occurs (e.g. Ietto et al. 2018c).

The geographic position and the mountainous nature make the region characterized by a variable climate, known as Mediterranean climate, with dry subtropical summers and wet winters. Indeed, during the winter and autumn seasons the coastal mountains trap the wet air currents, moving inland from the Tyrrhenian sea, able to produce high-intensity rainfalls. Precipitation values, ranging from 600-1000 mm/year to more than 1800 mm/year, occur in lower and higher elevations of the coastal mountain, respectively (Caloiero 1975; Petrucci et al. 1996). Intense downpour, overcoming the historic average rainfall values, are frequent, triggering landslides and flooding in littoral areas (Ietto et al. 2014, 2015; Ietto and Perri 2015, Antronico et al. 2017a).

2.2. Geomorphology of the Tyrrhenian hydrographic network

The Calabria Tyrrhenian side is mainly characterized by a drainage network, constituted by deep and narrow incisions, orientated with a prevalent NE-SW direction in according with the main structural lineaments of the zone (e.g. Sorriso-Valvo et al. 1998; Ietto et al. 2015; Antronico et al. 2017b). In the Calabria Tyrrhenian flank, five river basins have a catchment area larger than 200 km^2 (Figure 2 and Table 2).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 25 May 2023 doi:10.20944/preprints202305.1751.v1

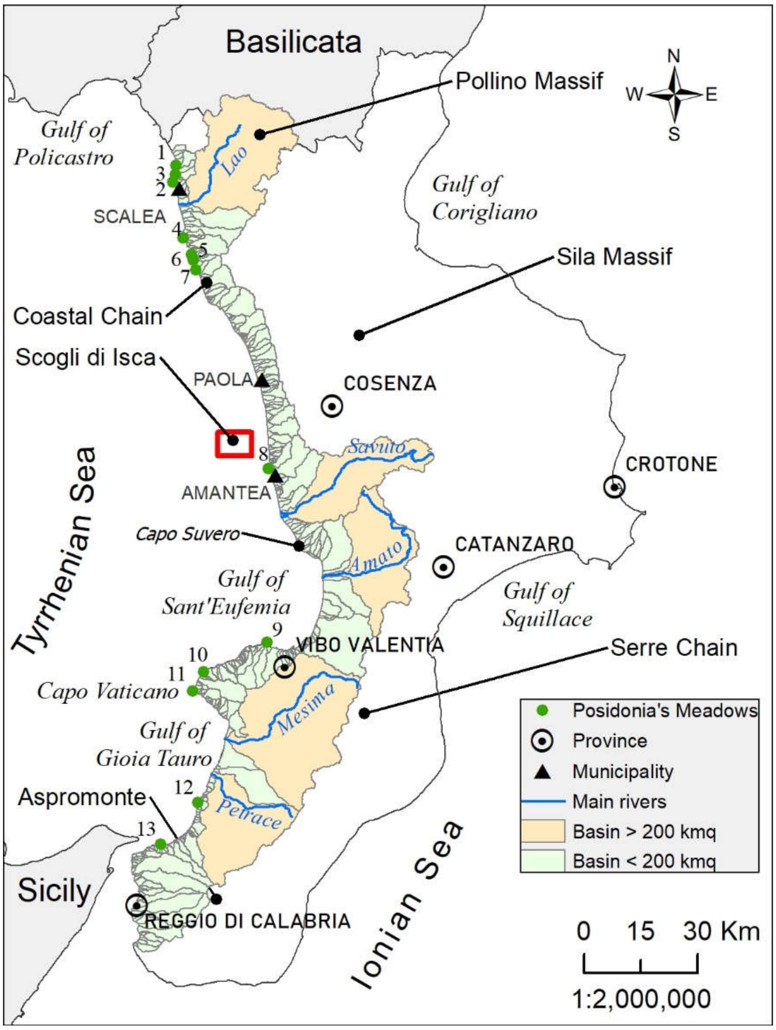

Figure 2. Location of the main river basins (pink areas) and of the meadows of *Posidonia oceanica* (numbers cited in Table 2 and green circles) on the Calabria Tyrrhenian Coast. In the red rectangle is showed the tested area.

 doi:10.20944/preprints202305.1751.v1

Table 2. The meadows of *Posidonia oceanica* along the Calabria Tyrrhenian side, for the location see Fig. 2.

NUMBERS	STATIONS	LATITUDES	LONGITUDES
1	ISOLA di DINO	39°52'14.00"N	15°46'59.62"E
2	SAN NICOLA ARCELLA	39°50'57.53"N	15°46'51.22"E
3	CAPO SCALEA	39°49'52.80"N	15°46'27.62"E
4	ISOLA di CIRELLA	39°41'55.15"N	15°48'14.70"E
5	PUNTA SANTA LITTERATA	39°39'28.54"N	15°49'45.31"E
6	PETROSA MARINA	39°38'40.87"N	15°50'04.96"E
7	CAPO TIRONE	39°37'17.49"N	15°50'35.86"E
8	SCOGLI di ISCA	39°08'47.36"N	16°03'27.96"E
9	TORRE di BRIATICO	38°44'03.21"N	16°02'49.68"E
10	SANTA DOMENICA	38°39'52.03"N	15°51'12.43"E
11	CAPO VATICANO	38°37'09.48"N	15°49'13.50"E
12	PALMI MARINA	38°21'15.70"N	15°49'58.66"E
13	SCILLA	38°15'19.09"N	15°43'09.97"E

In particular, the surface of each considered basins ranges from 400 km^2 to 800 km^2 and is dominated by a great variety of rocky masses often strongly weathered (e.g. Ietto and Ietto 2004; Perri et al. 2016; Borrelli et al. 2016) and, therefore, easily erodible by the runoff water. The morphometric analysis, performed with GIS techniques, was used to calculate some features as hierarchy degree and hypsometric curve. In particular, the drainage network of the five basins was automatically extracted from the DEMs, with the support of the Hydrology tool of ArcGIS according the methodology described by Peckham and Jordan (2007). The DEMs, with a spatial resolution of 5 meters, were downloaded from the website of the Centro Cartografico Regione Calabria (http://geoportale.regione.calabria.it/opendata). Subsequently, the drainage lines were hierarchically ordered according to the Strahler (1964) hierarchic scheme. Therefore, the geometrical analysis, performed for the five basins, shows a high hierarchy degree with values ranging between 6 and 7 (Table 3), denoting a well-organized fluvial network (e.g. Ciccacci et al. 1992; Centamore et al. 1996).

Table 3. Main river basins (area > 400 km^2) of the Calabria Tyrrhenian side, for the location see Figure 2.

N.	RIVER BASINS	AREAS (KM2)	LENGHTS (KM)	HORTON PARAMETRS
1	Lao	394.46	63.15	6
2	Savuto	411.54	55.14	6
3	Amato	441.09	61.17	7
4	Mesima	813.36	54.49	7
5	Petrace	406.62	37.46	7

Equally, the hypsometric curve and hypsometric integral were also computed using DEM and GIS software following the methodology described by Pike and Wilson (1971). These features are important indicators of watershed conditions (Strahler, 1952; Ritter et al., 2002) because the shape of the curve and the values of hypsometric integrals describe the stages of landscape evolution and provide an indication of the erosion status of fluvial basin (Ciccacci et al., 1992; Weissel et al., 1994). In particular, the convex shape of hypsometric curve (hypsometric value < 0.4) shows that the basin area is stabilized. By this way, the straight shape of the curve (hypsometric value = 0.5) denotes that the vertical erosion is a dominant process, while the concave shape (hypsometric value > 0.6) points out a more proneness to the erosion processes in the catchment zone (Strahler, 1952; Hurtrez et al., 1999). In the study area, the assessment of a state of geomorphic equilibrium of the five basins shows the presence of two groups characterized by a different evolutionary tendency of the landforms. To the first group belong Lao, Savuto and Amato basins, showing a straight-shape of the hypsometric curve, that corresponds to a hypsometric integral value close to 0.5 (Fig. 3). The geomorphological condition based on this value is typical of a mature stage or an equilibrium phase for the drainage network, where the vertical erosion of the river bed is mostly vertical and it is balanced by the sediments produced by slope instability (e.g. Strahler 1952; Ciccacci et al. 1992; Willgoose and Hancock 1998). Two basins, surrounding Mesima and Petrace rivers, belong to the second group having a hypsometric curve with upward concavity and corresponding to a hypsometric integral value less than 0.4 (Figure 3).

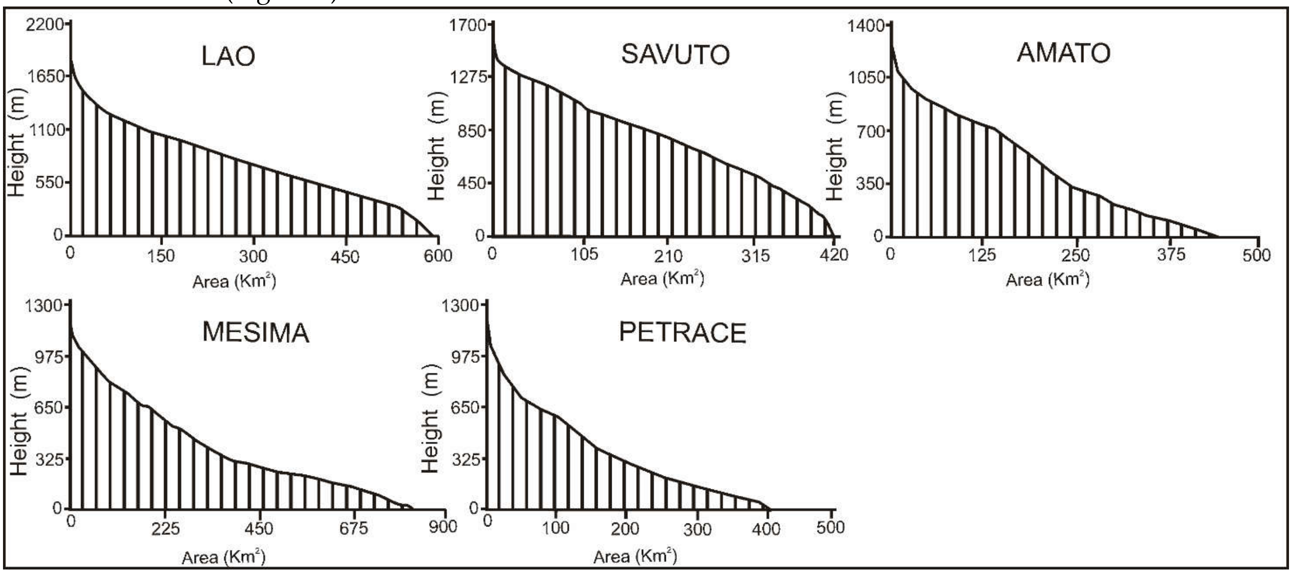

Figure 3. Hypsometric curves of the five main river basin in the study area. The y-axis shows the height in m, instead the x-axis points the area in km².

This value shows an old stage (nicknamed as 'Monadnock stage' in Strahler 1952) for the drainage networks where the instability slope is the dominant process in the basin area.

Basins with a very small area, characterized by channels with steep bed gradient and potential high sediment transport load, are widespread on the Calabria Tyrrhenian side. Usually, these small basins have a fluvial axis with a river bed gradient over 20% that decrease notably only towards the mouths. A hierarchy degree (Horton's parameters in Horton 1945) very low, with value less than 3, characterizes the drainage network of these small catchments, showing a limited organization of the drainage streams and a high predisposition to undergo significant modifications (Ietto and Perri 2015). In these basins, the water discharge occurs with high energy and in short time (Marchi et al. 2010; Ietto and Perri 2015; Ietto et al. 2015). These geomorphological features, during heavy rainfalls, favor the triggering of dangerous flash flood events, characterized by short-term phenomena with rapid and abundant flow of water and debris material. These fast events often cause flooding with consequent damage and, sometimes, fatalities in littoral areas (e.g. Ietto et al. 2014, 2015), as well as high supply of debris to the shelf area.

In particular, in this area mass-movements are abundant mainly in basins characterized by weak metamorphic rocks where the landslide areal incidence can reach values over the 40 per cent (e.g., Sorriso-Valvo and Sylvester, 1993). So, the fluvial sediment load is distributed by littoral currents oriented southward on the northern side of the Calabria Tyrrhenian coastline while in the central part of Tyrrhenian Calabria coasts the littoral currents show frequent directions change. Finally, littoral currents with a northward direction characterize the southern portion of the western Calabria coasts (Fig. 1) (Lupia Palmieri and Raffi, 1983).

2.3. Case study: Marine Regional Park "Scogli di Isca"

To assess how the level of sediment burial impacts the health of *Posidonia oceanica*, we conducted a monitoring program in an area of the continental Calabria Tyrrhenian shelf. The site, chosen as a place representative of the full coast, falls in the Marine Regional Park "Scogli di Isca" (Figure 2) that is part of the marine Site of Community Interest (SIC – IT9310039) within Natura 2000 Network, where a large submerged meadow of *Posidonia oceanica* (Linnaeus) Delile is present. The test area, known as "Scogli di Isca" is placed between the littoral town of Amantea and the outlet of Verri stream (Figure 4).

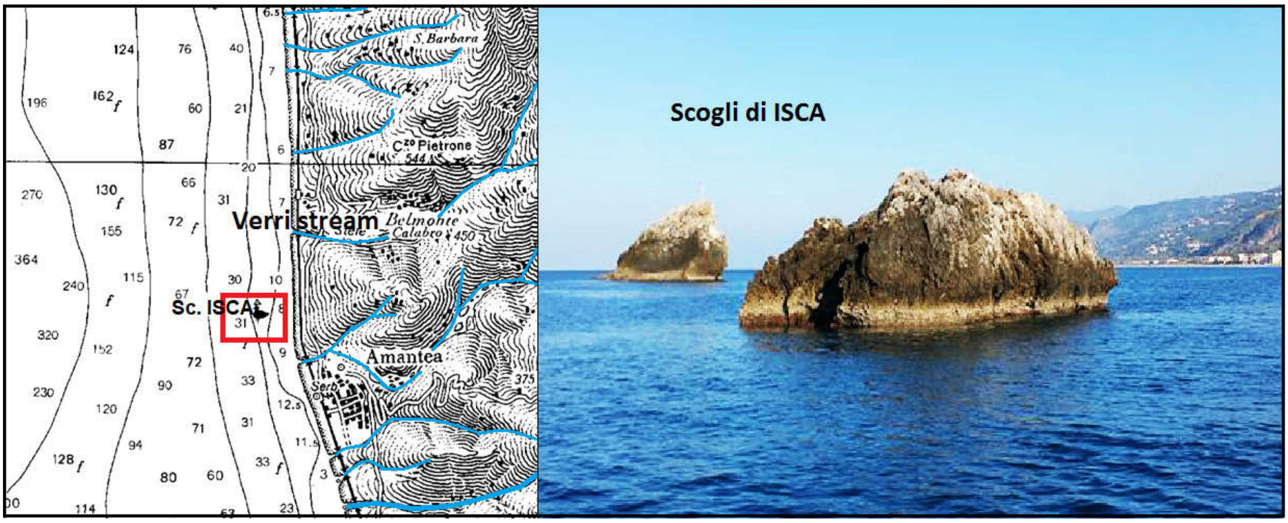

Figure 4. In the red box is shown the Marine Regional Park "Scogli di Isca" (Hydrographic Institute, 1993, scale 1:100.000) while in blue lines the streams in the surrounding area; for the location of the areas see Fig. 2. (Legends in the left square: numbers represent the depths of marine floor; f =muddy depths).

This marine hotspot is, actually, a Special Area of Conservation (SAC), just for the presence in its shallow water of Posidonia beds (Habitat 1120*, Priority Habitat). The seabed gradient is about equal to 10% and is mainly constituted by sandy deposits with rocky spurs (Ietto et al. 2018c). This stretch coast is characterized by narrow sandy beach, where infrastructures and buildings are located close to the coastal fringe or within the backshore area. Heavy erosional processes by sea-waves affect the coastal area, which was classified as high risk zone (Cantasano et al. 2020).

The quality state of the *Posidonia oceanica* was valued according to the formula of Cabaço et al. 2008, which estimates the state of seagrass leaf mortality as:

$$M\ (\%) = (d_f - d_i)\ /\ d_i \times 100$$

where M = mortality rate of *Posidonia oceanica* leaves; d_i = starting density of the meadow; d_f = final density of the meadow subjected to burial process.

In particular, the state of the *Posidonia oceanica* meadow was studied at -12 m depth. The whole monitoring program was conducted as citizen science, in the period 2000-2010 during the spring seasons, through three separate stages. Firstly, the detrital materials and the related burial levels were measured yearly at the base of the seagrass bed using PVC cylinders 35 cm in diameter and height. Thirty box corers were planted into the sea bottoms at 800 m from the shoreline, close to the upslope limit of the meadow. The box corers were placed at the same depth and they were positioned 20 cm above the seabed and strictly approached at least 1 m apart from each other. Secondly, it was analyzed yearly the ecological conditions of the meadow through diving activities. By this way, it was used a synthetic descriptor, that is the density of the seagrass, measured in the number of leaf-shoots for square meter. For this kind of biological description, diving operators counted the number of leaf-shoots in grids of 40 cm per side. The count was repeated twenty times on different experimental plots in the examined station and, then, the results were extrapolated at one square meter. According to the results highlighted by the survey program, it was ascribed the state of health

 doi:10.20944/preprints202305.1751.v1

of the meadow. Thirdly, it was analyzed the grain size distribution into the used box corers. Amongst them, the one located in the most central position of the studied area was chosen to collect the sediment samples used for the analysis of grain-size distributions. The analyzed samples were preliminary washed using H_2O_2 to remove clays and organic matter, air-dried and sieved. The 0.25 – 0.50 mm size fraction has been selected to prepare thin sections that were analyzed for petrographic composition of the medium sand with the scope to study the provenance of the sediments. Each thin section was etched and stained using HF and sodium cobaltinitrite for feldspars grains identification.

3. Results and discussions

The analysis of detritus and the study of geomorphic equilibrium state of the fluvial basins are important aspects in order to assess the health state of *Posidonia oceanica* bed and its sensibility to silting processes. Indeed, the assessment of the geomorphology condition of a catchment gives useful information on its landform evolution in terms of landslide occurrence and then on potential abundance of detritus material carried in shelf areas. The study of grain-size analysis and petrographic composition of detritus give sound information on the potential silting processes of *Posidonia oceanica* meadows in the Tyrrhenian bays. At this scope, the geomorphological analysis of the fluvial basins, on the Calabria Tyrrhenian flank, denotes a high predisposition of the slopes to mass movements, causing large amounts of debris material in the drainage networks. In particular, the areas and the length of the river catchments have been drawn by Centro Cartografico Regione Calabria (Http://geoportale.regione.calabria.it/opendata). Indeed, the hypsometric analysis shows that in Mesima and Petrace basins the landslides are the dominant process in the landform evolution, while the hierarchy degree is equal to 7, highlighting both a large expansion and a well-organization of fluvial network. Similar hierarchization evaluations were achieved for Lao, Savuto and Amato basins, in which the hypsometric integral value is close to 0.5, denoting valleys with a strong predisposition to vertical erosion. These conditions enhance the formation of steep slopes able to trigger widespread instability processes. So, on the Tyrrhenian Calabria side, the landslides are very widespread processes due to both geomorphological features of the basins and to strong weathering processes, involving all the outcropping rock masses (e.g. Sorriso-Valvo et al. 1998; Le Pera and Sorriso-Valvo 2000; Ietto et al. 2015, 2018a, 2018b; Antronico et al. 2017a; Conforti and Ietto 2020). This geomorphological setting shows a potential high tendency of the Tyrrhenian basins to supply abundant debris material in the shelf areas, causing a high potential risk for Posidonia meadows survival. Indeed, *Posidonia oceanica* suffers very much the silting process, which causes a high mortality rate (e.g. Badalamenti et al. 2006; Cabaço et al. 2008). Direct consequence is that the Posidonia meadows, in Tyrrhenian Calabria coast, are lacking in the shelf areas close to the mouths of all great basins (Fig. 2), where great amount of sediment is carried. Really, there are other abiotic factors, such are sunlight, salinity and temperature, that can influence the state of health of *Posidonia oceanica* meadows. In fact, it is well known that the species requires high sunlight levels necessary for its photosynthetic activity. So, the meadows are very sensitive to any variations in water clarity, mainly caused by high sedimentation rates. Really, the enhanced water turbidity and the resulting reduction of water transparency are the main causes for the regression of the meadows (Boudouresque and Meinesz, 1982). Besides, this marine seagrass is very responsive to changes in sea water salinity caused by watershed loadings and fluvial discharges leading to an increased nutrient and sediment runoff, that could affect the survival of the meadows. Finally, *Posidonia oceanica* shows an effective capacity of acclimatization against the increasing overheating of Mediterranean waters through the high thermo-tolerance of the species (Marin-Guirao et al., 2016, 2018). However, it cannot be excluded the hypothesis that also pollution, human activities and strong erosion process affecting the coast, could contribute to the loss of Posidonia meadows, according to several authors (Thomas et al. 2005, Boudouresque et al. 2009, 2012; Pergent et al. 2014, Tuya et al. 2014; Marbà et al. 2014).

3.1. The meadows of Posidonia oceanica in the Calabria Tyrrhenian coast

The survey program was carried out between 2000 and 2010 years through the use of report cards designed by the regional division of the World Wildlife Fund of Italy. These forms were distributed to local fishermen, scuba diving centers and tourist organizations so to provide an easy and handy tool for collecting the distribution of *Posidonia oceanica* meadows in the Tyrrhenian Calabria waters. Then, every single notification was verified and examined by personal diving activities to check the position, the extent and the limits of the meadows. The regional survey of *Posidonia oceanica* meadows, highlights the presence of thirteen meadows (Table 3) concentrated in the northern and southern waters of Calabria Tyrrhenian seaside, except the only one localized in its central coastal area, placed on the seabed of the Marine Regional Park "Scogli di Isca" (Cantasano 2017). Most of these meadows are located (Fig. 2) in shallow waters from two to twenty meters in depth while the only three ones in deep waters, below twenty meters in depth, are localized in the coastal areas of Briatico, Santa Domenica and Capo Vaticano (Vibo Valentia province, southern Italy). All these seagrasses reach a global area of 544.97 hectares and, amongst them, eight are based on mobile substrates and five on hard bottoms as, respectively 61.54% and 38.46% of the whole (Cantasano 2017). On the Calabria Tyrrhenian flank, extensive Posidonia meadows are located in the coastal stretches dominated by the presence of small fluvial basins, with area less than 200 km^2. The latter, however, are able to carry high solid loads in shelf areas mostly during the frequent heavy downpours (Ietto et al. 2015; Ietto and Perri 2015; Antronico et al. 2017a). In the pristine waters of the Marine Regional Park "Scogli di Isca", it was decided, on 2000 year, to value the effects of silting processes on a *Posidonia oceanica* meadow, at first in a good ecological conditions (Figure 5).

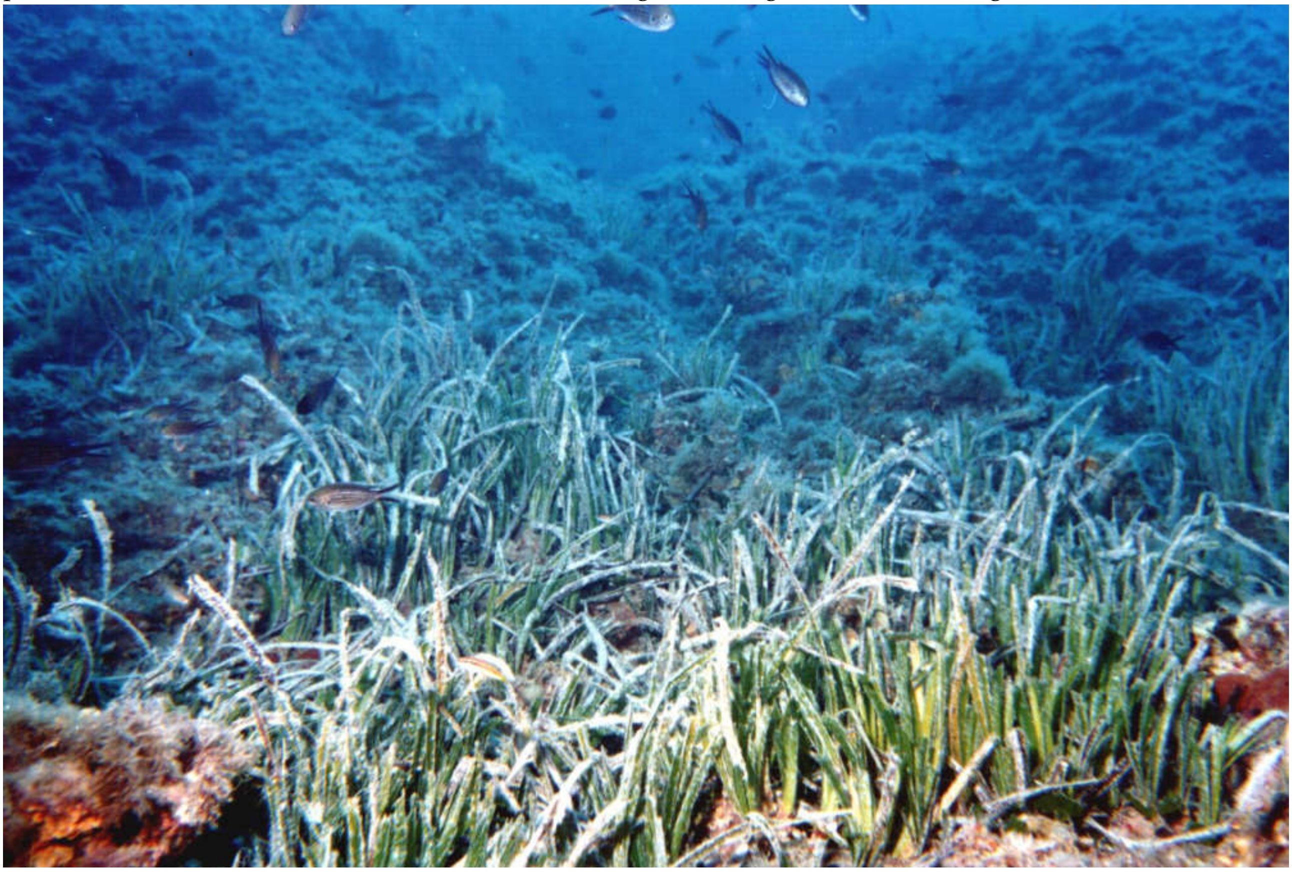

Figure 5. The meadow of *Posidonia oceanica* in the Marine Regional Park "Scogli di Isca" in a good state of health at the beginning of the survey period, recorded on 2000 year.

The monitoring program in "Scogli di Isca" site highlighted that at the beginning of the sampling, in the years 2000-2002, was observed an average silting rate of 4.5 cm/year. At this silting rate, the half of the meadow died in this period. At this regard, the high coastal erosion rate, affecting the studied area (Ietto 2001; Ietto et al. 2018c), could also contribute to determine the high rate of *Posidonia oceanica* mortality. However, the plants were partially able to reply against silting processes, thanks to the physiological response of the roots able to counteract low rates of sedimentation with a marked lengthening of their orthotropic rhizomes, at a growth rate of about 1.5 cm/year, so protecting

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 25 May 2023 doi:10.20944/preprints202305.1751.v1

the Shot Apical Meristems (SAM) of their leaves. In the following period, the silting trend increased year by year, reaching, on 2010, the impressive rate of 12 cm/year. This sedimentary overloading, at the base of the meadow, caused a marked reduction in the ability of the plants to reply against burial process through the vertical growth of their rhizomes. As a matter of fact, it is well known by scientific literature that the species is characterized by a low elongation rate of their orthotropic rhizomes ranging from 0.5 to 1.5 cm/year (Jeudy de Grissac and Boudouresque 1985). So, the health state of *Posidonia oceanica* beds appears strictly connected to burial dynamics because the species is very sensitive to silting processes (Boudouresque et al. 1984; Vermaat et al. 1997). Probably, this high sedimentary loading was caused by heavy rainfall values achieved in the period 2009-2010 in the whole Calabria region. So, the historic average precipitation rates were often overcome with maximum rainfall intensity greater than 290 mm/day while widespread landslides and flooding events occurred (Petrucci et al. 2010; Ietto and Perri 2015; Ietto et al. 2015; Antronico et al. 2017b). The excessive silting rate caused a decrease in the photosynthetic ratio of the plants. Therefore, the *Posidonia oceanica* meadow was suffering from the high sedimentary rate, leading to a reduction in its leaf density. At the end of the survey period, in 2009/2010 years, it was observed, at a burial level of 12 cm/year, an impressive necrosis of the leaves meristem leading to a sharp increase in shoot mortality (Figure 6).

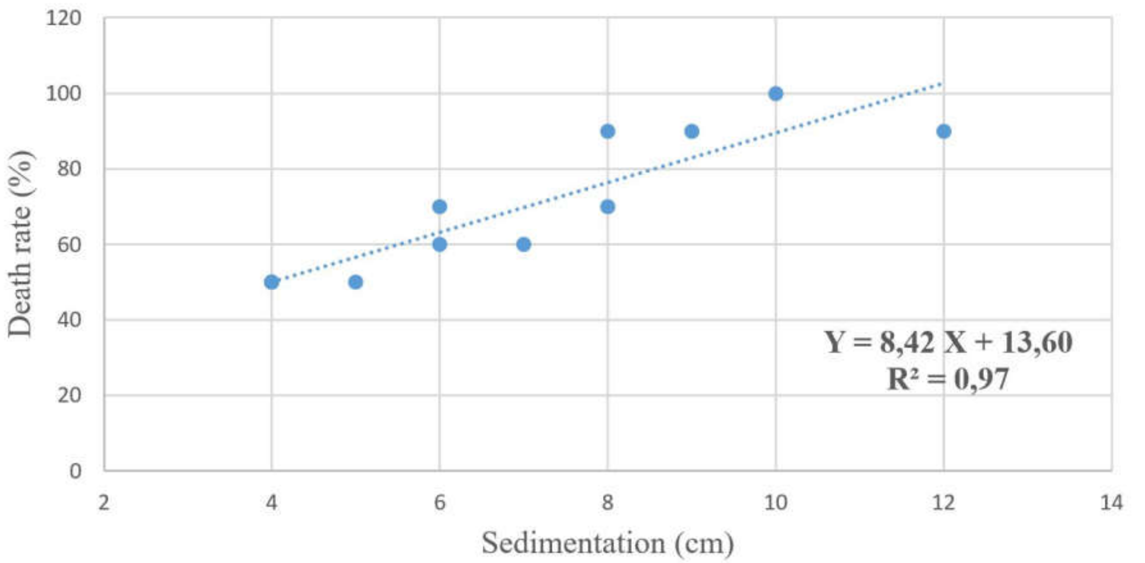

Figure 6. Mortality rate of *Posidonia oceanica* leaves related to their level of sedimentation ($r^2 = 0.97$) in meadows subjected to silting processes, pointed out in the period 2000 – 2010.

So, it is possible to assume that for every 1 cm/year increase in sedimentation rate, the seagrass mortality rate increases by ~8.4%. This condition highlights the close connection between sedimentation processes and mortality rates, as key factors directly proportional, so affecting the survival of the meadows. In this critical condition, the vertical growth of rhizomes stopped and the plants, with a rate of mortality fluctuating from 90% to 100%, began to decay, driving this process to the mortality and to the complete disappearance of the meadow (Figure 7).

 doi:10.20944/preprints202305.1751.v1

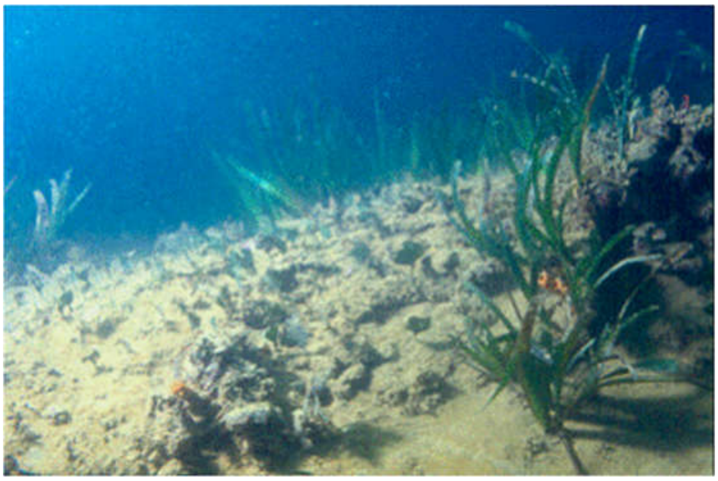

Figure 7. The meadow of *Posidonia oceanica*, subjected to high rate of sedimentation in the Marine Regional Park "Scogli di Isca", recorded on 2010 year.

The grain-size analysis, performed on the collected sediment samples, allowed to define their granular distribution. The analysis showed a unimodal grain-size distribution, dominated by the sand fraction. Thus, the shore-face samples collected at a depth of -12 m exhibit different peaks among the grain-size fraction characterized by coarse, medium, fine and very fine, with a majority between 50% and 60% (in weight) corresponding to a medium sand fraction (size 0.5 mm – 0.25 mm) (Figure 8). The grain-size features are very important to assess the environmental conditions of *Posidonia oceanica* species highly vulnerable to changes in sediment levels (Montefalcone et al. 2010; Abadie et al., 2015). In particular, the granular analysis of sediments supplies useful information on the type of material fraction that could bury the meadows causing their mortality. Usually, in Mediterranean area, the seabed zones exposed to *Posidonia oceanica* colonization are dominated by coarse and/or medium grained sediments (e.g. Papadimitriou et al., 2005; Gobert et al., 2016; Bonamano et al., 2021) testifying that the grain-size values collected in the study area are coherent with ones showed in previous researches. Finally, the presence of sediments with a high sandy fraction at -12 m depth, is mainly imputable to the high hydrodynamic energy of the sea waves (e.g. Morrone and Ietto 2021) enabling transport processes of the coarse material at elevate depths.

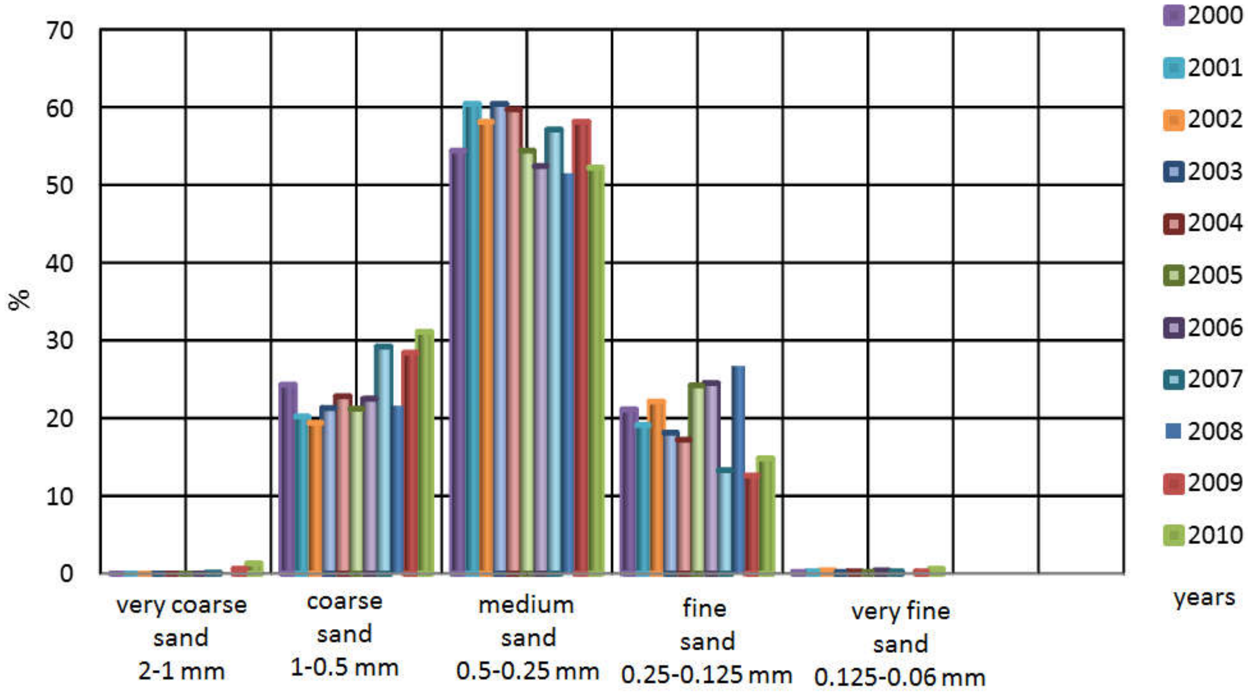

Figure 8. Results of grain-size analysis of the 11 samples. The gran-size sand fractions are shown on the x-axis; while, on the y-axis is shown the class weight in percentage. Each peak shows the weight in percentage of the particles retained on each sieve corresponding to a sand fraction class collected during the laboratory test.

The petrographic composition, carried out through observation of thin sections of the sand samples, showed that the detritus was derived mostly from metamorphic source rock lithotypes (schists + phyllites). In particular, a different abundance in metamorphiclastic sandy grains were found which, from the most to less abundant, are: schistose lithic fragments, phyllitic lithic fragments, gneissose rock fragments and serpentinite. The latter identify the signature of distinct structural domains outcropping in the Coastal Range and carried in shelf area by the outflow of drainage network. The recognized sand composition shows a mineral assemblage comparable to the one identified by several authors in the same area (Le Pera and Critelli 1997; Le Pera et al. 2000; Le Pera and Sorriso-Valvo 2000).

The environmental negative conditions, found in the tested area, leading to a general loss of Posidonia beds, were also confirmed in many other meadows scattered all along Italian coasts (De Falco et al. 2000; Guidetti 2001; Peirano et al. 2005; De Falco et al. 2006; Badalamenti et al. 2006; Montefalcone et al. 2007). This critical state was observed, also, in other coastal waters of Mediterranean Sea, showing some weakness of *Posidonia oceanica* meadows towards sedimentary dynamics (Blanc 1975; Blanc and Jeudy de Grissac 1984, 1989; Meinesz at al. 1991; Manzanera et al. 1998; Ruiz et al. 2001; Marbà and Duarte 2003; Ruiz and Romero 2003; Cabaço et al. 2008; Manzanera et al. 2011; Boudouresque et al, 2006; 2012). At last, the progressive reduction of *Posidonia oceanica* meadows could bring about the disappearance of some endemic species just living into this valuable coastal ecosystem. Really, sedimentation processes affect other *Posidonia oceanica* meadows in some littoral regions of Southern Australia (Orth et al. 2006). Generally, the increased loading of sediments is a real threat, also, for the survival of different seagrass beds widespread in North American waters (Orth et al. 2006). So, it is necessary to include such meadows in monitoring programs and restoration projects, worldwide, increasing the level of public awareness."

This paper highlights the great importance of the multidisciplinary study regarding the relationships between two different environments in coastal area, such as: the fluvial basins with their geomorphological features and the potential negative impacts that they generate on the biological ecosystems in the shelf area. This connection highlights the growing need for a joint coastal area and river basin management, which still receives poor attention by society and by local authorities (Cantasano et al. 2020). Therefore, the integration of coastal regions in the management of river basins becomes an urgent need for a sound regional planning, as established in the pattern of an Integrated Coastal Area and River Basin Management (ICARM process, in U.N.C.H.S. 1996). The close relationship, argued in this research, proves that the principle of a "river continuum concept" (Vannote et al. 1980), able to regard catchments and coasts as a single system, should be reinforced (Meybeck 1998, 2003; Seastedt et al. 2004) in order to preserve also the coastal ecosystems. In other words, it is crucial the necessity to consider coastal, marine and riverine systems in the same landscape unit so that it could be envisaged a new kind of coastal management based on the linkages between shelf and catchment areas (Cantasano et al. 2017, 2020).

4. Conclusions

Marine pollution by silting process is one of the main factors causing the regression of *Posidonia oceanica* meadows along Italian coasts as well as along Calabria Tyrrhenian coasts. The study of this kind of silting process cannot exclude the analysis on composition and provenance of the detritus material. Thus, this research was firstly based on the geomorphological study of the fluvial basins of the Calabria western side, representing the sediment source area. This approach showed that the western coastal waters of Calabria is potentially subjected to a marked sediment loading carried by 5 great basins and numerous small basins able to generate dangerous flooding events with a high transport of debris materials into the shelf areas. Abundant landslides characterize all basin areas and contribute to increase the down-flow of sediments into coastal waters. For these reasons, it was planned a monitoring program, in the period 2000-2010, with the scope to assess the increasing level of burial at the base of a *Posidonia oceanica* meadow. Several detritus samples were analyzed to study their composition and provenance. The test area, located in the Marine Regional Park of Isca (Calabria, southern Italy), showed that *Posidonia oceanica* beds began to suffer for silting processes at sedimentation rates of about 4-5 cm/year. In these critical conditions the mortality rate of the leaves approached a level of about 50% of the whole. At increasing burial trend, the vegetative growth was partially limited by the Shot Apical Meristem of the leaves leading to a gradual decrease in the density of the meadow. In the 2010 year the silting process increased its heavy impact, reaching a sedimentation rate of 12 cm/year and affecting the survival of the meadow. The SAM was completely inhibited causing the death of the leaves and the progressive decay of the seagrass. By this way, the decay of this endemic species could produce important effects on the sensitive balance of some coastal ecosystems causing, in time, severe loss in marine biodiversity. The abundance of silting process is imputable to widespread landslides triggered in the period 2009-2010 in whole Calabria region affected by heavy downpours. Furthermore, the analysis on the sampled detrital material showed that it is constituted by medium sand fraction and its provenance comes from the Calabria Coastal range through the numerous small river basins.

The paper points out the crucial importance of combining complementary scientific disciplines to the study of shelf and river basins in the same landscape unit, useful to a sound and integrated coastal management. This strategy is essential to find adequate plans useful to limit the growing trend of silting processes affecting *Posidonia oceanica* meadows and, at last, their possible disappearance.

Funding informations: This study was funded by MIUR (Ministero dell'Istruzione, dell'Università e della Ricerca), ex 60% fund (2019 year) to Ietto Fabio Compliance with ethical standards

Conflicts of Interests: The author declares that he has no conflict of interest.

Ethical approval: No animal testing was performed during this study.

Sampling field studies: Permits for sampling and observational field studies are not applicable.

Data availability: All data generated or analyzed during this study are included in this published article.

References

1. Abadie A, Gobert S, Bonacorsi M, Lejeune P, Pergent G et al. (2015) Marine space ecology and seagrasses. Does patch type matter in Posidonia oceanica seascapes? Ecol. Indic. 57:435-446.
2. Amodio-Morelli L, Bonardi G, Colonna V, Dietrich D, Giunta G., Ippolito F, Liguori V, Lorenzoni S, Paglionico A, Perrone V, Piccarreta G, Russo M, Scandone P, Zanettin-Lorenzoni, E Zuppetta A (1976) L'Arco Calabro-Peloritano nell'orogene appenninico-maghrebide. Società Geologica Italiana Memorie 17:1-60 (In italian).
3. Antonioli F, Ferranti L, Fontana A, et al. (2009) Holocene Relative Sea-Level Changes and Vertical Movements along the Italian and Istrian Coastlines. Quat. Int. 206(1/2):102–133.
4. Antronico L, Borrelli L, Coscarelli R (2017a) Recent damaging events on alluvial fans along a stretch of the Tyrrhenian coast of Calabria (southern Italy). Bull. Eng. Geol. Environ 76:1399–1416.
5. Antronico L, Coscarelli R, De Pascale F, Muto F (2017b) Geo-hydrological risk perception: a case study in Calabria (Southern Italy), International Journal of Disaster Risk Reduction 25:301-311.
6. Badalamenti F, Carlo DG, D'Anna G, Gristina M, Toccaceli M (2006) Effects of dredging activities on population dynamics of Posidonia oceanica (L.) Delile in the Mediterranean Sea: The case study of Capo Feto. Hydrobiologia 555:253-261.
7. Barca D, Cirrincione R, De Vuono E, Fiannacca P, Ietto F, Lo Giudice A (2010) The Triassic rift system in the northern Calabrian-Peloritani Orogen: evidence from basaltic dyke magmatism in the San Donato Unit. Period. Mineral. 79(2):61–72.
8. Blanc JJ (1975) Reserches de sédimentologie appliquée au littoral rocheuz de la Provence. Aménagement et protection. Centre National Exploit Océans (France), pp. 23-28.
9. Blanc JJ, Jeudy de Grissac, A (1984) Erosion sous-marine des herbiers à Posidonia oceanica (Méditerranée). In: Boudouresque C.F., Jeudy de Grissac A., Olivier J. (eds) International Workshop on *Posidonia oceanica* meadows. GIS Posidonie Publishers, Marseille, pp. 23-28.
10. Blanc JJ, Jeudy de Grissac A (1989) Réflexions géologiques sur la regression des herbiers à Posidonies (Departaments du Var et des Bouches-di Rhone). In: Boudouresque C.F., Meinesz A., Fresi E., Gravez V. (eds) International Workshop on *Posidonia oceanica* beds. GIS Posidonie Publishers, Marseille, pp. 273-285.
11. Boero F, Chessa L, Chimenz C, Fresi E (1985) The zonation of Epiphytic Hidroids on the Leaves of Some Posidonia oceanica (L.) Delile Beds in the Central Mediterranean. Marine Ecology 6(1): 27-33.
12. Bonamano S, Piazzolla D, Scanu S, Mancini E, Madonia A, Piermattei V, Marcelli M (2021) Modelling approach for the evaluation of burial and erosion processes on Posidonia oceanica meadows. Estuar. Coast. Shelf Sci. 254:107321.
13. Bonardi G, Compagnoni R, Messina A, Perrone V, Russo S, De Francesco AM, Del Moro A, Platt, J (1992) Sovrimpronta metamorfica alpina nell'unità dell'Aspromonte (settore meridionale dell'Arco Calabro–Peloritano). Bolletino Societa` Geologica Italiana 111:81–108 (In italian).
14. Borrelli L, Perri F, Critelli S, Gullà G (2016) Characterization of granitoid and gneissic weathering profiles of the Mucone River basin (Calabria, southern Italy). Catena 113:325–340.
15. Borum J, Duarte CM, Krause-Jensen D, Greve TM (2004) European Seagrasses: an Introduction to Monitoring and Management The M & MS Project, Copenhagen, pp. 95.
16. Boudouresque CF, Meinesz A (1982) Decouvert de l'herbier de posidonie. Cahier Parc National de Port Cross. Fr. 4, pp. 1-81.
17. Boudouresque CF, Jeudy de Grissac A, Meinesz A (1984) Relations entre la sedimentation et l'allongement des rhizomes orthotropes de Posidonia oceanica dans la baie d'Elbu (Corse). In: Boudouresque C.F., Jeudy de Grissac A., Olivier J. (eds). International Workshop on Posidonia occeanica beds, 1. GIS Posidonie Publishers, Marseille, pp. 185-191.
18. Boudouresque CF, Bernard CF, Bonhomme P, Charbonnel E, Diviacco G, Meinesz A, Pergent G, Pergent-Martini C, Ruitton S, Tunesi L (2006) Preservation et conservation des herbiers à Posidonia oceanica. Ra.Mo.Ge. Publ., https://www.ramoge.org/filesfr/pdf. Accessed 02 April 2020.
19. Boudouresque CF, Bernard CF, Pergent G et al. (2009) Decline of Mediterranean seagrasses caused by natural processes and anthropogenic disturbances and stress: a critical review. Bot. Mar. 52: 395-418.
20. Boudouresque CF, Bohomme P, Charbonnel E, Diviacco G, Meinesz A, Pergent G, Pergent-Martini C, Ruitton S, Tunesi L (2012) Protection and conservation of Posidonia oceanica meadows. RAMOGE and RAC/SPA Publishers, Tunis, pp. 202.
21. Cabaço S, Santos R, Duarte CM (2008) The impact of sediment burial and erosion on seagrasses: a review. Estuarine, Coastal and Shelf Science 79:354-356.
22. Caloiero D (1975) Le precipitazioni in Calabria nel cinquantennio 1921-70 e carta delle isoiete alla scala 1: 500.000. CNR-IRPI Istituto di ricerca per la protezione idrogeologica, Cosenza, Italy (In italian).
23. Canals M, Puig P, de Madron XD, Heussner S, Palanques A, Fabres J (2006) Flushing submarine canyons. Nature 444(7117):354-357.
24. Cantasano N (2017) Sedimentazione nelle praterie di *Posidonia oceanica* (L.) Delile lungo le coste tirreniche calabresi. Biologi Italiani 47(1):51-58 (In italian).

25. Cantasano N, Pellicone G, Ietto F (2017) Integrated coastal zone management in Italy: a gap between science and policy. J. Coast. Conserv. 21:317–325.
26. Cantasano N, Pellicone G, Ietto F (2020) The Coastal Sustainability Standard method: A case study in Calabria (Southern Italy). Ocean and Coastal Management 183:104962.
27. Carrara A, Zuffa GG (1976) Alpine structures in northwestern Calabria, Italy. Geological Society of America Bulletin 87:1229-1246.
28. Casas D, Chiocci F, Casalbore D, Ercilla G, de Urbina JO (2016) Magnitude-frequency distribution of submarine landslides in the Gioia Basin (southern Tyrrhenian Sea). Geo-Mar. Lett. 36(6):405-414.
29. Centamore E, Ciccacci S, Del Monte M, Fredi P, Lupia Palmieri E (1996) Morphological and structural arrangement of North-eastern Abruzzo (Central Italy). Geomorphology 16:127–137.
30. Chiocci FL, Casalbore D (2017) Unexpected fast rate of morphological evolution of geologically-active continental margins during quaternary: examples from selected areas in the Italian seas. Mar. Pet. Geol. 82:154-162.
31. Ciccacci S, D'Alessandro L, Fredi P, Lupia Palmieri E (1992) Relation between morphometric characteristics and denudation processes in some drainage basins of Italy. Zeitschrift fuer Geomorphologie NF 36(1):53–67.
32. Conforti M, Ietto F (2019) An integrated approach to investigate slope instability affecting infrastructures. Bulletin of Engineering Geology and the Environment 78(4):355-2375.
33. Conforti M, Ietto F (2020) Influence of Tectonics and Morphometric Features on the Landslide Distribution: A Case Study from the Mesima Basin (Calabria, South Italy). Journal of Earth Science 31(2):393–409.
34. D'Alessandro L, Davoli E, Lupia Palmieri E, Raffi R (2002) Natural and anthropogenic factors of the recent evolution of the Calabria beaches. In: Allison R.J (Ed.) Applied geomorphology: theory and practice. Wiley, New York, 22:397-427.
35. D'Alessandro F, Tomasicchio GR, Frega F, Carbone M (2011) Design and management aspects of a coastal protection system. A case history in the South of Italy. Journal of Coastal Research, suppl Special Issue SI 64:492–495.
36. De Falco G, Ferrari S, Cancemi G, Baroli M (2000) Relationship between sediment distribution and Posidonia oceanica seagrass. Geo-Marine Letters 20:50–57.
37. De Falco G, Baroli M, Murru E, Piergallini G, Cangemi G (2006) Sediment analysis evidences two different depositional phenomena influencing seagrass distribution in the Gulf of Oristano (Sardinia, Western Mediterranean). Journal of Coastal Research 225:1043-1050.
38. Fonseca MS (1996) The role of seagrasses in nearshore sedimentary processes: a review. In: Estuarine Shores: Hydrological, Geomorphological and Ecological Interactions. Ed. Blackwell, Boston, pp. 261– 286.
39. Gacia E, Duarte CM (2001) Sediment retention by a Mediterranean Posidonia oceanica meadow: the balance between deposition and resuspension. Estuarine, Coastal and Shelf Science 52:505-514.
40. Gacia E, Duarte CM, Marbà N, Terrados J, Kennedy H, Fortes MD, Tri NH (2003) Sediment deposition and production in SE-Asia seagrass meadows. Estuarine, Coastal and Shelf Science 56:909-919.
41. Ghisetti F (1981) Upper Pliocene–Pleistocene Uplift Rates as Indicators of Neotectonic Pattern: An Example from Southern Calabria (Italy). Z. Geomorphologie 40:93–118.
42. Gobert S, Lepoint G, Pelaprat C, Remy F, Lejeune P, Richir J, Abadie A (2016) Temporal evolution of sand corridors in a Posidonia oceanica seascape: a 15-years study. Mediterr. Mar. Sci. 17(3):777–784.
43. Graeßner T, Schenk V (1999) Low-pressure metamorphism of Palaeozoic pelites in the Aspromonte, southern Calabria: constraints for the thermal evolution in the Calabrian crustal cross-section during the Hercynian orogeny. J. Metamorphic Geol. 17:157–172.
44. Guidetti P (2001) Detecting environmental impacts on the Mediterranean seagrass Posidonia oceanica (L.) Delile: the use of reconstructive methods in combination with "beyond BACI" designs. Journal of Experimental Marine Biology and Ecology 260:27-39.
45. Holon F, Boissery P, Guilbert A, Freschet E, Deter J (2015). The impact of 85 years of coastal development on shallow seagrass beds (Posidonia oceanica L. (Delile) in South Eastern France: A slow but steady loss without recovery. Estuarine, Coastal and Shelf Science 165:204-212.
46. Horton RE (1945) Erosional development of streams and their drainage basin; hydrophysical approach to quantitative morphology. Geol. Soc. Am. Bull. 56(3):275–370.
47. Hurtrez JE, Lucazean F, Avouac JP (1999) Investigation of the relationship between basin morphology, tectonic uplift and denudation from the study of an active fold belt in Siwalik Hills (Central Nepal). J. Geophys. Res. 104:779-796.
48. Ietto A, Ietto F (1998) Sviluppo e annegamento di un Sistema carbonatico piattaforma bacino nel Trias superiore della Catena Costiera Calabrese. Boll. Soc. Geol. It. 117:313-331 (In italian).
49. Ietto F. (2001) Evoluzione delle spiagge tirreniche nord calabresi negli ultimi 50 anni. Italian Journal of Quaternary. Science 14(2):105–116 (In italian).
50. Ietto A, Ietto F (2004) Age and history of the weathering of granitoids in southern Calabria (Italy). Geografia Fisica e Dinamica Quaternaria 27:37–45.

51. Ietto F, Bernasconi MP (2005) The Cliff Bordering the Northwestern Margin of the Mesima Basin (Southern Calabria) is of Pleistocene Age. Geogr. Fis. Dinam. Quart. 28:205–210.
52. Ietto F, Le Pera E, Caracciolo L (2012) Geomorphology and sand provenance of the Tyrrhenian coast between capo Suvero and Gizzeria (Calabria, southern Italy). Rend. Online Soc. Geol. Ital. 21: 487–488.
53. Ietto F, Le Pera E, Perri F (2013) Weathering of the 'Rupe di Tropea' (southern Calabria): consolidation criteria and erosion-rate estimate. Rend. Online Soc. Geol. It. 24:178-180.
54. Ietto F, Cantasano N, Salvo F (2014) The quality of life conditioning with reference to the local environmental management: a pattern in Bivona country (Calabria, southern Italy). Ocean and Coastal Management 102:340–349.
55. Ietto F, Perri F (2015) Flash flood event (october 2010) in the Zinzolo catchment (Calabria, southern Italy). Rend. Online Soc. Geol. Ital. 35:170-173.
56. Ietto F, Perri F, Fortunato G (2015) Lateral spreading phenomena and weathering processes from the Tropea area (Calabria, southern Italy). Environmental Earth Science 73:4595-4608.
57. Ietto F, Perri F, Cella F (2018a) Weathering characterization for landslides modelling in granitoid rock masses of the Capo Vaticano promontory (Calabria, Italy). Landslides 15:43–62.
58. Ietto F, Perri F, Miriello D, Ruffolo SA, Laganà A, Le Pera E (2018b) Epoxy resin for the slope consolidation intervention on the Tropea sandstone cliff (southern Calabria, Italy). Geoheritage 10:287-300.
59. Ietto F, Cantasano N, Pellicone G (2018c) A New Coastal Erosion Risk Assessment Indicator: Application to the Calabria Tyrrhenian Littoral (Southern Italy). Environ. Process. 5:201–223.
60. Jeudy de Grissac A, Boudouresque CF (1985) Ròles des herbiers de phanérogames marines dan le mouvements des sediments côtiers: les herbiers a Posidonia oceanica. Colloque Franco-Japonais d'Oceanographie, 1:143-151.
61. Jordà G, Marbà N, Duarte C (2012) Mediterranean seagrass vulnerable to regional climate warming. Nature Climate Change 2:821–824.
62. Kocak F, Aydin-Onen S (2014) Epiphytic bryozoan community of Posidonia oceanica (L.) Delile leaves in two different meadows at disturbed and control locations. Mediterranean Marine Science 15(2):390-397.
63. Le Pera E, Critelli, S (1997) Sourceland controls on the composition of beach and fluvial sand of the Tyrrhenian coast of Calabria, Italy: implications for actualistic petrofacies. Sedimentary Geology 110:81-97.
64. Le Pera E, Mongelli G, Morelli F, Critelli S (2000) Compositional and geochemical signature of provenance in modern sediments from the Tyrrhenian continental shelf, Calabria, Italy. Giornale di Geologia 62:37-55.
65. Le Pera E, Sorriso-Valvo M (2000) Weathering, erosion and sediment composition in a high-gradient river, Calabria, Italy. Earth Surface Processes and Landforms 25:277-292.
66. Lepoint G, Mouchette O, Pelaprat C, Gobert S (2014) An ecological study of Electra posidoniae Gautier, 1954 (Cheilostomata, Anesca), a bryozoan epiphyte found solely on the seagrass Posidonia oceanica (L.) Delile, 1813. Belg. J. Zool. 144(1),51-63.
67. Lorenzoni S, Orsi G, Zanettin Lorenzoni E (1983) Metallogenesis in the tectonic units and lithogenetic environments of Calabria (southern Italy). Mem. Soc. Geol. It. 35:411–428.
68. Lupia Palmieri E, Raffi R (1983) Atlante delle spiagge italiane: Dinamismo - Tendenza evolutiva - Opere umane. In: Fierro, G. (Ed.). S.EL.CA. Firenze, Sheets, Scales 1: 100,000. 108 pp. (in italian).
69. Manzanera M, Perez M, Romero J (1998) Seagrass mortality due to oversedimentation: an experimental approach. Journal of Coastal Conservation 4:67-70.
70. Manzanera M, Alcoverro T, Tomas F, Romero J (2011) Response of Posidonia oceanica to burial dynamics. Marine Ecology Progress Series 423:47-56.
71. Marbà N, Duarte CM (1994) Growth response of the seagrass Cymodocea nodosa. Marine Ecology Progress Series 107:307-311.
72. Marbà N, Duarte CM (1998) Rhizome elongation and seagrass clonal growth. Marine Ecology Progress Series 174:269-280.
73. Marbà N, Duarte CM (2003) Scaling of ramet size and spacing in seagrasses: implications for stand development. Aquatic Botany 77:87-98.
74. Marbà N, Díaz-Almela E, Duarte CM (2014) Mediterranean seagrass (Posidonia oceanica) loss between 1842 and 2009. Biol. Conserv. 176:183-190.
75. Marchi L, Borga M, Preciso E, Gaume E (2010) Characterisation of selected extreme flash floods in Europe and implications for flood risk management. J. Hydrol. 394:118-133.
76. Marin-Guirao L, Ruiz JM, Dattolo E, Garcia-Muñoz R, Procaccini G (2016) Physiological and Molecular Evidence of Differential Short-Term heat tolerance in Mediterranean Seagrasses. Scientific Reports 6: 28615.
77. Marin-Guirao L, Bernardeau-Esteller J, Garcia-Muñoz R, Ramos A, Ontoria Y, Romero J, Pèrez M, Ruiz JM, Procaccini G (2018) Carbon Economy of Mediterranean Seagrasses in Response to Thermal Stress. Marine Pollution Bulletin 135: 617-629.
78. Meybeck M (1998) The IGP Water Group: a response to a growing global concern. IGBP, Stockholm, Global Change Newsl. 368:8–12.
79. Meybeck M (2003) Global Analysis of River Systems: from Earth System Controls to Anthropocene Syndromes. Phil. Trans. Royal Society London, pp. 21.

80. Meinesz A, Lefevre JR, Astier JM (1991) Impact of coastal development on the infralittoral zone along the Southeastern Mediterranean shore of continental France. Marine Pollution Bulletin 23: 343-347.
81. Mongardi S, Correggiari A, Trincardi F (2004) Terrazzi deposizionali sommersi al largo di Capo Suvero (Calabria). Memorie Descrittive Carta Geologica Italiana LVIII:63-74 (In italian).
82. Montefalcone M, Albertelli G, Morri C, Bianchi CN (2007) Urban seagrasses status of *Posidonia oceanica* facing the Genoa city waterfront (Italy) and implication for management. Marine Pollution Bulletin 54:206-213.
83. Montefalcone M, Parravicini V, Vacchi M, Albertelli G, Ferrari M et al. (2010) Human influence on seagrass habitat fragmentation in NW Mediterranean Sea. Estuar. Coast. Shelf Sci. 86:292-298.
84. Morrone C, Ietto F (2021) Shoreline evolution and modern beach sand composition along a coastal stretch of the Tyrrhenian Sea (southern Italy). J. Palaeogeogr. 10(1), 7. DOI: 10.1186/s42501-021-00088-y.
85. Orth RJ, Carruthers TJ, Dennison WC et al. (2006) A global crisis for seagrass ecosystems. Bioscience 56:987-996.
86. Papadimitriou S, Kennedy H, Kennedy DP, Duarte CM, Marbà N (2005) Sources of organic matter in seagrass-colonized sediments: a stable isotope study of the silt and clay fraction from Posidonia oceanica meadows in the western Mediterranean. Org. Geochem. 36(6):949-961.
87. Parthasarathy A, Natesan U (2015) Coastal vulnerability assessment: a case study on erosion and coastal change along Tuticorin, Gulf of Mannar. Natural Hazards 75:1713–1729.
88. Peckham RJ, Jordan G (2007) Digital Terrain Modeling. Development and Applications in a Policy Support Environment. Series: Lecture Notes in Geoinformation and Cartography. Springer Ed. Berlin.
89. Peirano A, Damasso V, Montefalcone M, Morri C, Bianchi CN (2005) Effects of climate, invasive species and anthropogenic impacts on the growth of the seagrass Posidonia oceanica (L.) Delile in Liguria (NW Mediterranean Sea). Marine Pollution Bulletin 50:817-822.
90. Pergent G, Semroud R, Djellouli A et al. (2010). The IUCN Red List of Threatened Species. Version 2020-2 www.iucnredlist.org (Accessed 26.11.2020).
91. Pergent G, Bazairi H, Bianchi CN et al. (2014) Climate change and Mediterranean seagrass meadows: a synopsis for environmental managers. Mediterr. Mar. Sci. 15:462-473.
92. Perri F, Ietto F, Le Pera E, Apollaro C (2016) Weathering processes affecting granitoid profiles of Capo Vaticano (Calabria, southern Italy) based on petrographic, mineralogic and reaction path modeling approaches. Geological Journal 51:368-386.
93. Petrucci O, Chiodo G, Caloiero D (1996) Eventi alluvionali in Calabria nel decennio 1971-1980. GNDCI, Pubb. 374. Ed. Rubbettino Arti Grafiche, Soveria Mannelli (Cz, Italy), pp. 142 (In italian).
94. Petrucci O, Pasqua AA, Gullà G (2010) Landslide damage assessment using the Support Analysis Framework (SAF): the 2009 landsliding event in Calabria (Italy). Adv. Geosci. 26:13–17.
95. Pike RJ, Wilson SE (1971) Elevation-Relief Ratio, Hypsometric Integral and Geomorphic Area-Altitude Analysis. Geol. Soc. Am. Bull. 82:1079-1084.
96. Pimm SL, Raven P (2000). Extinction by numbers. Nature 403:843-845.
97. Pierdomenico M, Martorelli E, Dominguez-Carrió C, Gili JM, Latino Chiocci F (2016). Seafloor characterization and benthic megafaunal distribution of an active submarine canyon and surrounding sectors: The case of Gioia Canyon (Southern Tyrrhenian Sea). Journal of Marine Systems 157:101-117.
98. Punzo M, Lanciano C, Tarallo D, Bianco F, Cavuoto G, De Rosa R, Di Fiore V, Cianflone G, Dominici R, Iavarone M, Lirer F, Pelosi N, Giordano L, Ludeno G, Natale A, Marsella E (2016) Application of X-Band Wave Radar for Coastal Dynamic Analysis: Case Test of Bagnara Calabra (South Tyrrhenian Sea, Italy). Journal of Sensors Vol. 2016, Article ID 6236925, pp. 9.
99. Ritter DF, Kochel RC, Miller JR (2002) Process Geomorphology. McGraw Hill Ed., Boston.
100. Roca G, Romero J, Columbu S et al. (2014). Detecting the impacts of harbour construction on a seagrass habitat and its subsequent recovery. Ecol. Indic. 45:9-17.
101. Ruiz JM, Pérez M, Romero J (2001) Effects of fish farm loadings on seagrass (Posidonia oceanica) distribution, growth and photosynthesis. Marine Pollution Bulletin 42(9):749-760.
102. Ruiz JM, Romero J (2003) Effects of disturbances caused by coastal constructions on spatial structure, growth dynamics and photosynthesis of the seagrass Posidonia oceanica. Marine Pollution Bulletin 46:1523-1533.
103. Scandone P (1982) Structure and evolution of the Calabrian Arc. Earth Evolution Sciences 3:172–180.
104. Seastedt TR, Bowman WD, Caine N, McKnight D., Townsend A, Williams M.W., 2004. The landscape continuum: a model for high – elevation ecosystems. Bioscience 54(2):111–121.
105. Shadrin NV, Mironov SS, Ferat TA (2012) Interrelations between the losses of sandy beaches and biodiversity in seas: case of the Bakalskaya Spit (Crimea, Ukraine, Black Sea). Turkish Journal of Fisheries and Aquatic Sciences 12:411-415.
106. Shepard FP (1972) Submarine canyons. Earth-Science Reviews 8(1):1-12.
107. Sorriso-Valvo M, Sylvester AG (1993) The relationship between geology and landforms along a coastal mountain front, northern Calabria, Italy. Earth Surface Processes and Landforms 18:257-273.

108. Sorriso-Valvo M, Antronico L, Le Pera E (1998) Controls on modern fan morphology in Calabria, Southern Italy. Geomorphology 24:169-187.
109. Strahler AN (1952) Hypsometric (Area-Altitude) analysis of erosional topography. Geological Society of American Bulletin 63(1):117–142.
110. Strahler AN (1964) Quantitative Geomorphology of Drainage Basins and Channel Networks. In: Chow, V., Ed., Handbook of Applied Hydrology, McGraw Hill, New York, 439-476.
111. Thomas F, Turon X, Romero J (2005) Seasonal and small-scale spatial variability of herbivory pressure on the temperate seagrass Posidonia oceanica. Mar. Ecol. Prog. Ser. 301:95-107.
112. Tuya F, Ribeiro-Leite L, Arto-Cuesta N et al. (2014) Decadal changes in the structure of Cymodocea nodosa seagrass meadows: natural vs. human influences. Estuar. Coast. Shelf Sci. 137:41-49.
113. U.N.C.H.S. (United Nations Centre for Human Settlements Habitat) (1996) Issues in the Integrated Planning and Management of River/Lake Basins and Coastal Areas. A Human Perspective, Nairobi, pp. 1–57.
114. Vannote RL, Minshall GW, Cummins KW, Sedell JR, Cushing CE (1980) The river continuum concept. Can. J. Fish. Aquat. Sci. 37:130-137.
115. Vermaat JE, Agawin NSR, Duarte CM, Enriquez S, Fortes MD, Uri JS, van Vierssen W (1997) The capacity of seagrasses to survive increased turbidity and siltation: the significance of growth forms and light use. Ambio 26:499-504.
116. Zaitsev Yu P (2006) Littoral concentration of life in the Black Sea and coastal management requirements. Journal of the Black Sea/Mediterranean Environment 12:113-128.
117. Weissel JK, Pratson LF, Malinverno A (1994) The length scaling properties of topography. J. Geophys. Res. 99:13997-14012.
118. Willgoose G, Hancock G (1998) Revisiting the hypsometric curve as an indicator of form and process in transport-limited catchment. Earth Surf. Process. Landforms 23:611–623.
119. W.W.F. (2014) Living Planet Report 2014, Summary, pp. 1-35.