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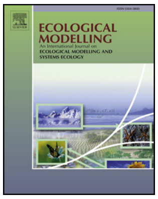

Marine natural capital and ecosystem services: An environmental accounting model

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ABSTRACT

Healthy, resilient, and diverse marine ecosystems are capable of generating the biotic and abiotic components of natural capital stocks interacting and providing a bundle of ecosystem services vital to human well-being. Increasing pressures and impacts of human activities on marine ecosystems cause habitat degradation and biodiversity loss, and, as a consequence, seriously affect their capacity to provide benefits to humans. Integrated approaches capable of combining ecological and socioeconomic aspects are much needed to protect natural capital stocks and ensure the delivery of ecosystem services. In this context, marine protected areas (MPAs) are important tools for conserving biodiversity while promoting sustainable human activities. In this study, an interdisciplinary approach to the assessment of natural capital and ecosystem services in marine ecosystems was adopted. In particular, the emergy and eco-exergy accounting methods were jointly used to account for the biophysical value of natural capital stocks in the Mediterranean MPA “Punta Campanella”, located in Southern Italy. The assessment focused on four main macro-habitats: sciaphilic hard bottom (coralligenous bioconstructions), photophilic hard bottom, soft bottom, and *Posidonia oceanica* seagrass beds. The habitat *Posidonia oceanica* seagrass beds showed the highest value of eco-exergy density ($3.58 \cdot 10^{6}$ kJ m^{-2}) while the highest value of emergy density resulted for the sciaphilic hard bottom habitat ($4.94 \cdot 10^{12}$ sej m^{-2}). The high eco-exergy value of *Posidonia oceanica* seagrass beds habitat is mainly due to the complex evolutionary history and high biomass density of the *Posidonia oceanica* seagrass. On the other hand, the high emergy value calculated for the sciaphilic hard bottom habitat reflects the high convergence of natural input flows for the generation of its biomass stocks and high biodiversity. In addition, to complement the biophysical assessment with an economic perspective, the emergy values of natural capital stocks were also converted into monetary units. The total value of natural capital stocks in the MPA resulted about 12 M€. Furthermore, a set of ecosystem services generated by *Posidonia oceanica* seagrass beds and Coralligenous bioconstructions was identified and their economic value was estimated (3.05 M€ and 0.62 M€, respectively). Finally, the value of natural capital and ecosystem services was also estimated by using a 3D bionomic map to consider the presence of Coralligenous bioconstructions and other habitats on cliffs characterizing the investigated MPA. This study highlighted the importance of *Posidonia oceanica* seagrass beds and Coralligenous bioconstructions in terms of both natural capital stocks and delivery of ecosystem services, confirming the need for their protection and conservation in marine and coastal management. The biophysical and economic values of natural capital stocks and ecosystem services, together with their spatial distribution in the MPA, can support local managers and policy makers in implementing and developing nature conservation strategies while ensuring the sustainable use of marine resources.

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1. Introduction

1.1. Scientific background

Marine and coastal ecosystems are recognized as among the most productive ecosystems in the world (UNEP, 2006; Hattam et al., 2015). The biotic and abiotic components of marine natural capital stocks interact and provide a bundle of ecosystem services vital to human well-being, including food provision, coastal protection against storms and floods, water purification, nutrients cycling, carbon sequestration, tourism, recreational and spiritual benefits (Böhnke-Henrichs et al., 2013; Costanza et al., 1997, 2014; Liquete et al., 2013). The long-term delivery of ecosystem services depends on healthy, resilient, and diverse marine ecosystems (Smith et al., 2017). There is a growing evidence that biodiversity increases the stability of ecosystem functions thus representing the basis for the generation of ecosystem services (Cardinale et al., 2012; Franzese et al., 2018a; Teixeira et al., 2019; Vihervaara et al., 2019).

Marine ecosystems are heavily exploited throughout the world. The coastal zones represent only about 4% of the Earth's total land area. Yet, they contain more than one third of the world's population and account for about 90% of the catches from marine fisheries (Barbier, 2017).

The multiple pressures and impacts of human activities on marine ecosystems are increasing globally (Franzese et al., 2018b; Halpern et al., 2015; Pauna et al., 2019). The major drivers of change and degradation of marine and coastal ecosystems are population growth and related increasing food demand, overexploitation of fish stocks, introduction of invasive species, climate change, eutrophication, and waste release (Halpern et al., 2012; UNEP, 2006). The anthropogenic pressures on marine ecosystems cause biodiversity loss, and, as a consequence, seriously affect their capacity to provide benefits to humans (Halpern et al., 2008; Haines-Young and Potschin, 2010).

Therefore, integrated approaches capable of combining ecological and socioeconomic aspects are much needed to protect natural capital stocks and ensure the delivery of ecosystem services through the sustainable exploitation of marine resources (Franzese et al., 2008, 2019; Picone et al., 2017).

Marine protected areas (MPAs) are recognized worldwide as important tool for mitigating human impacts on marine ecosystems, conserving biodiversity while promoting sustainable human activities (Zupan et al., 2018).

MPAs play a crucial role in the Mediterranean area where coastal tourism is one of the main economic sector and employment producer. While tourism is crucial for the economic development of the Mediterranean region, its increasing growth can generate several environmental pressures on the coastal zones cumulating with other impacts generated by local populations (Drius et al., 2019). In light of this, in the Mediterranean context, MPAs are essential to protect marine ecosystems while allowing sustainable coastal tourism and local economic activities.

The biophysical and economic assessments of the value of natural capital and ecosystem services are much needed for achieving nature conservation goals, while ensuring the sustainable exploitation of marine resources. In fact, they are crucial to convey the importance of natural resources to managers and policy makers supporting the development and implementation of policies and strategies oriented to natural capital conservation and sustainable delivery of ecosystem services (Börger et al., 2014; Maes et al., 2016).

Environmental accounting is a useful tool to assess the biophysical and economic value of natural capital and ecosystem services in both terrestrial and marine ecosystems (Häyhä et al., 2015; Mellino et al., 2015; Nikodinoska et al., 2018; Caro et al., 2018). In particular, environmental accounting allows the assessment of multiple aspects dealing with marine ecosystems, among which: the environmental costs sustained for the generation and maintenance of natural capital stocks and ecosystems function, the received benefits (i.e., the ecosystem services), and the impacts generated by human activities for the exploitation of marine resources (Franzese et al., 2015; Häyhä and Franzese, 2014).

The assessment of natural capital and ecosystem services in marine ecosystem is more challenging compared to terrestrial ecosystems (Townsend et al., 2018). In fact, the dynamics and complexity of marine ecosystems, the high connectivity among marine habitats, the dispersal of species, and the widespread spatial distribution of the ecological processes make the assessment of natural capital and ecosystem services demanding and time- and resource- consuming (Manea et al., 2019).

In spite of this, over the past decades, there has been an increasing research effort to assess the value of natural capital and ecosystem services in marine ecosystems and to incorporate these values into marine planning and decision making (Börger et al., 2014; Buonocore et al., 2018; Christie et al., 2015; Geange et al., 2019; Franzese et al., 2015; Pauna et al., 2018).

Among the environmental accounting methods, the emergy accounting method (Odum, 1988, 1996) has been recently used to assess the value of natural capital and ecosystem services in marine ecosystems in terms of environmental support needed for their generation (Berrios et al., 2017; Franzese et al., 2017; Paoli et al., 2018; Picone et al., 2017; Vassallo et al., 2017).

The eco-exergy method (Jørgensen and Mejer, 1979) has been also suggested to assess the value of natural capital in terms of chemical energy stored in organic matter and genetic information embodied in living organisms (Mandal et al., 2012; Vihervaara et al., 2019).

Previous studies suggested the parallel application of the emergy and eco-exergy methods for the assessment of natural capital and ecosystem services (Buonocore et al., 2019; Coscieme et al., 2013; Ulgiati et al., 2011).

1.2. Goal of the study

In this study, an interdisciplinary approach to the assessment of natural capital and ecosystem services in marine ecosystems was adopted. In particular, the study aimed at assessing the biophysical value of natural capital stocks in the Mediterranean Marine Protected Area (MPA) “Punta Campanella”, located in Southern Italy, through the parallel use of the emergy and eco-exergy accounting methods. The assessment focused on four main macro-habitats: sciaphilic hard bottom (coralligenous bioconstructions), photophilic hard bottom, soft bottom, and *Posidonia oceanica* seagrass beds. In addition, to complement the biophysical assessment with an economic perspective, the emergy values of natural capital stocks were also converted into monetary units. The study also aimed at identifying a set of ecosystem services generated by *Posidonia oceanica* seagrass beds and Coralligenous bioconstructions and estimating their economic value.

2. Materials and methods

2.1. The area of study

“Punta Campanella” is a MPA located in the Sorrento Peninsula of the Gulf of Naples, Southern Italy. It was established in 1997 by the Italian Ministry of the Environment. The MPA covers a total area of about 1500 hectares with a coastline of about 40 km.

The Gulf of Naples is characterized by peculiar orographic features influencing wind and sea dynamics. In particular, the Vesuvius volcano and the hills system of the city of Naples can shelter north-easterly winds blowing over the basin mostly in winter, creating jet currents responsible for coastal water exchanges (Cianelli et al., 2012). These water exchanges provide a continuous supply of clean and deep water rich in nutrients supporting primary production and its transfer to higher trophic levels (Appolloni et al., 2018a).

The MPA is also characterized by a very peculiar geomorphological configuration. Due to the calcareous nature of the Sorrento Peninsula, the area has been subject to intense karst phenomena that have generated several emerged and submerged cavities (Cinque, 2017). More than 50 caves are included within the MPA. They are particular environments whose chemical-physical parameters strongly affect the composition of the ecological communities. The caves mainly host sciaphilic assemblages including rare species, such as the sea anemone *Halcampoides purpureus* (Studer, 1879) recorded in the IUCN Red List of Mediterranean Anthozoa (Otero et al., 2017).

The submerged overhanging walls and carbonate pinnacles allow the presence of pre-coralligenous formation at a depth of a few metres, while rich biocenoses of coralligenous banks occur at a depth of about 55 metres (Ferrigno et al., 2016, 2017).

Noteworthy is the presence of the endemic Mediterranean seagrass *Posidonia oceanica* whose biocenosis covers about 10% of the MPA total area.

The high biodiversity together with the peculiar geomorphological configuration and mild Mediterranean climate makes the MPA an attractive site for many touristic activities such as swimming, boating, and diving.

Like all the Italian MPAs, Punta Campanella MPA is characterized by three zones with different levels of protection and allowed human activities, namely Zone A, Zone B, and Zone C (Fig. 1), covering about 12%, 43%, and 45% of the total area, respectively.

All the biocenosis included within the boundaries of the MPA were identified through the analysis of the bionomic map (Appolloni et al., 2018b) and clustered into the following four macro-habitats: 1) sciaphilic hard bottom (SHB, coralligenous bioconstructions), 2) photophilic hard bottom (PHB), 3) soft bottom (SB), and 4) *Posidonia oceanica* seagrass beds (PSB) (Fig. 2).

2.2. *The environmental accounting model*

This study provides a biophysical and economic assessment of natural capital stocks and ecosystem services flows of Punta Campanella MPA. The conceptual diagram in Fig. 3 summarizes the main steps of the implemented environmental accounting model. All steps are described in details in the following paragraphs.

2.2.1. *Sampling procedures and data analysis*

Ad hoc sampling campaigns were performed in spring 2018 to collect data on macrobenthic communities and necto-benthic fishes in the four investigated macro-habitats. Samplings of macrobenthic organisms were performed through the “air-lift - scraping - air-lift” technique (Chemello and Russo, 1997) and randomly replicated three times in each habitat using different frames (Buonocore et al., 2019).

After sorting, species were identified and clustered in the following main taxonomic groups: Algae, Annelida, Ascidiacea, Bryozoa, Cnidaria, Crustacea, Demospongiae, Echinodermata, and Mollusca. The dry biomass of the different macrobenthic groups was assessed by using a drying oven and then converted to grams of ash free dry weight (AFDW) and grams of carbon (gC) through appropriate conversion factors (Brey, 2016). The biomass of necto-benthic fishes was assessed based on visual census transects (Harmelin-Vivien et al., 1985)

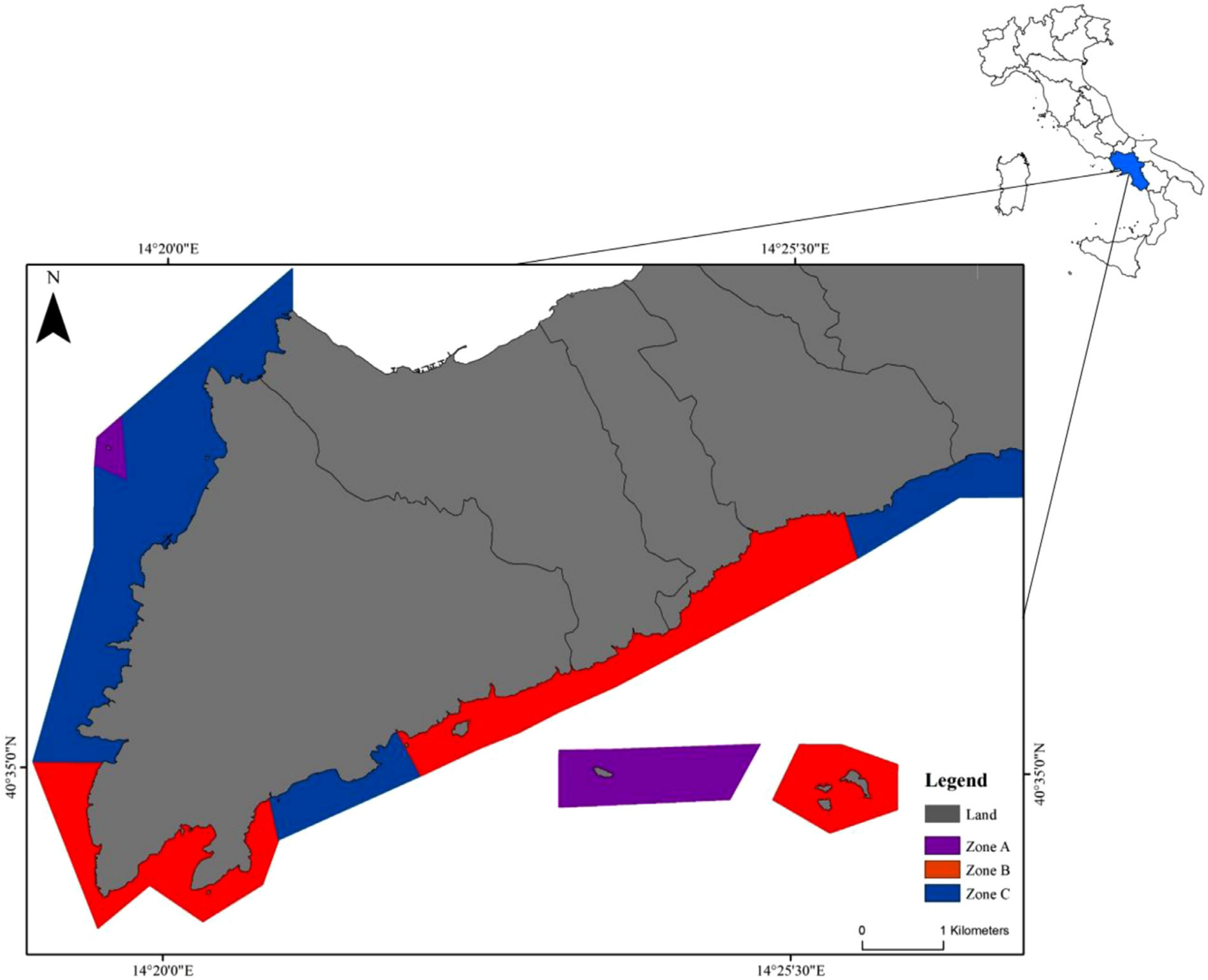

Fig. 1. Area of study: “Punta Campanella” MPA (Southern Italy).

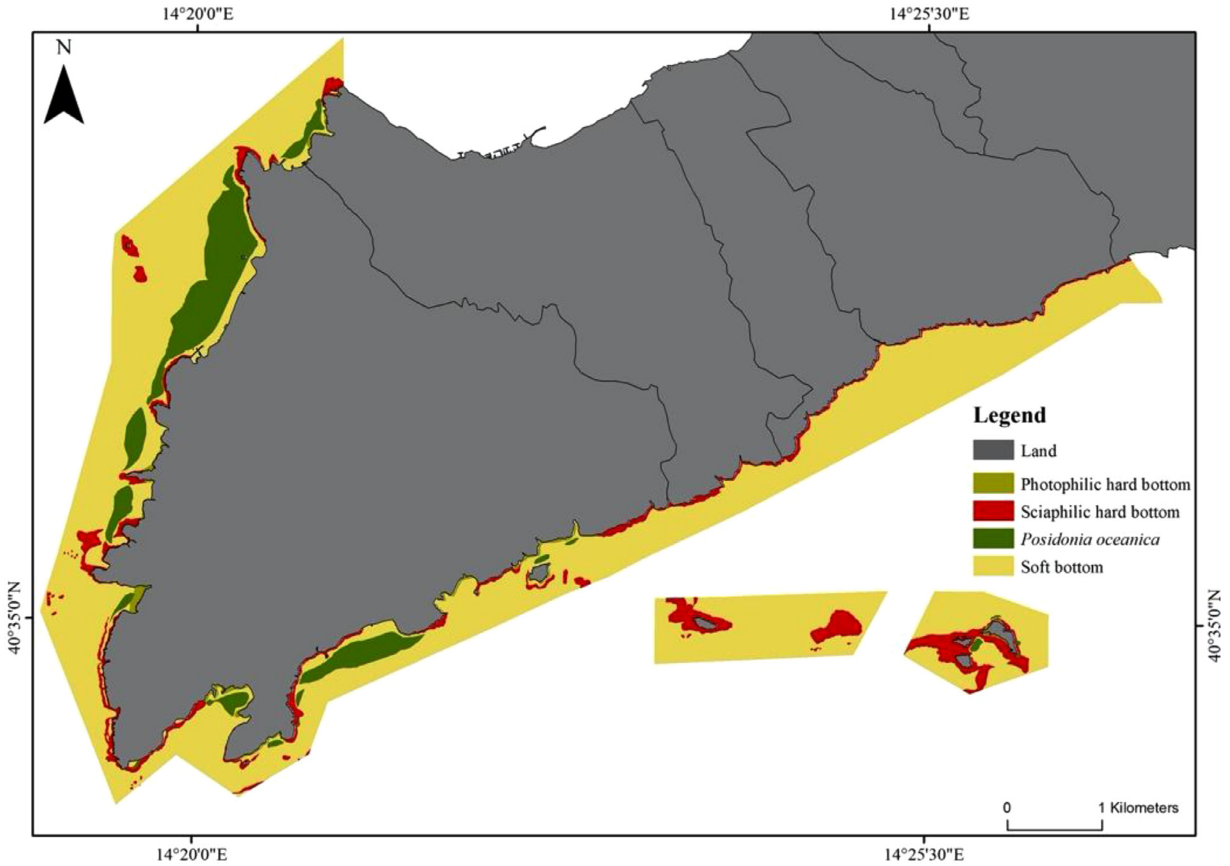

Fig. 2. Bionomic map of “Punta Campanella” MPA (Southern Italy).

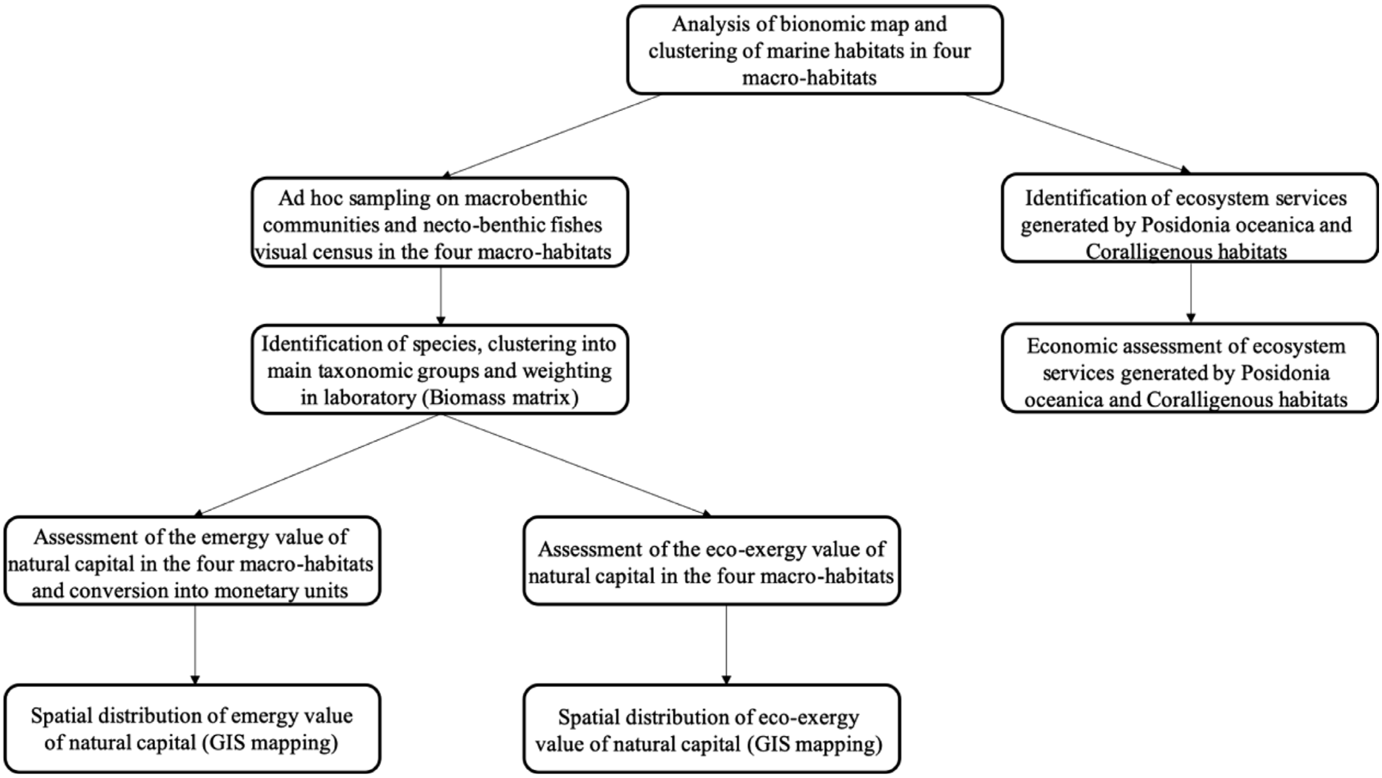

Fig. 3. Conceptual model of the environmental accounting model implemented in this study.

randomly performed on the investigated macro-habitats (Buonocore et al., 2019). Average biomass data on the groups Epiphytes, Microphytobenthos, Phytoplancton, and *Posidonia* were estimated from literature (Boudouresque et al., 2006; Charpy-Roubaud and Sournia, 1990).

The matrix of the biomass density calculated for the different taxonomic groups and the four macro-habitats was the basis for the implementation of the emergy and eco-exergy natural capital assessment.

2.2.2. *The eco-exergy accounting method*

The eco-exergy method accounts for the chemical energy in organic matter and the genetic information embodied in living organisms, providing a measure of the organizational level and complexity of an ecosystem (Jørgensen and Mejer, 1979).

Eco-exergy for living organisms is calculated according to the following equation:

$$\text{Eco-exergy} = \beta \times B \times f$$

where β is a weighting factor expressing the information content of the organism's genes, B is the organism's biomass, and f is the average value of work energy per unit of biomass (Jørgensen, 2015).

The total eco-exergy of an ecosystem is calculated as the sum of the eco-exergy values of all the organisms present in that ecosystem.

In this study, the eco-exergy value of natural capital stocks in the investigated macro-habitats was calculated. The biomass values of the different taxonomic groups were multiplied by their specific β-values and then summed to obtain the total eco-exergy value of each macro-habitat. More details on the accounting procedures can be found in Buonocore et al. (2019).

2.2.3. *The emergy accounting method*

The emergy accounting method (Odum, 1988, 1996) aims at evaluating the cumulative environmental support to a system on the global scale of the biosphere, taking into account free environmental inputs, human-driven material and energy flows, and the indirect environmental support embodied in human labor and services (Brown and Ulgiati, 2004; Brown et al., 2016a, 2016b; Franzese et al., 2009, 2014). According to this method, inputs are accounted for in terms of their solar emergy, defined as the total amount of solar available energy (exergy) directly or indirectly used to make a given product or support a given flow, and measured in sej (solar emergy joules). The solar emergy required to generate one unit of product or service is referred to as Unit Emergy Value (UEV, sej J^{-1}, sej g^{-1}). All inputs to an investigated system are converted into emergy units by using appropriate UEVs and then summed to calculate the total emergy support.

In this study, the emergy accounting method was used to assess the biophysical value of natural capital stocks in the investigated MPA according to the biophysical and trophodynamic environmental accounting model described in Vassallo et al. (2017) and Buonocore et al. (2019).

In addition, the biophysical values of natural capital were converted into equivalent monetary units by using the Emergy to Money Ratio (EMR) indicator (Lou and Ulgiati, 2013; Tian et al., 2017). In particular, in this study the EMR of $9.60 \cdot 10^{11}$ sej €$^{-1}$ calculated for Italy (Pereira et al., 2013) was used. The equivalent monetary value of natural capital for each macro-habitat was calculated dividing the emergy value by the EMR.

2.2.4. *Emergy and eco-exergy indicators*

A set of emergy and eco-exergy indicators was calculated for the four investigated habitats. In particular, the total emergy value of each habitat was calculated to account for the emergy flows that supported the generation of its natural capital stocks. Since this indicator is an extensive measure depending on the area of the investigated habitats, the emergy density values were also calculated to account for the emergy flows concentrated per unit area. These values represent an intensive measure of the emergy support to each habitat.

Similarly, the total eco-exergy value of each habitat was calculated as an extensive measure of chemical energy and genetic information embodied in its living organisms. In addition, the eco-exergy density was calculated to account for the eco-exergy flows concentrated per unit area.

Finally, the emergy-ecoexergy ratio was calculated for all the investigated habitats. This indicator represents the amount of emergy flows required to generate a unit of organization and reflects the efficiency of an ecosystem in building its complexity (Bastianoni and Marchettini, 1997). The emergy-ecoexergy ratio was calculated dividing the emergy density value by the eco-exergy density value calculated for each habitat.

2.2.5. *Ecosystem services assessment*

The assessment of the ecosystem services generated by the MPA of Punta Campanella was focused on two main habitats: *Posidonia oceanica* seagrass beds and Coralligenous bioconstructions.

Posidonia oceanica plays a crucial ecological role in the Mediterranean marine ecosystem and provides several valuable ecosystem services (Campagne et al., 2015). Its presence implies a unique enrichment of species enhancing the biodiversity of coastal waters. The meadows are nursery and foraging areas for several fish and shellfish species and improve water quality by reducing particle loads in the water and absorbing dissolved nutrients (Hemminga and Duarte, 2000). *Posidonia oceanica* also develops a web of roots stabilizing sediments and provides protection against coastal erosion. In addition, the seagrass beds play a significant role in nutrient cycling and in carbon fixation and storage (Pergent et al., 2012).

In this study, the following ecosystem services generated by *Posidonia oceanica* seagrass beds were evaluated: raw materials provision, food provision, carbon sequestration, nursery, and nutrient cycling.

Coralligenous habitats are very complex marine habitats and, together with *Posidonia oceanica* seagrass beds, are considered as the most important Mediterranean marine ecosystems (Giakoumi et al., 2013). Coralligenous habitats are hotspot of biodiversity and provide a large set of ecosystem services (Ballesteros, 2006). Among them, the regulating service of carbon sequestration by coralligenous bioconstructions is controversial (Chisholm and Barnes, 1998; Lønborg et al., 2019). In fact, the sequestering of carbon in the precipitation of calcium carbonate is accompanied by release of CO_2. For this reason, coralligenous bioconstructions can be considered as sink of carbon and source of carbon dioxide (Ware et al., 1991). Since the role of coralligenous bioconstructions in global carbon cycles needs to be further investigated, the carbon sequestration service provided by the Coralligenous habitat was not evaluated.

In this study, the following ecosystem services generated by Coralligenous bioconstructions were estimated: raw materials provision, food provision, nursery, and recreation.

The TEEB Valuation Database (https://www.es-partnership.org/services/data-knowledge-sharing/ecosystem-service-valuation-database/) was used to estimate the economic values per unit area of the ecosystem services generated by *Posidonia oceanica* seagrass beds and Coralligenous bioconstructions (Table 1).

These values were then multiplied by the area covered by the two habitats in the MPA to provide an economic estimation of the ecosystem services generated at MPA scale.

The total area covered by Coralligenous bioconstructions and *Posidonia oceanica* seagrass beds was calculated from the bionomic map of the MPA that is two-dimensional (2D). Yet, a peculiarity of the investigated MPA is the high presence of Coralligenous bioconstructions on cliffs not represented in the 2D bionomic map.

For this reason, a three-dimensional (3D) bionomic map was developed by using the “interpolate shape” tool of the ArcGIS software

Table. 1
Value of ecosystem services generated per unit area by *Posidonia oceanica* seagrass beds and Coralligenous bioconstructions.

Ecosystem services	Unit	*Posidonia oceanica* seagrass beds	Coralligenous bioconstructions
Raw materials provision	USD ha^{-1} yr^{-1}	2.00E + 00	2.67E + 01
Food provision (Fish)	USD ha^{-1} yr^{-1}	1.71E + 03	1.50E + 03
C-sequestration	USD ha^{-1} yr^{-1}	4.52E + 02	not accounted
Nursery	USD ha^{-1} yr^{-1}	1.33E + 02	7.00E-02
Nutrient cycling	USD ha^{-1} yr^{-1}	1.90E + 04	not accounted
Recreation	USD ha^{-1} yr^{-1}	not accounted	3.01E + 03

Table. 2
Biomass density of the main taxonomic groups in the habitats of “Punta Campanella” MPA.

	Biomass (g_{AFDW} m^{-2})			
Groups	SHB	PHB	SB	PSB
Algae	18.64	47.50	0.00	1.54
Epiphytes	0.00	17.98	0.00	2.90
Microphytobenthos	55.37	55.37	55.37	55.37
Phytoplancton	1.51	1.51	1.51	1.51
Posidonia	0.00	0.00	0.00	475.11
Annelida	8.88	0.80	4.38	1.02
Ascidiacea	0.04	0.00	0.00	0.00
Bryozoa	5.26	0.47	0.17	0.96
Cnidaria	5.94	2.82	0.00	0.00
Crustacea	0.99	0.53	0.07	0.13
Demospongiae	12.81	29.83	0.00	0.00
Echinodermata	0.29	0.00	0.79	0.08
Fishes	39.40	15.54	0.24	4.69
Mollusca	27.36	5.33	3.84	2.75

version 10.1 and the Digital Elevation Model as reference surface.

3. Results

3.1. Natural capital assessment

Table 2 shows the main taxonomic groups identified in the four habitats of the investigated MPA and relative biomass density expressed in grams of AFDW per unit area. These biomass values represent the basic information for the implementation of the emergy and eco-exergy accounting.

Table 3 shows the eco-exergy value of the main autotrophic groups. The PSB habitat showed the highest values of eco-exergy density ($3.51 \cdot 10^6$ kJ m^{-2}) and total eco-exergy ($5.03\ 10^{12}$ kJ). Table 4 shows the eco-exergy value of the main heterotrophic groups. In this case, the SHB habitat showed the highest values of eco-exergy density ($6.03 \cdot 10^5$ kJ m^{-2}) and total eco-exergy ($8.29 \cdot 10^{11}$ kJ).

Table 5 shows the emergy flows supporting the generation of autotrophic natural capital stocks. Inputs accounted for include natural and nutrients flows that supported the formation of autotrophic natural capital stocks.

The total emergy values range from $3.01 \cdot 10^{16}$ sej (for the habitat

Table. 3
Eco-exergy value of autotrophic natural capital stocks in the four habitats of “Punta Campanella” MPA.

	Eco-exergy (kJ m^{-2})			
Groups	**SHB**	**PHB**	**SB**	**PSB**
Algae	6.97E + 03	1.78E + 04	0.00E + 00	5.76E + 02
Epiphytes	0.00E + 00	6.72E + 03	0.00E + 00	1.08E + 03
Microphytobenthos	2.07E + 04	2.07E + 04	2.07E + 04	2.07E + 04
Phytoplancton	5.65E + 02	5.65E + 02	5.65E + 02	5.65E + 02
Posidonia	0.00E + 00	0.00E + 00	0.00E + 00	3.49E + 06
Eco-exergy density (kJ m^{-2})	2.82E + 04	4.58E + 04	2.13E + 04	3.51E + 06
Total eco-exergy (kJ)	3.88E + 10	8.59E + 09	2.66E + 11	5.03E + 12

Table. 4
Eco-exergy value of heterotrophic natural capital stocks in the four habitats of “Punta Campanella” MPA.

	Eco-exergy (kJ m^{-2})			
Groups	**SHB**	**PHB**	**SB**	**PSB**
Annelida	2.21E + 04	1.98E + 03	1.09E + 04	2.55E + 03
Ascidiacea	1.73E + 02	0.00E + 00	0.00E + 00	0.00E + 00
Bryozoa	1.61E + 04	1.44E + 03	5.07E + 02	2.96E + 03
Cnidaria	1.01E + 04	4.80E + 03	0.00E + 00	0.00E + 00
Crustacea	4.30E + 03	2.29E + 03	2.87E + 02	5.74E + 02
Demospongiae	2.35E + 04	5.47E + 04	0.00E + 00	0.00E + 00
Echinodermata	7.79E + 02	0.00E + 00	2.11E + 03	2.23E + 02
Fishes	3.68E + 05	1.45E + 05	2.24E + 03	4.38E + 04
Mollusca	1.59E + 05	3.09E + 04	2.23E + 04	1.60E + 04
Eco-exergy density (kJ m^{-2})	**6.03E + 05**	**2.41E + 05**	**3.83E + 04**	**6.61E + 04**
Total eco-exergy (kJ)	**8.29E + 11**	**4.53E + 10**	**4.79E + 11**	**9.46E + 10**

Table. 5
Emergy value of autotrophic natural capital stocks in the four habitats of “Punta Campanella” MPA.

INPUT	Emergy (sej)			
	SHB	**PHB**	**SB**	**PSB**
Solar radiation	1.88E + 16	2.63E + 15	1.66E + 17	5.32E + 16
Rain	5.01E + 16	7.02E + 15	4.45E + 17	1.42E + 17
Wind	7.30E + 15	1.02E + 15	6.48E + 16	2.07E + 16
Geothermal flow	1.52E + 16	2.13E + 15	1.35E + 17	4.31E + 16
Tides	8.10E + 15	1.13E + 15	7.19E + 16	2.30E + 16
Currents	1.13E + 13	1.59E + 12	1.00E + 14	3.21E + 13
Runoff	5.25E + 16	7.36E + 15	4.66E + 17	1.49E + 17
C	4.56E + 15	1.01E + 15	3.13E + 16	3.45E + 16
N	5.64E + 16	1.25E + 16	3.86E + 17	4.26E + 17
P	3.11E + 16	6.89E + 15	2.13E + 17	2.35E + 17
Total emergy (sej)	1.82E + 17	3.01E + 16	1.50E + 18	7.83E + 17
Emergy density (sej m^{-2})	1.33E + 11	1.60E + 11	1.20E + 11	5.47E + 11

Table. 6
Emergy value of heterotrophic natural capital stocks in the four habitats of “Punta Campanella” MPA.

INPUT	Emergy (sej)			
	SHB	**PHB**	**SB**	**PSB**
Solar radiation	3.03E + 17	1.77E + 16	5.60E + 16	3.65E + 16
Rain	8.11E + 17	4.74E + 16	1.50E + 17	9.75E + 16
Wind	1.18E + 17	6.90E + 15	2.18E + 16	1.42E + 16
Geothermal flow	2.46E + 17	1.44E + 16	4.53E + 16	2.95E + 16
Tides	1.31E + 17	7.66E + 15	2.42E + 16	1.58E + 16
Currents	1.83E + 14	1.07E + 13	3.38E + 13	2.20E + 13
Runoff	8.50E + 17	4.97E + 16	1.57E + 17	1.02E + 17
C	3.70E + 17	2.16E + 16	6.83E + 16	4.45E + 16
N	4.57E + 18	2.67E + 17	8.43E + 17	5.49E + 17
P	2.52E + 18	1.47E + 17	4.66E + 17	3.03E + 17
Total emergy (sej)	6.61E + 18	3.86E + 17	1.22E + 18	7.94E + 17
Emergy density (sej m^{-2})	4.81E + 12	2.06E + 12	9.75E + 10	5.55E + 11

Table. 7
Cumulative emergy and eco-exergy indicators calculated with reference to both autotrophic and heterotrophic natural capital stocks.

Indicators	SHB	PHB	SB	PSB
Emergy density (sej m^{-2})	4.94E + 12	2.22E + 12	2.18E + 11	1.10E + 12
Total emergy (sej)	6.79E + 18	4.16E + 17	2.72E + 18	1.58E + 18
Eco-exergy density (kJ m^{-2})	6.32E + 05	2.87E + 05	5.96E + 04	3.58E + 06
Total eco-exergy (kJ)	8.68E + 11	5.39E + 10	7.45E + 11	5.12E + 12
Emergy / eco-exergy (10^6 sej kJ^{-1})	7.83	7.73	3.66	0.31

PHB) to $1.50 \cdot 10^{18}$ sej (for the habitat SB). Instead, the highest value of emergy density resulted $5.47 \cdot 10^{11}$ sej m^{-2} for the habitat PSB (Table 5).

Table 6 shows the emergy flows supporting the generation of heterotrophic natural capital stocks in the MPA. The total emergy values range from $3.86 \cdot 10^{17}$ sej (for the habitat PHB) to $6.61 \cdot 10^{18}$ sej (for the habitat SHB). The highest value of emergy density was $4.81 \cdot 10^{12}$ sej m^{-2} for the habitat SHB (Table 6).

Table 7 summarizes the cumulative emergy and eco-exergy indicators calculated for each of the four investigated habitat with reference to both autotrophic and heterotrophic natural capital stocks. The SHB habitat showed the highest total emergy value of natural capital ($4.94 \cdot 10^{12}$ sej m^{-2}), while the highest eco-exergy value resulted for the PSB habitat ($3.58 \cdot 10^{6}$ kJ m^{-2}).

The emergy-ecoexergy ratio ranges from $7.83 \cdot 10^{6}$ sej kJ^{-1} (for the habitat SHB) to $0.31 \cdot 10^{6}$ sej kJ^{-1} (for the habitat PSB) (Table 7).

Table 8 displays the (non-market) monetary equivalents of the emergy values of natural capital stocks. The value per unit area ranges from 5.16 € m^{-2} (for the SHB habitat) to 0.23 € m^{-2} (for the SB habitat). The total value of natural capital of the whole MPA, calculated as the sum of the values of all the habitats, resulted about 12 M€ (Table 8).

Fig. 4 shows the spatial distribution of the emergy and eco-exergy values of natural capital in the MPA and its current zonation. The map of emergy values distribution (Fig. 4a) shows that areas with high-density values of natural capital are currently included in the A and B zones, designed to ensure high levels of protection within the MPA. In particular, zone A, B, and C include 16%, 45%, and 39% of the total emergy value of natural capital, respectively. Instead, the map of eco-exergy values distribution (Fig. 4b) shows that areas with high-density values of natural capital are mainly included in zone C. In fact, zone A, B, and C represent 4%, 19%, and 77% of the total eco-exergy natural capital value, respectively. These results show that most of the eco-exergy value of natural capital falls in zone C (the protection zone mainly devoted to promote socioeconomic activities), thus highlighting a possible conflict between the protection of natural capital and the development of human activities.

3.2. Ecosystem services assessment

The economic value of the ecosystem services generated by *Posidonia oceanica* seagrass beds and Coralligenous bioconstructions are shown in Table 9a,b. The total economic value of the ecosystem services annually generated by *Posidonia oceanica* seagrass beds and Coralligenous bioconstructions were 3.05 M€ and 0.62 M€.

Table. 8
Equivalent monetary value of natural capital stocks.

	Indicators	
Habitat	Monetary value per unit area (€ m^{-2})	Monetary value for the whole habitat area (€)
SHB	5.16	7.09E + 06
PHB	2.32	4.36E + 05
SB	0.23	2.93E + 06
PSB	1.18	1.69E + 06
Total value (€)		1.21E + 07

Nutrient cycling was the highest ecosystem service generated by *Posidonia oceanica* (2.72 M€, Table 9a), while the recreation service resulted the highest ecosystem service generated by Coralligenous bioconstructions (0.41 M€, Table 9b).

Fig. 5 shows the 2D and 3D bionomic maps for the investigated MPA. The generated 3D map allowed detecting many differences compared to the 2D map, especially for those habitats growing on vertical substrate (mainly SHB and PHB).

Table 10 shows the area of the different habitats calculated by using both 2D and 3D maps. The SHB was the most underestimated habitat in the 2D map (Table 10).

Therefore, the values of natural capital and ecosystem services were recalculated according to the new values of habitats area estimated by using the 3D map (Table 11). The accounting of 3D areas increased the emergy value of natural capital and the related economic value by 8%, the eco-exergy value of natural capital by 5%, and the economic value of ecosystem services by 5%.

4. Discussion

In this study, the emergy and eco-exergy methods were used to assess the value of natural capital of a Mediterranean MPA. The assessment focused on four macro-habitats: sciaphilic hard bottom (SHB, coralligenous bioconstructions), photophilic hard bottom (PHB), soft bottom (SB), and *Posidonia oceanica* seagrass beds (PSB). The emergy and eco-exergy assessments highlighted the importance of two main habitats: SHB and PSB.

In fact, the cumulative eco-exergy density of natural capital stocks ($3.58 \cdot 10^{6}$ kJ m^{-2}, Table 7) was higher for PSB habitat compared to all the other habitats. The high eco-exergy value of PSB habitat is mainly due to the high *ß* value of the seagrass *Posidonia oceanica* (reflecting its complex evolutionary history) and its high value of biomass density.

The calculated eco-exergy density of PSB was in line with the values calculated by Buonocore et al. (2019) for the same habitat in other Mediterranean MPAs. Moreover, the cumulative emergy density value of the SHB ($4.94 \cdot 10^{12}$ sej m^{-2}, Table 7) was higher than all the other habitats. The high emergy value calculated for the SHB habitat reflects the high convergence of natural input flows for the generation of its biomass stock and high biodiversity. This value is also comparable with the values calculated by Buonocore et al. (2019), Franzese et al. (2017) and Paoli et al. (2018) for the Coralligenous habitat in other Mediterranean MPAs.

The low value of the emergy/eco-exergy ratio calculated for PSB showed that this habitat is the most efficient among the others in building its organization and complexity. Instead, the high value of the same indicator calculated for SHB is due to the high convergence of natural flows generating the complex ecological structure characterizing coralligenous bioconstructions (Paoli et al., 2016).

In addition, the integration of the emergy and ecoexergy value with the bionomic map of the MPA showed that maps of the spatial distribution of natural capital value are useful in support of local managers and policy makers to evaluate the effectiveness of zonation and other nature conservation strategies.

Furthermore, to complement the biophysical assessment with an economic perspective, the emergy values of natural capital stocks calculated for the four investigated macro-habitats were converted into monetary units. The monetary values calculated for the different macro-habitats (e.g., 7.09 M€ for SHB and 1.69 M€ for PSB, Table 8) and for the whole MPA (12 M€, Table 8) allow for an easier understanding of the value of nature in socioeconomic contexts.

The biophysical and economic assessment of natural capital value was then complemented with an estimation of a set of ecosystem services generated by *Posidonia oceanica* seagrass beds and Coralligenous bioconstructions at MPA scale. The total economic value of the

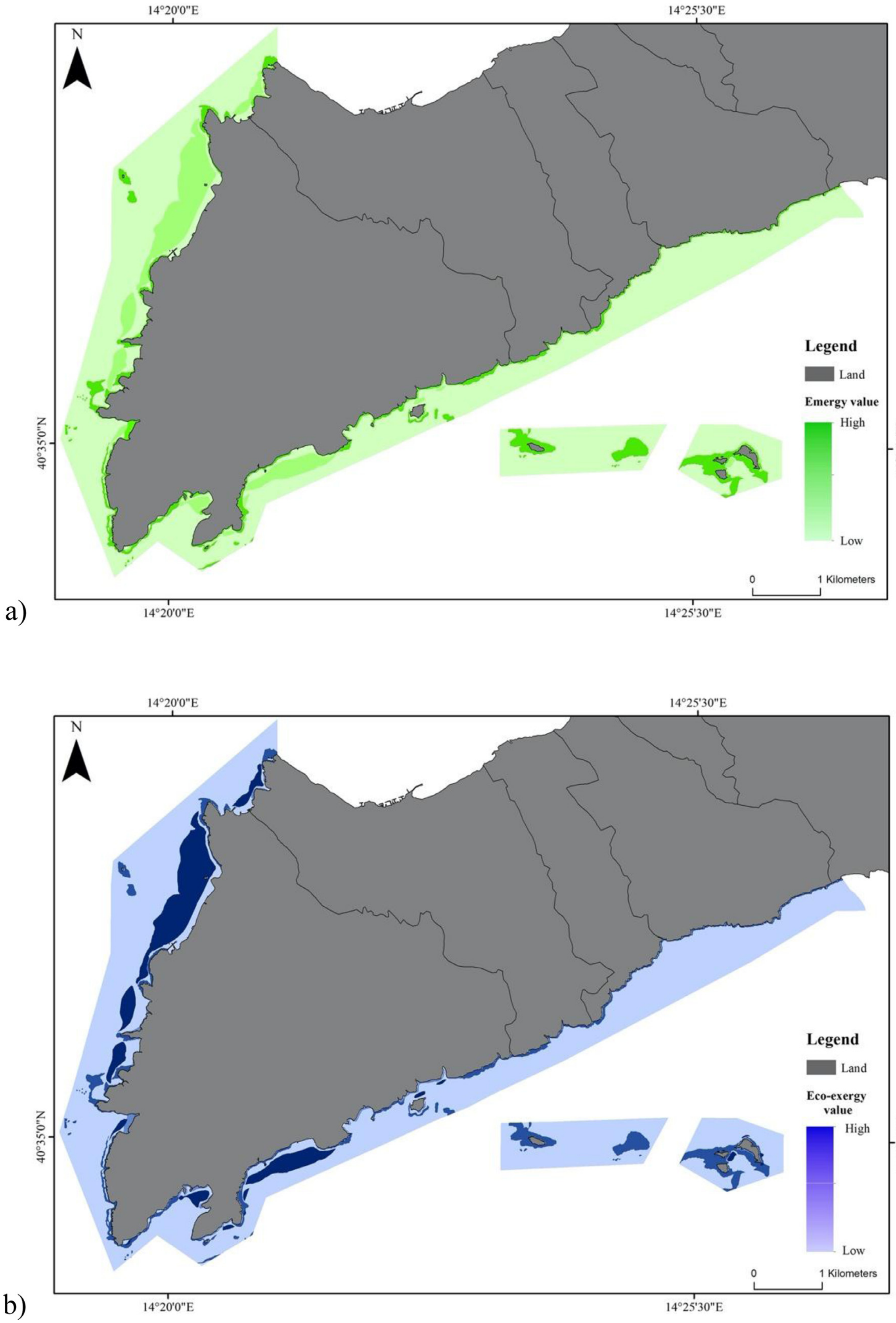

Fig. 4. Spatial distribution of emergy (a) and eco-exergy (b) natural capital value in "Punta Campanella" MPA (darker colors represent higher values of natural capital stocks).

Table. 9
Value of ecosystem services generated by *Posidonia oceanica* seagrass beds (a) and Coralligenous bioconstructions (b).

a) **Ecosystem services**	**Unit**	**Value**
Raw materials provision	€ yr^{-1}	2.86E + 02
Food provision (Fish)	€ yr^{-1}	2.45E + 05
C-sequestration	€ yr^{-1}	6.47E + 04
Nursery	€ yr^{-1}	1.91E + 04
Nutrient cycling	€ yr^{-1}	2.72E + 06
Total value	€ yr^{-1}	**3.05E + 06**
b)		
Ecosystem services	**Unit**	**Value**
Raw materials provision	€ yr^{-1}	3.67E + 03
Food provision (Fish)	€ yr^{-1}	2.06E + 05
C-sequestration	€ yr^{-1}	not accounted
Nursery	€ yr^{-1}	9.62E + 00
Recreation	€ yr^{-1}	4.13E + 05
Total value	€ yr^{-1}	**6.23E + 05**

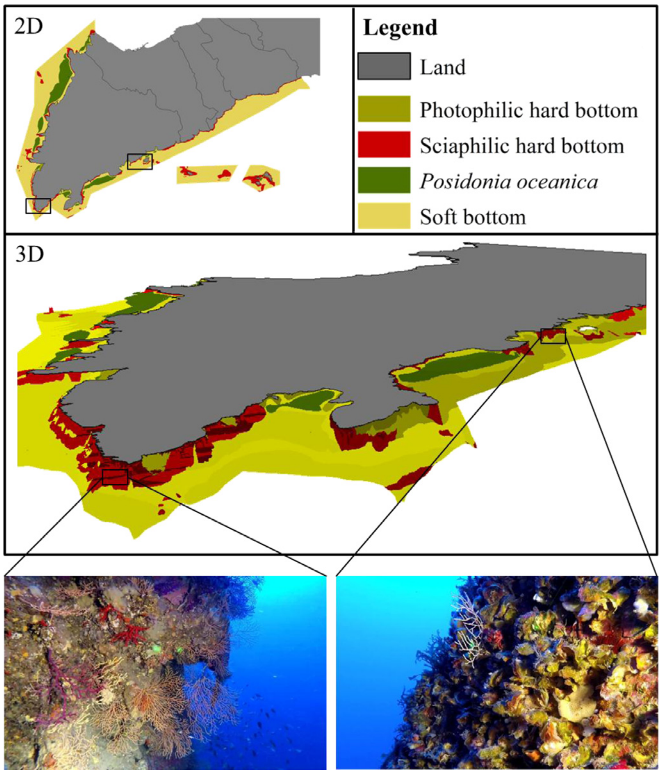

Fig. 5. 2D and 3D bionomic maps of “Punta Campanella” MPA.

Table. 10
Area of the investigated habitats calculated by using 2D and 3D maps.

Habitat	2D area (ha)	3D area (ha)	Increment (%)
SHB	137.39	151.11	10%
PHB	18.78	19.91	6%
SB	1250.08	1322.18	6%
PSB	143.10	148.78	4%

ecosystem services generated by both habitats (3.05 M€ and 0.62 M€, Table 9) was underestimated for two main reasons. Firstly, the assessment of ecosystem services was based on the area covered by the two macro-habitats calculated by using a 2D bionomic map of the MPA that does not include habitats on vertical substrates. To face this limitation, a 3D bionomic map for Punta Campanella MPA was generated to detect differences in the value of both natural capital and ecosystem services, confirming the importance of considering cliffs when accounting for the value of coastal ecosystems.

Table. 11
Value of natural capital and ecosystem services calculated by using the 3D map.

Habitat	Emergy value of natural capital (sej)	Eco-exergy value of natural capital (kJ)	Economic value of natural capital (€)	Ecosystem services value (€ yr^{-1})
SHB	7.46E + 18	9.55E + 11	7.80E + 06	6.86E + 05
PHB	4.42E + 17	5.71E + 10	4.62E + 05	–
SB	2.88E + 18	7.88E + 11	3.04E + 06	–
PSB	1.64E + 18	5.33E + 12	1.76E + 06	3.17E + 06
Total	1.24E + 19	7.13E + 12	1.31E + 07	3.85E + 06

In addition, the data available in this study allowed for an estimation of selected ecosystem services that, although very important for human well-being, do not reflect the overall set of ecosystem functions and services generated by *Posidonia oceanica* seagrass beds (Hemminga and Duarte, 2000; Pergent et al., 2012) and Coralligenous bioconstructions (Ballesteros, 2006; UN-MAP, 2017). Future studies might focus on the assessment of other ecosystem services generated by *Posidonia oceanica* seagrass beds, Coralligenous bioconstructions, and other marine habitats.

The main findings of the present study are useful to complete the assessment of natural capital value in the network of MPAs located in Campania region (Southern Italy), providing a more solid benchmark for future assessment at larger scales. In terms of novelty with respect to a previous study performed in the same region (Buonocore et al., 2019), the environmental accounting model was further improved. In particular, the assessment of natural capital was enriched by the calculation of integrated emergy-ecoexergy indices and complemented by the assessment of a set of ecosystem services. In addition, the generation of a 3D bionomic map allowed for the assessment of marine habitats laying on vertical surfaces that, in some contexts, do not represent a negligible contribution.

In light of these aspects, although the use of a standardized environmental accounting protocol is surely desirable for a consistent comparison of results calculated for different MPAs, we maintain the importance of adapting the accounting model to comply with physical and biological peculiarities characterizing different marine ecosystems.

5. Conclusions

In this study, the emergy and eco-exergy accounting methods were jointly used to assess the biophysical value of natural capital stocks in the main habitats of a Mediterranean MPA.

The eco-exergy results showed the importance of the habitat formed by the seagrass *Posidonia oceanica* in terms of stored biomass and genetic information while the emergy method highlighted the high convergence of natural flows in generating the complexity of Coralligenous habitat.

The conversion of the emergy values into monetary equivalents also allowed an estimation of the economic value of natural capital stocks in the MPA.

In addition, the assessment of the biophysical and economic value of natural capital stocks was complemented by the economic assessment of selected ecosystem services generated by *Posidonia oceanica* seagrass beds and Coralligenous bioconstructions.

The results of this study showed the high value of these two habitats in terms of both natural capital stocks and delivery of ecosystem services, confirming the importance of their protection and conservation in marine and coastal management.

The biophysical and economic values of natural capital and ecosystem services, together with the maps showing the spatial distribution of their value in the MPA, can support local managers and policy makers to develop and implement nature conservation strategies while ensuring the sustainable use of marine resources.

Future studies could be oriented towards a more comprehensive assessment of the overall set of ecosystem services generated by all the marine habitats characterizing the investigated MPA. In addition, the proposed assessment framework could be applied to estimate the value of natural capital and ecosystem services in marine and coastal ecosystems at larger spatial scales.

CRediT authorship contribution statement

Elvira Buonocore: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Luigia Donnarumma:** Resources, Data curation. **Luca Appolloni:** Software, Data curation. **Antonino Miccio:** Funding acquisition. **Giovanni F. Russo:** Project administration, Supervision. **Pier Paolo Franzese:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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