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Exploring the convergence of natural flows for the generation of natural capital stocks in marine ecosystems

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ABSTRACT

Marine ecosystems are open, complex, adaptive, and hierarchical systems highly integrated through the exchange of matter and energy flows. This flows exchange allows marine ecosystems to operate at different scales acting as dissipative structures, building natural capital stocks capable of generating several ecosystem services vital for human well-being. Humans derive a wide range of goods and services from marine ecosystems while, at the same time, generate several impacts causing biodiversity loss and seriously affecting their capacity to provide benefits to humans. Effective management strategies are crucial to conserve healthy and diverse marine and coastal ecosystems, maintain the valuable functions and services they provide, and allow for sustainable human activities. In recent years, Marine Protected Areas (MPAs) have been increasingly acknowledged worldwide as important tools to conserve biodiversity and achieve human well-being and sustainable development goals. Assessing the value of natural capital and ecosystem services is crucial to raise awareness on their importance, support conservation strategies, and ensure the sustainable management of marine ecosystems. This study aimed at calculating biomass and emergy-based indicators to assess the value of natural capital stocks in a Mediterranean MPA. The assessment was performed through a biophysical and trophodynamic environmental accounting model fed with field biomass data collected through *ad hoc* sampling campaigns performed in the MPA. Four main macro-habitats were investigated: sciaphilic hard bottom (coralligenous bioconstructions), photophilic hard bottom, soft bottom, and *Posidonia oceanica* seagrass beds. The biomass density of the main autotrophic and heterotrophic taxonomic groups identified in the four macro-habitats of the MPA was evaluated. Based on this biomass matrix, the emergy value of natural capital stocks was assessed. The *Posidonia oceanica* seagrass beds habitat showed the highest biophysical value ($2.32 \cdot 10^{19}$ sej) at MPA scale, while coralligenous bioconstructions resulted the habitat with the highest biophysical value per unit area ($2.72 \cdot 10^{12}$ sej m^{-2}). In addition, to complement the biophysical assessment with an economic perspective, the emergy-based indicators were converted into monetary units. The total value of natural capital of the whole MPA resulted in about 46 M€. The results of this study can support local managers and policy makers in the development of management strategies to ensure nature conservation and sustainable human activities. They can be also used as a benchmark for the assessment of natural capital value at larger scales in support of a proper consideration and inclusion of nature value into processes of policy making.

1. Introduction

Marine ecosystems are open, complex, adaptive, and hierarchical systems highly integrated through matter and energy flow exchanges. Matter and energy flow exchanges allow ecological systems to operate at different scales acting as dissipative structures, building natural capital stocks capable of generating several ecosystem services vital for human well-being (Vihervaara et al., 2019).

Humans interact with marine ecosystems in different ways. They derive a wide range of vital goods and services from marine ecosystems including the provision of fish and raw materials, recreational opportunities for local communities and tourists, the regulation and

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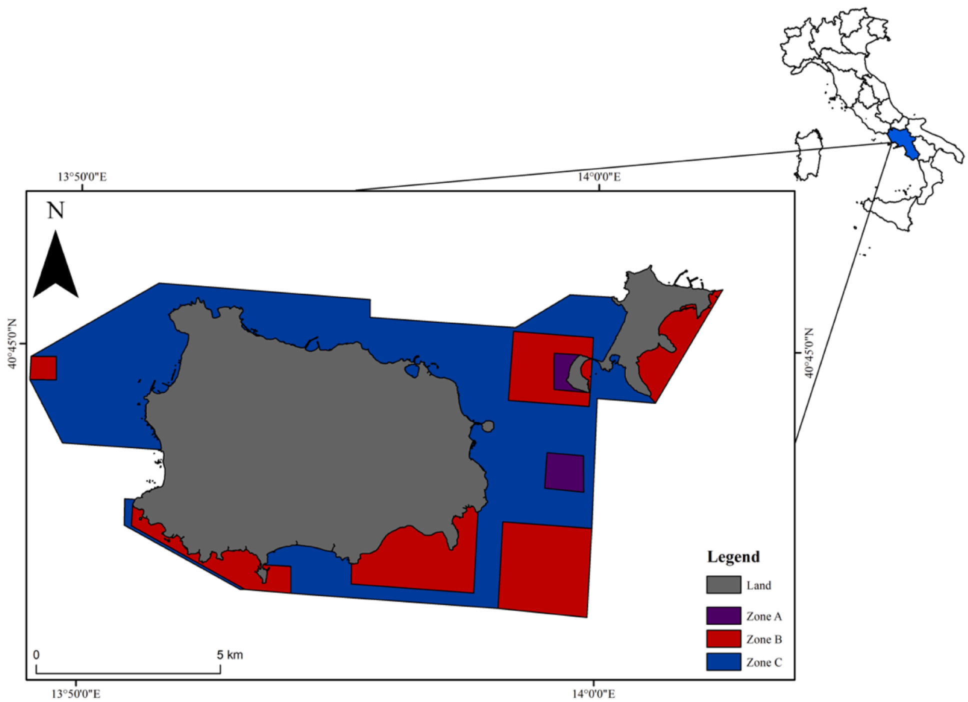

Fig. 1. Study area: the MPA “Regno di Nettuno”, Southern Italy.

sequestration of nutrients and toxic substances, and climate regulation (Blythe et al., 2020; Buonocore et al., 2020a; Chakraborty et al., 2020). At the same time, human activities cause several impacts on marine ecosystems, among which overexploitation of fish stocks, introduction of invasive species, climate change, eutrophication, and waste release (Cattaneo-Vietti et al., 2016; Halpern et al., 2019; Hughes et al., 2017; Renzi et al., 2018). The cumulative anthropogenic pressures on marine ecosystems cause biodiversity loss, seriously affecting their capacity to provide benefits to humans (Halpern et al., 2008; Haines-Young and Potschin, 2010).

Anthropogenic impact on marine ecosystems is a growing concern especially in coastal areas where multiple human activities occur, generating considerable inflows of pollutants and hazardous wastes (Filipkowska et al., 2018). In fact, although the coastal zones represent only about 4% of the Earth’s total land area, they contain more than one third of the world’s population and account for about 90% of the catches from marine fisheries (Barbier, 2017).

In view of the current human pressures on coastal areas, effective management strategies are crucial to conserve healthy and diverse marine ecosystems, maintain the valuable functions and services they provide, and allow for sustainable human activities.

In recent years, Marine Protected Areas (MPAs) have been increasingly acknowledged worldwide as important tools to achieve local and global marine conservation targets (Börger et al., 2014; Coleman et al., 2013; Rasheed, 2020). MPAs are recognized also across multiple international policy processes, including the 2030 Agenda for Sustainable Development, the Convention on Biological Diversity (CBD) and the Ramsar Convention, as tools to conserve biodiversity and achieve human well-being and sustainable development goals (UNEP-WCMC, IUCN and NGS, 2018; Terraube et al., 2017).

In 2010, the CBD’s Parties adopted the Strategic Plan for Biological Diversity 2011-2020 that includes the Aichi target 11 calling for protecting at least 10% of the oceans through coastal and marine protected areas by 2020. In line with the Aichi target 11, there has been a remarkable growth of the number of MPAs in the last decades (Maestro et al., 2019). At global level, MPAs have increased more than 15-fold since 1993 when the CBD entered into force. Since 2016, more than 8 million km^2 of new protected areas have been added to the already existing MPAs (UNEP-WCMC, IUCN and NGS, 2018). Nowadays, the number of MPAs at global level is 16,916, covering about 7.5% of the global ocean. MPAs are more concentrated within national waters than in international ones. In fact, national waters represent about 39% of the global ocean of which about 17% are designated as protected areas (UNEP-WCMC and IUCN, 2020).

Assessing the stocks of natural capital and the flows of ecosystem services is crucial to ensure the sustainable management of marine ecosystems (Buonocore et al., 2018; Caro et al., 2018; Pauna et al., 2018). It is particularly useful in those areas where a protection regime is established to support conservation strategies and, eventually, assess their efficacy over the long term.

Environmental accounting represents a useful tool to assess the biophysical and economic value of ecosystem goods and services. In particular, environmental accounting allows the assessment of multiple aspects dealing with marine resources exploitation, among which sustained environmental costs, received benefits, and generated impacts (Häyhä and Franzese, 2014).

Several authors performed a monetary evaluation of natural capital and ecosystem services in marine and terrestrial ecosystems (Cavalletti et al., 2020; Costanza et al., 2014; Nikodinoska et al., 2018; Teoh et al., 2019), while others adopted a biophysical perspective (Berrios et al., 2017; Buonocore et al., 2019; Mancini et al., 2018; Monfreda et al., 2004; Yang et al., 2019). Nonetheless, the integration of economic valuations with biophysical accountings is much needed to capture the complex relationships between human and nature economy (Franzese et al., 2019; Myers, 2002).

In addition, environmental accounting can be usefully complemented by the use of spatial analysis. Assessing the value of natural capital and ecosystem services and mapping their spatial distribution enable identifying priority areas and related optimal management strategies, also facilitating the communication in policy contexts (Maes et al., 2012; Sannigrahi et al., 2019).

In 2014, the Italian Ministry of the Environment and Protection of Land and Sea funded a research programme for the implementation of an environmental accounting system for the network of Italian MPAs. The main goal of this research programme was the assessment of the biophysical and economic value of natural capital stocks and ecosystem

Table 1
Biomass indicators (dry weight) of main groups identified in 9 replicates performed on the SHB macro-habitat.

SHB	Replicates (g $_{dry\ weight}$)								
Groups	1/9	2/9	3/9	4/9	5/9	6/9	7/9	8/9	9/9
Mollusca	0.1747	1.1516	0.2075	0.0000	0.6689	0.1320	0.2693	0.0471	2.2710
Bryozoa	0.4401	3.7298	0.0000	0.3248	1.3019	0.0000	0.0000	0.1895	0.0000
Anellida	0.0089	0.0018	0.0071	0.0199	0.3649	0.0880	0.0537	0.4272	0.0201
Crustacea	0.0040	0.1777	0.0008	0.0141	0.0023	0.0251	0.0090	0.0088	0.0283
Sipuncula	0.0120	0.0098	0.0207	0.0000	0.0000	0.0000	0.0007	0.0138	0.0259
Echinodermata	0.0004	0.0000	0.0000	0.0000	0.6336	0.0000	0.0000	0.0010	0.0010
Ascidiacea	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9116
Porifera	0.0000	0.0472	0.0000	0.0000	0.0000	0.0000	0.6994	0.3372	2.2207
Algae	2.1006	5.5038	9.0936	1.0036	0.7872	3.6245	26.5545	18.3800	17.1422

services flows in the Italian MPAs (Franzese et al., 2015). Such environmental accounting system is meant to support the management and monitoring of the MPAs, supporting both local managers and policy makers committed to implement strategies for nature conservation and sustainable development.

Several recent studies assessed the biophysical and economic value of natural capital in marine ecosystems and MPAs. In particular, Franzese et al. (2017) applied an environmental accounting model to value natural capital stocks in the MPA “The Islands of Ventotene and S. Stefano” (Central Italy). Picone et al. (2017) calculated the biophysical value of natural capital stocks in the Egadi Islands MPA, also assessing the trade-offs between conservation measures and human activities. Paoli et al. (2018) calculated the emergy value of natural capital stocks in two MPAs located in Liguria Region (Northern Italy). Berrios et al. (2017) performed an emergy evaluation of marine benthic ecosystems in northern Chile assessing their contribution to the regional economy. Buonocore et al. (2020a) calculated emergy and eco-exergy indicators to assess the value of natural capital stocks in two MPAs located in Campania Region (Southern Italy) while Buonocore et al. (2020b) assessed natural capital value in the Gulf of Naples and Campania region (Southern Italy).

The present study aimed at calculating biomass and emergy-based indicators to assess the value of natural capital stocks in the MPA “Regno di Nettuno” (Southern Italy). The assessment was performed through a biophysical and trophodynamic environmental accounting model fed with field biomass data collected through *ad hoc* sampling campaigns performed in the MPA. In particular, the assessment focused on four main macro-habitats: sciaphilic hard bottom (coralligenous bioconstructions), photophilic hard bottom, soft bottom, and *Posidonia oceanica* seagrass beds. Finally, to complement the biophysical assessment with an economic perspective, the emergy-based indicators were converted into monetary units to better convey the results of the assessment into policy and socio-economic contexts.

2. Materials and methods

2.1. The study area

The MPA “Regno di Nettuno” is located in the Gulf of Naples of Campania Region, Southern Italy (Fig. 1). The MPA was established in 2007 and it includes coastal waters of the three Islands of Ischia, Procida and Vivara, west of the Gulf of Naples.

According to the Italian law on protected areas, it includes three zones named A, B, and C characterized by different levels of protection and allowed human activities and covering a total surface of about 6300 ha (Fig. 1).

In particular, the A zone, so-called “no-take/no-access zone”, covers an area of about 149 ha and entails the maximum level of protection (i. e., tourists’ access is not allowed while diving is only authorized for research purposes). The B zone, defined “general protection zone”, embraces an area of about 1893 ha where some touristic activities are allowed, while professional and recreational fishing must be authorized. The C zone, defined “partial protection zone”, covers an area of 4251 ha and allows a higher degree of human activities. In addition, an extra zone, named D, is located off the north-western coast of the Ischia Island and it is devoted to safeguard marine mammals.

A very diverse marine environment characterizes the MPA. Noteworthy is the presence of *Posidonia oceanica* seagrass beds, covering an area of about 1800 ha, together with rich sciaphilic communities and coralligenous formations.

The MPA is embedded within the Gulf of Naples that includes the port of Naples, an important commercial hub in the Mediterranean Sea. Therefore, marine ecosystems are exposed to multiple anthropogenic pressures connected to maritime traffic and tourism activities. In this context, the MPA plays a special role in preserving marine biodiversity while maintaining these important economic activities (Picone et al., 2021; Rosales, 2018; Trouillet and Jay, 2021).

2.2. Data collection

On the base of the bionomic map, all the biocenoses included in the MPA were clustered in the following main macro-habitats: 1) soft

Table 2
Biomass indicators (dry weight) of main groups identified in 9 replicates performed on the PHB macro-habitat.

PHB	Replicates (g $_{dry\ weight}$)								
Groups	1/9	2/9	3/9	4/9	5/9	6/9	7/9	8/9	9/9
Mollusca	0.3450	0.0000	2.9060	0.5526	0.5757	0.0452	2.5944	0.2261	0.3588
Bryozoa	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Anellida	0.0734	0.0012	0.0054	0.0389	0.0243	0.0315	0.0328	0.0070	0.0289
Crustacea	1.6091	0.0210	0.3744	0.0519	0.0366	0.0867	0.0261	0.0194	0.0473
Sipuncula	0.0619	0.0841	0.0374	0.0357	0.0792	0.0515	0.0959	0.0671	0.0604
Echinodermata	0.0146	0.0000	0.0000	0.0051	0.0753	0.0131	0.0314	0.1345	3.1241
Ascidiacea	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Porifera	0.0000	0.0000	0.0000	29.2201	0.0000	0.0000	0.7349	13.8648	0.0000
Algae	13.4478	8.7884	3.3612	13.2460	21.6947	7.3053	8.2741	10.3170	26.6471

Table 3
Biomass indicators (dry weight) of main groups identified in 9 replicates performed on the SB macro-habitat.

SB	Replicates (g $_{dry\ weight}$)								
Groups	1/9	2/9	3/9	4/9	5/9	6/9	7/9	8/9	9/9
Mollusca	0.3457	0.0634	0.4345	0.0299	0.2222	0.0767	0.3876	0.1422	0.4976
Bryozoa	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Anellida	0.0214	0.0025	0.0126	0.0461	0.0162	0.0026	0.0301	0.0046	0.0023
Crustacea	0.0014	0.0123	0.0018	0.0033	0.0048	0.0160	0.0044	0.0024	0.0009
Sipuncula	0.0000	0.0000	0.0000	0.0000	0.0000	0.0015	0.0000	0.0000	0.0000
Echinodermata	0.0000	0.0055	0.0000	0.0000	0.0000	0.2817	0.0039	0.0000	1.0475
Ascidiacea	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Porifera	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Algae	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0181	0.0000	0.0315

Table 4
Biomass indicators (dry weight) of main groups identified in 9 replicates performed on the PBS macro-habitat.

PSB	Replicates (g $_{dry\ weight}$)								
Groups	1/9	2/9	3/9	4/9	5/9	6/9	7/9	8/9	9/9
Mollusca	0.0464	9.2653	5.8956	28.5566	2.4997	7.4023	0.3998	0.5405	0.0953
Bryozoa	0.0000	0.0000	0.0000	0.0000	0.1809	0.0000	0.0000	0.0000	0.0000
Anellida	0.0020	0.0418	0.0006	0.0459	0.0000	0.0023	0.0000	0.0013	0.0000
Crustacea	0.0742	0.4046	0.1806	0.4279	0.1201	0.0684	0.0101	0.0419	0.0316
Sipuncula	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Echinodermata	0.3192	0.0000	0.0000	1.2135	0.0124	1.2998	0.0000	0.0830	0.0035
Ascidiacea	0.0000	0.0000	0.0000	0.0000	0.5470	0.9146	0.0000	0.0000	0.0000
Porifera	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Algae	0.5370	0.5234	0.3272	15.8175	4.1050	3.7999	1.8586	10.2310	6.5199

bottom (SB), 2) *Posidonia oceanica* seagrass beds (PSB), 3) sciaphilic hard bottom (SHB) (coralligenous bioconstruction), and 4) photophilic hard bottom (PHB) (covered by algal turf).

The SB macro-habitat includes biocenoses of sandy and muddy seabed, among which detritic bottoms and coastal terrigenous muds, fine and coarse sands, and mud sands. The PSB macro-habitat includes meadows of *Posidonia oceanica*, the most important endemic seagrass species of the Mediterranean Sea. The SHB macro-habitat includes rocky bottoms covered by sciaphilic assemblages and coralligenous bioconstructions, while the PHB macro-habitat embeds biocenoses of photophilic algae on hard substrata.

Ad hoc sampling activities were carried out to collect data on macro-benthic communities in the different macro-habitats. Samplings of macro-benthic organisms were performed through the "air-lift - scraping - air-lift" technique and randomly replicated three times in three sites for each macro-habitat (Bianchi et al., 2004; Chemello and Russo, 1997). A frame of 0.30 × 0.30 m was used for the SHB and PHB macro-habitats, while a frame of 0.5 × 0.5 m and 0.4 × 0.4 m was used for the SB and PSB macro-habitats, respectively.

After sorting, species were clustered in main taxonomic groups. The dry biomass of the macro-benthic 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). Tables 1-4 show the dry biomass value of the main taxonomic groups sampled in the four macro-habitats.

The biomass of necto-benthic fishes was calculated on the base of *visual census* transects (Harmelin-Vivien et al., 1985) randomly performed on the investigated macro-habitats. In particular, visual census strip transects of 5 × 20 m were randomly performed on the different investigated macro-habitats. Once abundance data for the different surveyed fish species were obtained, fish biomass was estimated by using the length-weight relationship of each species and the FishBase database (www.fishbase.org).

In addition, the biomass of Epiphytes, Microphytobenthos, Phytoplancton, and *Posidonia oceanica* was estimated from literature (Boudouresque et al., 2006; Charpy-Roubaud and Sournia, 1990).

The biomass data collected through the multiple replicates performed on the four macro-habitats were averaged and referred to unit area generating a matrix of average biomass density values (gC m^{-2}) that was the basis for the implementation of the trophodynamic environmental accounting model used to value natural capital stocks.

2.3. *The environmental accounting model*

Emergy Accounting (Odum, 1988, 1996) is an environmental accounting method aimed at assessing the environmental support to a system on the global scale of the biosphere, evaluating 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). Emergy represents a measure of the past and present environmental support to a system and allows to explore the complex relationships between natural ecosystem and human activities.

In particular, solar emergy is defined as the total amount of solar available energy (exergy) directly or indirectly used to generate a certain product or flow and it is measured in sej (solar emergy joules). The solar emergy used up to generate one unit of product or service is referred to as Unit Emergy Value (UEV, sej J^{-1}, sej g^{-1}). According to the emergy accounting rules, all the inputs supporting an investigated system are accounted for in their units of measure. Then, all these inputs are multiplied by suitable UEVs to be converted into emergy units and then totaled to compute the total emergy supporting the system.

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). The environmental accounting model was implemented in different steps. Firstly, the spatial and temporal boundaries of the MPA and its main macro-habitats were defined. Then, the biomass of the main taxonomic groups identified in the macro-habitats of the MPA was assessed and the primary productivity supporting the generation of the biomass stocks within the study area was estimated through a trophodynamic analysis. Therefore, the nutrient and natural flows that supported the generation of biomass stocks in the different macro-habitats

Table 5
UEVs used in this study, updated to the $1.20 \cdot 10^{25}$ sej yr^{-1} biosphere emergy baseline (Brown et al., 2016b).

INPUT	UEV (sej unit^{-1})	References
Solar radiation (J)	1.00	By definition
Rain (J)	2.31E+04	Odum, 1996
Wind (J)	1.90E+03	Odum, 1996
Geothermal flow (J)	1.58E+04	Brown and Ulgiati, 2010
Tides (J)	5.68E+04	Brown and Ulgiati, 2010
Currents (J)	3.00E+04	Odum, 1996
Runoff (J)	5.22E+04	Odum, 1996
C (g)	8.07E+07	Campbell et al., 2014
N (g)	5.84E+09	Odum, 1996
P (g)	8.07E+07	Odum, 1996

Table 6
Biomass density of autotrophic and heterotrophic groups in the macro-habitats of "Regno di Nettuno" MPA.

	Biomass (gC m^{-2})			
Groups	SHB	PHB	SB	PSB
Algae	29.93	40.22	0.03	8.75
Epiphytes	0.00	7.73	0.00	1.25
Microphytobenthos	23.81	23.81	23.81	23.81
Phytoplancton	0.65	0.65	0.65	0.65
Posidonia oceanica	0.00	0.00	0.00	209.05
Annelida	0.39	0.10	0.02	0.02
Ascidiacea	0.27	0.00	0.00	0.24
Bryozoa	1.15	0.00	0.00	0.02
Crustacea	0.12	1.03	0.01	0.35
Echinodermata	0.19	1.00	0.14	0.49
Fishes	9.72	8.74	0.41	1.84
Mollusca	0.56	0.86	0.09	3.49
Porifera	8.44	0.64	0.00	0.00
Sipuncula	0.04	0.25	0.00	0.00

Table 7
Emergy-based indicators of autotrophic natural capital value in the macro-habitats of the MPA.

INPUT	Emergy (sej)			
	SHB	PHB	SB	PSB
Solar radiation	2.47E+16	2.48E+16	5.44E+17	6.84E+17
Rain	4.94E+16	4.97E+16	1.09E+18	1.37E+18
Wind	9.60E+15	9.65E+15	2.12E+17	2.66E+17
Geothermal flow	2.00E+16	2.01E+16	4.41E+17	5.54E+17
Tides	1.07E+16	1.07E+16	2.35E+17	2.95E+17
Currents	8.09E+13	8.13E+13	1.78E+15	2.24E+15
Runoff	1.91E+17	1.92E+17	4.21E+18	5.29E+18
C	1.01E+16	1.31E+16	1.02E+17	4.58E+17
N	1.24E+17	1.62E+17	1.26E+18	5.66E+18
P	6.86E+16	8.96E+16	6.98E+17	3.12E+18
Total emergy (sej)	3.95E+17	4.35E+17	7.24E+18	1.32E+19
Emergy density (sej m^{-2})	2.19E+11	2.45E+11	1.77E+11	7.16E+11

of the MPA were calculated and converted into solar emergy units through appropriate UEVs (Table 5). Finally, the emergy flows were summed to calculate the total emergy value of natural capital stocks in the AMP.

Furthermore, the emergy values of natural capital were converted into non-market monetary units by using the Emergy to Money Ratio (EMR) indicator (Lou and Ulgiati, 2013) calculated for Italy ($9.60 \cdot 10^{11}$ sej €$^{-1}$) by Pereira et al. (2013). The monetary value of natural capital for each macro-habitat was calculated dividing the relative emergy value by the EMR.

3. Results

The average biomass density values of the main autotrophic and heterotrophic groups identified in the four macro-habitats of the MPA are summarized in Table 6. This matrix represents the basic dataset for the trophodynamic analysis and the calculation of the mass and energy flows needed to generate natural capital stocks.

Table 8
Emergy-based indicators of heterotrophic natural capital value in the macro-habitats of the MPA.

INPUT	Emergy (sej)			
	SHB	PHB	SB	PSB
Solar radiation	1.74E+17	1.50E+17	1.59E+17	3.87E+17
Rain	3.48E+17	3.00E+17	3.18E+17	7.74E+17
Wind	6.76E+16	5.84E+16	6.19E+16	1.50E+17
Geothermal flow	1.41E+17	1.22E+17	1.29E+17	3.13E+17
Tides	7.51E+16	6.48E+16	6.87E+16	1.67E+17
Currents	5.70E+14	4.92E+14	5.22E+14	1.27E+15
Runoff	1.34E+18	1.16E+18	1.23E+18	2.99E+18
C	2.12E+17	1.83E+17	1.94E+17	4.72E+17
N	2.62E+18	2.26E+18	2.40E+18	5.83E+18
P	1.45E+18	1.25E+18	1.32E+18	3.22E+18
Total emergy (sej)	4.53E+18	3.91E+18	4.14E+18	1.01E+19
Emergy density (sej m^{-2})	2.51E+12	2.20E+12	1.01E+11	5.48E+11

Table 9
Biophysical and economic indicators of natural capital value in the macro-habitats of the MPA.

Natural capital value	SHB	PHB	SB	PSB
Total biophysical value (sej)	4.92E+18	4.34E+18	1.14E+19	2.32E+19
Biophysical value per unit area (sej m^{-2})	2.72E+12	2.45E+12	2.79E+11	1.26E+12
Total economic value (M€)	5.13	4.52	11.85	24.21
Economic value per unit area (€ m^{-2})	2.84	2.55	0.29	1.32

The emergy value of the main inputs (natural and nutrient flows) that supported the generation of autotrophic natural capital stocks in the four macro-habitats of the MPA are presented in Table 7. The total values of natural capital stocks, with reference to the whole area covered by the macro-habitats, range from $3.95 \cdot 10^{17}$ sej (for the SHB habitat) to $1.32 \cdot 10^{19}$ sej (for the PSB habitat). The emergy density values (calculated per unit area) range from $1.77 \cdot 10^{11}$ sej m^{-2} (for the SB habitat) to $7.16 \cdot 10^{11}$ sej m^{-2} (for the PSB habitat).

The emergy value of the main inputs flows that supported the generation of heterotrophic natural capital stocks in the four macro-habitats of the MPA are shown in Table 8. The total value of heterotrophic natural capital stocks ranges from $3.91 \cdot 10^{18}$ sej (for the PHB habitat) to $1.01 \cdot 10^{19}$ sej (for the PSB habitat), while the emergy density values range from $1.01 \cdot 10^{11}$ sej m^{-2} (for the SB habitat) to $2.51 \cdot 10^{12}$ sej m^{-2} (for the SHB habitat).

The total values of natural capital, calculated by summing the autotrophic and heterotrophic components and referred to both unit area and the total area of the four macro-habitats, are summarized in Table 9. The PSB habitat showed the highest total biophysical value ($2.32 \cdot 10^{19}$ sej), while the SHB resulted the habitat with the highest biophysical value per unit area ($2.72 \cdot 10^{12}$ sej m^{-2}). Table 9 also displays the (non-market) monetary equivalents of the emergy values of natural capital stocks. The monetary values per unit area range from 0.29 € m^{-2} (for the SB habitat) to 2.84 € m^{-2} (for the SHB habitat). The total value of natural capital of the whole MPA, calculated as the sum of the value of all macro-habitats, resulted in about 46 M€.

4. Discussion

In this study, the biophysical value of natural capital in marine ecosystems was assessed in terms of work performed by nature for generating and concentrating autotrophic and heterotrophic biomass stocks. The assessment focused on benthic communities that, being more

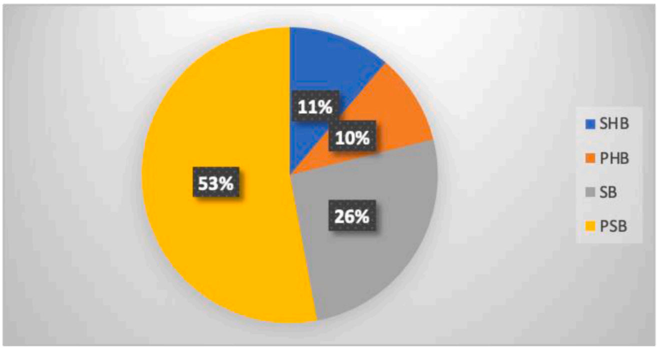

Fig. 2. Contribution of the four macro-habitats to the total value of natural capital.

persistent over time than the pelagic ones, are effective indicators of long-term changes of both natural and anthropogenic origins (Ehrnsten et al., 2019).

The value of autotrophic natural capital of the PSB macro-habitat was higher than all other macro-habitats, both for the value per unit area and total value (Table 7). These high values reflect the importance of producing and stocking primary biomass on which marine food webs are based and corroborate the important role that *Posidonia oceanica* plays in marine ecosystems (Campagne et al., 2015). In the case of heterotrophic natural capital stocks, the highest value per unit area was found for the SHB macro-habitat (Table 8). This high emergy value confirms the importance of coralligenous bioconstructions acknowledged as one of the most important hotspots of biodiversity in the Mediterranean Sea requiring special attention in the implementation of conservation strategies (Ballesteros, 2006; Ferrigno et al., 2017).

Fig. 2 shows the contribution of the four macro-habitats to the total value of natural capital calculated at the MPA scale. The PSB shows the highest contribution to the total value of natural capital, suggesting the importance of its protection in the management strategies of the MPA. Moreover, it is noteworthy that while the contribution of the SHB at the MPA scale is lower than other macro-habitats, it only covers about 3% of the total MPA area. This means high concentration of natural capital stocks in a small area whose depreciation would imply high loss of biodiversity and value for both ecosystems and human well-being (Zunino et al., 2020).

In addition, the biophysical perspective to the assessment of natural capital in the MPA was complemented with an economic perspective by expressing the emergy values into non-market monetary units. However, it is important to note that this further step does not change the biophysical feature of the applied environmental accounting model but, instead, it is meant to allow for an easier understanding of the value of marine resources in socio-economic and policy contexts.

This study completes the assessment of natural capital value of the MPAs network of Campania Region including four MPAs. In fact, the same standardized accounting protocol adopted in this study was also used to assess the value of natural capital stocks for the MPAs of "Santa Maria di Castellabate" and "Costa degli Infreschi e della Masseta" (Buonocore et al., 2019) and for the MPA of "Punta Campanella" (Buonocore et al., 2020). The values of natural capital stocks calculated for the four macro-habitats in this study were comparable with the values calculated in the abovementioned studies performed at regional scale and also with the values calculated for other Mediterranean MPAs (Franzese et al., 2017; Paoli et al., 2018). In particular, the natural capital value of the SHB ($2.72 \cdot 10^{12}$ sej m^{-2}, Table 9) resulted comparable to the average value of $2.57 \cdot 10^{12}$ sej m^{-2} calculated for the other MPAs located in Campania Region (Buonocore et al., 2020b). The values for the PHB and SB also resulted very similar to the average values assessed at regional scale (Buonocore et al., 2020b). Instead, the natural capital value of the PSB calculated in this study ($1.26 \cdot 10^{12}$ sej m^{-2}, Table 9) was higher (about 30%) than the average value calculated at regional scale. This outcome highlights the high biomass stock and health status of *Posidonia oceanica* meadows in the MPA "Regno di Nettuno" and the need of preserving their natural capital stocks in the highly anthropized context of the Gulf of Naples.

Therefore, the standardized sampling protocol and accounting model for natural capital assessment implemented in this study and for other MPAs at both regional and national scale allow for the comparison among macro-habitats inter- and intra-MPAs. In addition, the outcomes of the environmental accounting model can be used as a benchmark for the assessment of natural capital value at larger scales (i.e., regional, national) in support of a proper consideration and inclusion of nature

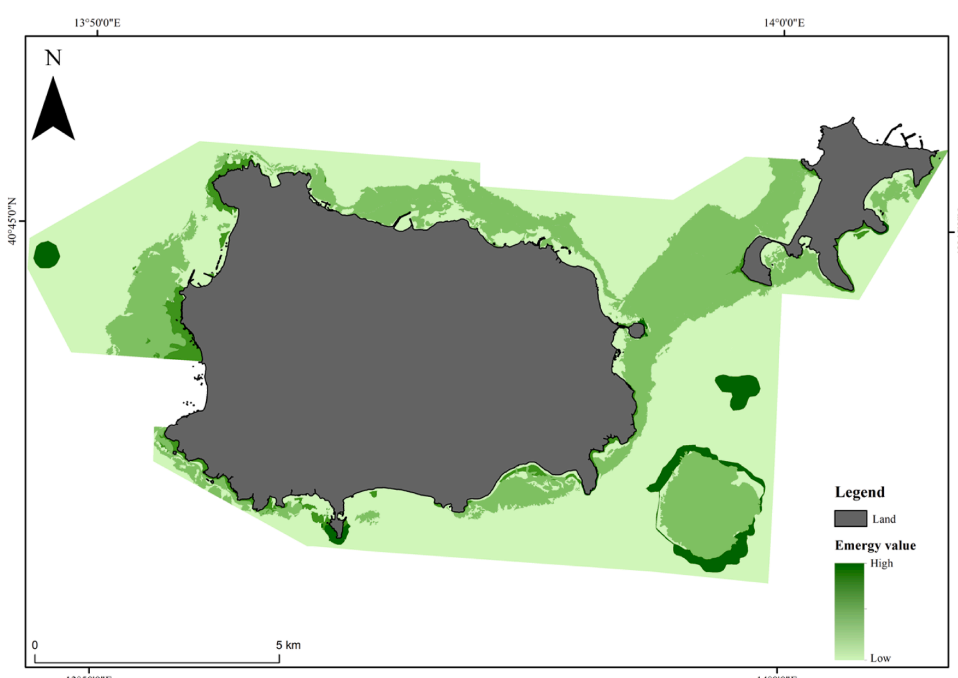

Fig. 3. Spatial distribution of natural capital value in the MPA (Darker green areas represent higher concentration of natural capital stocks).

value into processes of policy making.

Finally, with the goal of making the results of this study useful for the management of the MPA, the values of natural capital per unit area were integrated with the bionomic map of the MPA to show the spatial distribution of natural capital value in relation to the presence of the different macro-habitats (Fig. 3). The generated map shows that the current zonation of the MPA allows a good level of protection of marine habitats. In fact, although some areas with high density of biophysical and monetary value of natural capital are included in the B zone, the A zone, established to safeguard marine ecosystems and their biodiversity, mainly contains areas with high natural capital value. Such outcome strengthens the usefulness of the biophysical and trophodynamic environmental accounting model for the improvement of management schemes oriented to nature conservation and sustainable development.

4. Concluding remarks

This study provided an ecological assessment of natural capital value in a Mediterranean MPA. The assessment was performed through an environmental accounting model fed with field data collected through *ad hoc* sampling campaigns in the investigated MPA.

The value of natural capital stocks was calculated in both biophysical and economic terms. The biophysical values are based on a deeper understanding of the complex ecological dynamics in marine ecosystems while the economic values, still based on a solid biophysical accounting, are useful to convey the importance of nature value in policy contexts.

In addition, the integration of natural capital values with the bionomic map of the MPA through a GIS tool allowed the spatial identification of areas where natural capital stocks are more concentrated. Such integration can support local managers in the development of zonation schemes and management strategies to ensure nature conservation and sustainable human activities.

Future studies will be devoted to the integration of the assessment of natural capital stocks with the assessment of ecosystem services flows generated by marine protected areas to further shed light on the important role that marine ecosystems play in support of human economy.

CRediT authorship contribution statement

Elvira Buonocore: Conceptualization, Methodology, Software, Writing – review & editing. **Maria Cristina Buia:** Investigation, Data curation. **Giovanni F. Russo:** Conceptualization, Methodology, Supervision. **Pier Paolo Franzese:** Conceptualization, Methodology, 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.

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