Assessing the value of natural capital in marine protected areas: A biophysical and trophodynamic environmental accounting model

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A B S T R A C T

Changes imposed to nature by human activities and related impacts on all environmental matrices have become a critical issue. Gradually, humans began to perceive and face the magnitude of the impact of human economy on natural ecosystems and the implications for human well-being. From this perception, the concepts of natural capital and ecosystem services arose, highlighting the relationships between natural and human economy while boosting environmental conservation and management. In this framework, the definition and application of metrics and models capable of accounting for natural capital value are much needed. This is even more important when a protection regime is established (such as in the case of marine protected areas) to evaluate the efficacy of undertaken conservation measures. In this study, a biophysical and trophodynamic environmental accounting model was developed to assess the value of natural capital in marine protected areas. The model of natural capital assessment is articulated in three main steps: 1) trophodynamic analysis, providing an estimate of the primary productivity used to support the benthic trophic web within the study area, 2) biophysical accounting, providing an estimate of the biophysical value of natural capital by means of emergy accounting, and 3) monetary conversion, expressing the biophysical value of natural capital into monetary units. This conversion does not change the biophysical feature of the assessment, but instead it has the merit of allowing an easier understanding and effective communication of the ecological value of natural capital in socio-economic contexts.

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1. Introduction

Over the past few decades, efforts were done to address the topic of the link between healthy natural ecosystems and human well-being. The lack of understanding about the societal dependence upon natural ecosystems generated several environmental issues, among which chemical pollution, eutrophication, biodiversity loss, water crisis, and climate change (Folke et al., 2010; Rockström et al., 2009a,b; MEA, 2005).

Gradually, humans began to perceive (and face) the magnitude of the impact of human economy on natural ecosystems and the implications for human well-being. From this perception, the concept of Ecosystem Services (ES) arose, highlighting the relationships between natural and human economy. Although the ES

approach was initially focusing on an economic perspective regarding ecosystems in terms of stock-flows supplying human economy, the increased awareness on the importance of ecosystem goods and services led to the development of environmental conservation and management schemes based on the principle of sustainable development (de Groot et al., 2010; Folke et al., 2011; Hein, 2011; Hein et al., 2015).

There are several possible definitions used to describe the concept of ES (MEA, 2005; Häyhä and Franzese, 2014; Paoli et al., 2016). Most commonly, ES are defined as the benefits people obtain from ecosystems (Diaz et al., 2015). In this context, Costanza and Daly (1992) elaborated the concepts of natural capital in relation to human and manufactured capital. Natural capital can be defined as the stock of natural resources generating valuable flows of different types of ecosystem goods and services. Human capital comprises individuals' capacities for work while manufactured capital encompasses material goods generated through economic activity and technological change (UNU-IHDP and UNEP, 2012). Under the perspective of "strong sustainability", natural capital is irreplaceable

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with manufactured capital and a balanced interaction between these types of capital generates the basis for human well-being. The sustainable exploitation of natural capital stocks is vital as it ensures a continuous provision of ES over time (de Groot et al., 2002, 2012).

The European Union, with a dedicated action under the EU Biodiversity Strategy to 2020 (COM/2011/0244), calls Member States to map and assess the state of ecosystems and their services to estimate their economic value while promoting the integration of such values into national accounting systems by 2020. It is therefore urgent to define and apply metrics and assessment frameworks capable of assessing and valuing natural capital stocks and ES flows (UN et al., 2014).

The biophysical and economic assessment of natural capital is particularly useful in those areas where a protection regime is established (such as in the case of marine protected areas) to assess the efficacy of undertaken conservation strategies.

The assessment of natural capital in ecological and monetary terms requires scientifically sound environmental accounting methods providing results easily interpretable by policy makers and other stakeholders. The neoclassical economic approach to natural capital assessment is based on an instrumental and anthropocentric perspective and typically values ecosystems, their functions and services generating benefits to humans. Indeed, conventional economic approaches are based on users' preferences and on a utilitarian perspective according to which an entity has economic value if people consider it desirable and are willing to pay for it. Under this view, natural resources are regarded as instruments devoted to human satisfaction.

The perspective of neoclassical economics is then based on an instrumental value arising from the subjective preferences of individuals, and often caused the undervaluation and unsustainable use of many ecosystem goods and services due to their lack of a market price.

A number of authors estimated the value of natural capital and ES using economic valuation methods (e.g, Costanza et al., 1997, 2014; Dasgupta, 2008; Farber et al., 2002; Farley and Costanza, 2010; Hein et al., 2016; Nikodinoska et al., 2015; Pearce, 1993; Patterson, 2002). These studies highlighted the importance of natural resources in support of human economy. Yet, economic valuation techniques are affected by limitations, among which the fact that money-based valuations only reflect values to the present human society, disregarding other species and future generations (Mellino et al., 2015).

Other authors recognized the existence of non-anthropocentric measures of value and developed biophysical evaluation methods providing a complementary approach to the economic assessment of natural resources (Jørgensen, 2010; Müller, 2005; Müller and Burkhard, 2012; Odum, 1988, 1996; Wackernagel et al., 1999). In particular, Odum (1996) introduced a measure of natural value named "emergy" that has been widely used to evaluate goods and services sustaining the biosphere including the economy of humans (Brown et al., 2016; Brown and Ulgiati, 1999; Franzese et al., 2014; Geng et al., 2013).

The emergy method is a "donor-side" approach that can provide a biophysical measure of value of natural capital and ES by assessing their cost of production in terms of biophysical flows used to support their generation (Ulgiati et al., 2011). According to the emergy accounting method, the more work of biosphere is embodied in generating natural resources and ES, the greater is their value (Odum, 1988, 1996).

The outcomes of an emergy assessment can be converted into currency equivalents using an emergy-to-money ratio to better convey the importance of natural capital and ES to policy makers and other stakeholders. This conversion does not change the "donor-side" feature of emergy accounting, but provides results in monetary equivalent values still representing the biosphere's investment, thus helping to bridge the gap between biophysical and economic assessments.

In this study, a biophysical and trophodynamic environmental accounting model was developed to assess the value of natural capital in Marine Protected Areas (MPA hereinafter).

2. The emergy accounting method

Emergy Accounting (Odum 1988, 1996) is an environmental accounting method aimed at assessing the environmental performance and sustainability of processes and systems on the global scale of biosphere, taking into account free environmental inputs (e.g., solar radiation, wind, rain, and geothermal flows), human-driven flows as well as the indirect environmental support embodied in human labor and services (Brown and Ulgiati, 2004a).

In this method, all inputs supporting a system are accounted for in terms of their solar emergy, defined as the total amount of solar available energy (exergy) directly or indirectly required to make a given product or support a given flow, and measured as solar equivalent Joules (sej) (Odum, 1996). The amount of emergy required to generate one unit of each input is referred to as Unit Emergy Value (UEV) or emergy intensity (sej J^{-1}, sej g^{-1}, sej €$^{-1}$). UEVs represent a measure of the environmental support provided to a system: the higher the UEV of a product the greater the environmental cost to produce it (Brown and Ulgiati, 1997; Franzese et al., 2009). Raw data on mass, energy, labour, and money input flows are converted into emergy units, and then summed into a total amount of emergy used by the investigated system. When the system under investigation generates more than one output flow the following rules of the emergy algebra apply:

1. If the system generates only one output, all independent emergy input flows are assigned to the system's output.
2. When a flow splits (originating flows sharing the same physical-chemical characteristics), the total emergy splits accordingly, based on the available energy flowing through each pathway. In this case, the two splits have the same UEV.
3. When two or more co-products (i.e. product items showing different physical-chemical characteristics, but which can only be produced jointly) are generated in a process, the total source-emergy is assigned to each of them. This is because each of them cannot be produced without investing the whole emergy amount. In this case, the two co-products have the same emergy value but different UEV.
4. Since emergy cannot be counted twice within a system, emergy in feedbacks should not be double counted, and co-products, when reunited, cannot be summed but only the emergy of the largest co-product flow is accounted for.

The Emergy to Money Ratio (EMR) is used to convert the biophysical flows into emergy-based "currency equivalents" (Lou and Ulgiati, 2013). This indicator is calculated as the ratio between the total emergy supporting a nation and its gross domestic product in the same year (Brown and Ulgiati, 2004b). This indicator represents the average amount of emergy needed to generate one unit of money in the national economy (Odum, 1996). Emergy accounting has been widely applied to explore the interplay of natural ecosystem and human activities (Brown and Ulgiati, 2011; Buonocore et al., 2014; Franzese et al., 2013, 2014; Nikodinoska et al., 2017; Turcato et al., 2015; Vassallo et al., 2009). A fuller explanation of the concepts, principles and applications regarding the emergy accounting method can be found in Odum (1988, 1996), Brown and Ulgiati (2004a,b).

2.1. Emergy accounting of natural systems in marine protected areas

The literature on emergy studies of marine ecosystems is rather limited (Franzese et al., 2008, 2015; Paoli et al., 2008, 2013; Vassallo et al., 2013). One reason is that marine ecosystem is characterized by continuous movement and exchange of water and biomass. This high degree of openness and complexity of marine ecosystems makes them more difficult to be modeled compared to terrestrial ecosystems (Carr et al., 2003).

The emergy study of marine ecosystems requires the accurate accounting of input resources. In the marine domain, the identification of resources consumed by ecosystems and of the productive area where those resources are generated is often difficult and uncertain. A marine system may self-sustain through its productivity or take advantage of the productivity conveyed from surrounding systems by currents, and eventually caught by consumers or biological cycling mechanisms such as pelagic-benthic coupling (Mussap and Zavatarelli, 2017).

Therefore, the assessment of primary production maintaining marine systems represents an important step of the proposed environmental accounting model based on the donor-side perspective of the emergy method (i.e., assessment of the environmental costs sustained for the generation of natural capital). In particular, a trophodynamic analysis is needed to assess the primary productivity used to build up and maintain natural capital stocks. Furthermore, it is necessary to assess the areas needed to yield the primary productivity supporting the system ("supporting area" hereinafter) and related input flows (i.e., nutrients and environmental flows) generating and maintaining natural capital stocks. The procedures to apply this biophysical accounting model to the benthic system of MPAs are described in Sections 2.2–2.4.

2.2. A biophysical environmental accounting model based on trophodynamic

The environmental accounting model presented in this study aims at assessing the biophysical value of natural capital in MPAs. The model of natural capital assessment – and related environmental flows supporting its maintenance – is articulated in three main steps:

1. Trophodynamic analysis, providing an estimate of the primary productivity used to support the benthic trophic web within the study area;
2. Biophysical accounting, providing an estimate of the biophysical value of natural capital and environmental flows by means of emergy accounting;
3. Monetary conversion, expressing the biophysical value of natural capital and environmental flows into monetary units.

The next paragraphs provide a detailed overview of the main calculation procedures (summarized in Fig. 1) followed to assess the value of natural capital and environmental flows in MPAs.

2.3. Natural capital assessment of benthic marine ecosystems

The assessment of natural capital is based on the identification of the main benthic habitats included within the boundaries of the MPA. Their surface is assessed through the analysis of the bionomic maps of MPA. Afterwards, the main taxonomic groups (e.g., fish, molluscs, algae, microphytobenthos, among others) included in each habitat are identified and a database of biomass per unit area for each group is created.

The biomass of the taxonomic groups can be calculated by analyzing field samplings or estimated from literature. Data on fish abundance collected through the *visual census* technique (or by means of previous samplings) are converted into fish biomass by using FishBase (www.fishbase.org).

The biomass assessment of the main taxonomic groups included in each habitat is the basic information needed for the calculation of the primary productivity required to build up natural capital stocks.

The assessment of natural capital includes the evaluation of the autotrophic and heterotrophic stocks in the main habitats of the investigated MPA. The total autotrophic biomass density (Ba, $gC\,m^{-2}$) of each habitat is calculated as the sum of the biomass of all the primary producers.

The biomass of heterotrophic groups (B, $gC\,m^{-2}$) included in each habitat is converted into the primary biomass required for its formation according to the following equation derived from Pauly e Christensen (1995):

$$Be_i = B_i \cdot 7^{(TL_i-1)} \qquad i = 1, 2, 3, \ldots n \tag{1}$$

where, Be_i is the autotrophic biomass supporting the i-th heterotrophic group, B_i is the biomass and TL_i is the trophic level of the i-th group.

According to Christensen and Pauly (1993), the transfer efficiency between trophic levels is assumed equal to 15%, being MPAs coastal systems. The total primary biomass required to support the formation of all the heterotrophic groups in each habitat (Be) is calculated according to Eq. (2):

$$Be = \sum_i Be_i \qquad i = 1, 2, 3, \ldots n \tag{2}$$

The total primary biomass Btot (expressed as $gC\,m^{-2}$) supporting stocks formation in each habitat is then calculated as following:

$$Btot = Ba + Be \tag{3}$$

The amounts of N and P assimilated in organic matter are calculated according to the ratio C:N:P of 41:7:1 (Redfield et al., 1963). Furthermore, natural flows (solar radiation, wind, rain, geothermal flow, currents, tides, and runoff) supporting biomass production in the MPA are calculated according to Odum (1996) and accounted for the time of stocks formation (Table 1). Time of stocks formation is calculated as primary biomass (Be) divided by average productivity of the surrounding benthic systems.

All the inputs (i.e., nutrients and natural flows) are then converted into emergy units by using specific UEVs (Odum, 1996). Then, according to emergy algebra, emergy flows are summed to assess the emergy density value of natural capital for different habitats ($sej\,m^{-2}$). These values are multiplied by the areas of the habitats to estimate the total value of natural capital stock for each habitat (sej). Finally, the total emergy value of natural capital is calculated as the sum of natural capital values of all habitats included in the MPA.

2.4. Environmental flows assessment of benthic marine ecosystems

The environmental flows assessment, aimed at estimating the environmental flows that annually support natural capital maintenance, is also based on the biomass matrix of considered taxonomic groups previously used for natural capital assessment.

Data on primary biomass density for each autotrophic group are converted to annual primary production (Pa) density by using appropriate P/B ratios (Corrales et al., 2015). The total primary production of each habitat is calculated according to the following:

$$Pa = \sum_i Pa_i \qquad i = 1, 2, 3, \ldots n \tag{4}$$

where Pa is the total primary production per unit of area ($gC\,m^{-2}\,yr^{-1}$) and Pa_i is the primary production of the i-th
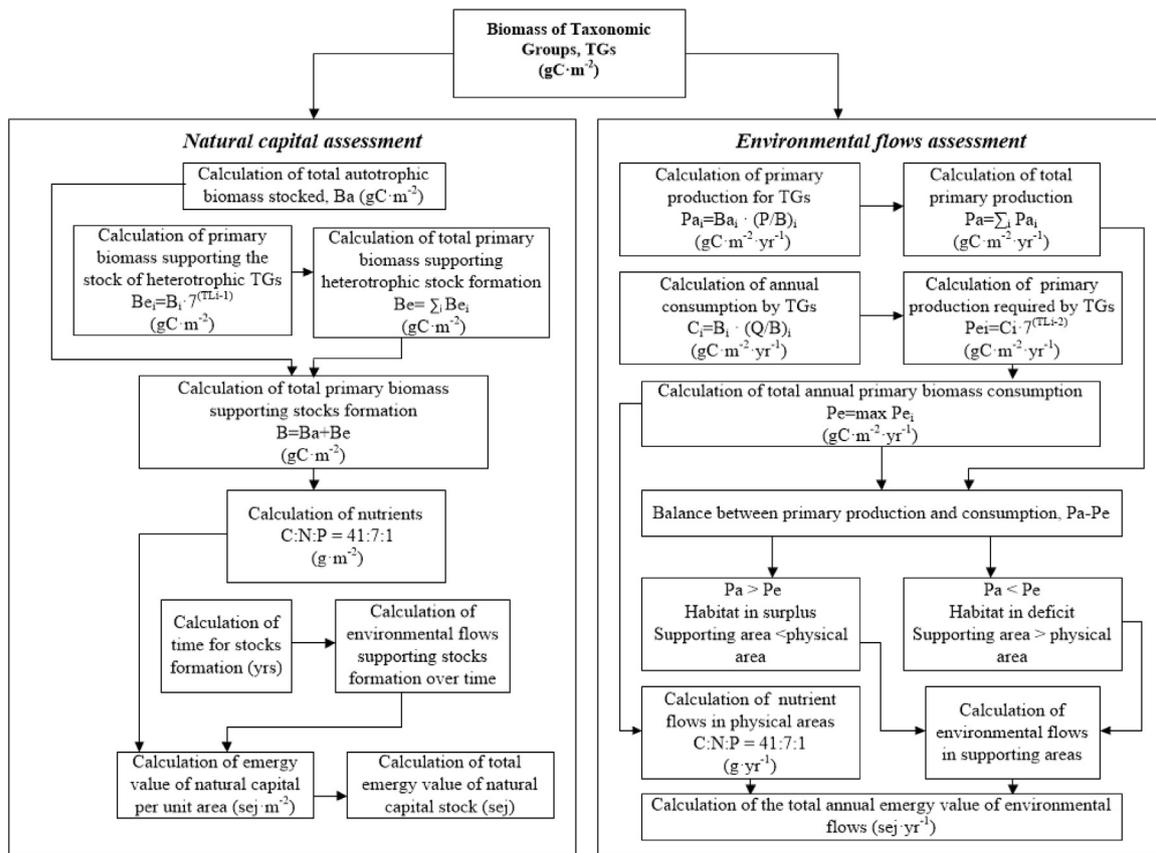
Fig. 1. Biophysical and trophodynamic environmental accounting model: flow diagram.   Note: calculation formulas are explained in paragraphs 2.3 and 2.4.

Table 1
Main formulas for the calculation of nutrients and natural flows supporting natural capital generation.

Items	Formula	Unit
Carbon	Btot (see Eq. (3))	g
Nitrogen	Btot·7/41	g
Phosphorus	Btot/41	g
Solar radiation	annual solar radiation per unit area area · (1-albedo) · area · time for stocks formation	J
Rain, chemical energy	annual rainfall · gibbs free energy · water density · area · time for stocks formation	J
Wind	air density · drag coeff. · (geostrophic wind velocity)³ · area · seconds per year · time for stocks formation	J
Currents	½ · water mass·velocity² · time for stocks formation	J
Geothermal heat	Area · Geothermal flux · time for stocks formation	J
Tides	½·number of tides per year · (height)² · density · gravity · area · time for stocks formation	J
Runoff	(annual rainfall – evaporation – aquifer infiltration) · water density · Gibbs free energy · catchment area	J

autotrophic group. Similarly, the annual consumption by heterotrophic group (C_i) is calculated by using appropriate (Q/B) ratios (Opitz 1996; Palomares et al., 2005; Okey et al., 2004a,b; Coll et al., 2006).

The consumption by each heterotrophic group is converted into required primary biomass according to the following equation derived from Eq. (1):

$$Pe_i = C_i \cdot 7^{(TLi-2)} \qquad i = 1,2,3, \ldots n \qquad (5)$$

where Pe_i is primary production supporting the consumption of the i-th heterotrophic taxonomic group, C_i is the consumption, and TL_i is the trophic level of the i-th heterotrophic group.

The total primary production (Pe) supporting consumption in each habitat is calculated as following:

$$Pe = \max \ (Pe_i) \qquad i = 1, 2, 3, \ldots n \qquad (6)$$

where Pe_i is the primary production supporting the annual consumption of the i-th taxonomic group.

Once the productivity needed to maintain the biomass stocks in the main habitats is assessed, the area where this productivity is generated (supporting area) is estimated. This is based on a balance between the annual primary production (Pa) and consumption (Pe) in each habitat, and for the whole MPA to recognize: a) if each habitat is capable to generate the amount of primary biomass necessary to support its internal consumption, and b) if the whole MPA is self-sufficient.

Two cases are possible. When Pa > Pe, the habitat is capable of sustaining its internal consumption and, in addition, the surplus of primary production can be exported to support other habitats (internal or external to the MPA). As a consequence, the supporting area of the habitat is considered smaller than its physical area.

When Pa < Pe, the habitat is not capable of sustaining its internal consumption and it requires additional primary production for its maintenance. Such an additional contribution can be imported from other habitats either internal or external to the boundary of the MPA. In this case, the supporting area of the habitat is considered larger than its physical area.

Furthermore, once the annual consumed carbon flow is calculated, the annual flows of nutrients (N and P) assimilated in organic matter are estimated according to the ratio C:N:P of 41:7:1 (Redfield et al., 1963).

For each habitat, natural flows (solar radiation, wind kinetic energy, rain geopotential flow, geothermal flow, currents, tides, and runoff) supporting annual biomass production are calculated according to the "supporting areas" that can be smaller or bigger of the physical areas.

As for natural capital assessment, nutrients and natural flows are converted into emergy units and summed according to emergy algebra to assess the total annual emergy flow (sej yr^{-1}) maintaining natural capital in each habitat, and in the whole MPA.

2.5. Conversion of the biophysical value of natural capital in monetary units

The emergy value of natural capital and environmental flows can be converted into a "virtual" money value or currency equivalent by using the EMR. The monetary value of natural capital for each habitat is calculated by dividing the emergy value by the EMR. The monetary value of natural capital for the whole MPA is calculated as the sum of the monetary values of all the habitats. The same procedure is used to assess the monetary value of the annual environmental flows maintaining natural capital stocks.

The money-equivalent of natural capital stocks provides an estimate of the potential contribution that natural ecosystems supply to human economy over time, and that could be loss due to over-exploitation (Lou and Ulgiati, 2013).

The proposed environmental accounting model was designed to assess natural capital value in the framework of a national project with strong policy and management implications. For this reason, although a debate on the use of the EMR is arguing the merging of biophysical and economic values, we used the conversion of emergy units into money equivalents to allow an easier understanding of the ecological value of natural capital in decision-making processes. However, this conversion does not change the biophysical feature of the proposed accounting model but, instead, it represents an additional step meant to facilitate the communication of the importance of natural capital in socio-economic and policy contexts.

3. Concluding remarks

In this paper, a biophysical and trophodynamic environmental accounting model is proposed to assess the value of natural capital in marine ecosystems, with specific reference to marine protected areas. The proposed model allows accounting for the biophysical value of natural capital based on the principle that the greater is the investment of nature in the generation of the capital the greater its value.

The trophodynamic characterization of benthic habitats and the assessment of the environmental flows supporting the generation of natural capital stocks are particularly complex due to the openness of marine ecosystems. For these reasons, the application of the proposed model requires extensive survey and sampling campaigns for data acquisition, processing and analysis.

The assessment of the biophysical and monetary value of natural capital stocks within marine protected areas is a pioneering research area requiring a system-oriented and interdisciplinary approach. Conventional economic valuations often fail when accounting for marine goods and services without a direct market value. The proposed biophysical model can ensure a solid accounting base for a monetary valuation built on ecological principles. Yet, the conversion of the biophysical value in monetary units is useful to facilitate the communication of the importance of marine goods and services to local managers and policy makers.

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