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First Evidence of Spatial Relationships between Ecosystem Functioning and Services in the marine environment

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Abstract

The complexity of the marine system and the rate of anthropogenic impacts on ecosystem functioning demand a synthetic conceptual framework to organize the scientific knowledge needed to better conserve Nature and maintain ecosystem services supply. Currently, the most used conceptual framework is the cascade model that describe a tight positive link among biodiversity, ecosystem functioning and services. The present study explores the spatial relationship between ecosystem functioning and services discussing its heterogeneity. It warns the next generation of researchers on ecosystem services to quantify even ecosystem functioning in their spatial efforts, to better set real sustainable management strategies. The unified framework of ecosystem services and ecosystem functioning assessment will further the goal for protecting nature while humans use it.

Keywords: Ecosystem functioning, Ecosystem services, marine ecosystem, Ecosystem-based Management

Abbreviations: ESs: Ecosystem Services; EF: Ecosystem Functioning; EbM: Ecosystem-based Management; ECI: Efficiency Cumulated Indicator; BRT: Biomass Residency Time; AIS: Automatic Identification System.

Introduction

Since the pioneer paper of Costanza, et al. [1] ecosystem services (ESs), defined as the benefits that ecological systems provide to humans, are a widely used metric to measure Nature and its conservation status [2-7]. Questioning the correctness of this metric as proxy of natural systems, several studies have focused on the spatial relationship between biodiversity and ESs [8-13]. Scattered and poor are the consideration about the spatial relationship between ecosystem functioning (EF) and services [14]. In ESs assessments EF measurement is often shaded using indirect metrics of it such as ecosystem structural components (i.e., habitats and their characteristics) [15,16]. Still, works that empirically demonstrated whether and how ESs spatially relates with EF indicators are lacking. Theoretically, biodiversity and EF underpins ESs supply as explained by one of the most known theoretical frameworks: the cascade model [17-19]. Notwithstanding the wealth of studies using the concept of the ES cascade and, its usefulness for making the ES concept more accessible to the non-science community [20] some authors Balvanera P, Mumby PJ, Peterson MJ, Cardinale BJ [21-24] have already pointed out the importance of explicitly presenting ESs as discreet and incomplete aspects of ecosystem functions to ensure the complementary valuation of EF indicator and biodiversity. Empirically, Naidoo, et al. [25] proved globally that regions selected to maximize biodiversity provide no more ecosystem services than regions chosen randomly. Furthermore, Costanza, et al. [26] highlighted that the conceptualization of ES through the cascade model is for some aspects an oversimplification, as it does not capture the complex and dynamic connections occurring between the ecosystem structures (i.e., biodiversity), EF, and ESs.

The main misconception of the ES cascade framework lies in the anthropocentric-defined concept of EF. In the cascade model, the functioning is described as the capacity or capability of the ecosystem to do something potentially useful to people [1,19,20,27-29]. However, as Jax [30] stated, the term 'function' can mean several other things in ecology. It can mean capability, but it is often used more generally to refer to processes that operate within an ecosystem (e.g., nutrient cycling, the flow of energy and matter through predation, top-down control), and especially exists even when a human beneficiary is absent. Accordingly, Wallace [31] and many other ecologists describe EF as functions serving Nature per se, without being necessarily useful to people. Hence, these functional aspects may even not be positively directly related to human benefits, as the ES cascade instead describes.

Overall, to understand any system, empirical knowledge is needed [32] as even the 'scientific method' simple states, in particular when the system described is complex such as the natural ecosystems. Unless we went back in time when for evaluating marine ecosystem status studying focal species or one indicator alone was acceptable, system-level phenomena should be the way forward in Ecosystem-based Management (EbM) [33-37].

The present article seeks a better understanding of the spatial relationships between marine EF and ES indicators using the Adriatic Sea as the study case. To accomplish it I have searched for an evidence-based direct and positive spatial relationship among different EF and ESs indicators as the cascade model theoretically supports. Given that both EF and ESs quantifications are highly dependent on the indicator chosen [30,38-40] to reduce this possible biased the present article considers different ES assessments and EF indicators.

Materials and Methods

The quantification of spatial overlaps or correlations between five EF indicators (i.e., bottom-up forces, top-down forces, biodiversity, and trophy-dynamics) and 11 ES indicators (i.e., supporting, provisioning, cultural, regulating) for the same area of study (i.e., the Adriatic Sea) and, where possible for the same year (2018/2019) have been gathered (Table 1). First, these indicators have been extracted on a common grid of 20km horizontal resolution (i.e., OSMOSE-MED model grid as the lowest resolution of the gathered data) to make them comparable. Second, all the indicators considered in the present analysis have been normalized through min-max normalization because of the different units of measurement. Eventually, pairwise relationships between all ES and EF indicators have been unrevealed by the average correlation between Kendal, Spearman and Pearson methods (alpha=0.05). Normality is not an assumption and transformation (square root or log) did not improve skewness values therefore untransformed data were used.

EF or ES	Indicator	Description	Unit of measurement	Source	Reference
Primary productivity	Total chlorophyll-A	Chlorophyll-A is the as proxy of primary production	Kg/m3	POLCOM-ERSEM model (~ 12Km of horizontal resolution)	[41]
Top Down Control	Biomass of 100 High Trophic Level species	Biomass of species exerting a top-down control on the community	Tons/pixel	OSMOSE-MED (~ 20Km horizontal resolution)	[42]
Trophodynamics	Efficiency Cumulated Indicator (ECI)	The process linked with the flow of matter and energy across trophic levels in an ecosystem. In particular ECI measures how efficient is the trophic transfer	Unitless	Calculated with biological variables of the species present by climate suitability in the Adriatic Sea (~ 7Km horizontal resolution)	Basconi, *under review*
Biodiversity	Species richness	Presence/Absence over the grid was calculated with climate suitability models for 579 fish species	Species richness	Modeled with Temperature and Salinity (BIOMOD2) (~ 7Km horizontal resolution)	Basconi, *under review*

Trophodynamics	Biomass Residency Time (BRT)	The process linked with the flow of matter and energy across trophic levels in an ecosystem. In particular BRT measures how efficient is the transfer of matter and energy.	Unitless	Calculated with biological variables of the species present by climate suitability in the Adriatic Sea (~ 7Km horizontal resolution)	Basconi, *under review*
Carbon sequestration capacity & flow	Carbon sequestered by the marine habitats	Important habitats for the sequestration of carbon in the Northern-Central Adriatic Sea have been mapped. The rate of sequestration per each habitat was retrieved from the literature. The habitat areas were multiplied by their carbon sequestration and estimate per each habitat have been summed together	Kg CO2/Km2/ Year	Calculated for Basconi et al., 2023	Basconi et al., 2023
Tourism capacity	Attractiveness potential	Questionnaires directed to seaside tourists have been used to give weight to different features of the coastal-marine environment included in the composite indicator of attractiveness potential	Unitless	Calculated for Basconi et al., 2023	Basconi et al., 2023
Recreational boating capacity	Attractiveness potential	Questionnaires directed to recreational boaters have been used to give weight to different features of the coastal-marine environment included in the composite indicator of attractiveness potential	Unitless	Calculated for Basconi et al., 2023	Basconi et al., 2023
Recreational boating flow	Usage of the marine space by recreational boaters	The number of leisure boats by maritime compartment was retrieved from the Coast Guard registry ('Capitaneria di Porto') and the Croatian Bureau of Statistics then divided in the marinas along both coastal sides. Questionnaires were used to set the number of both trips.	N° of boat trip/ Km2/Year	Calculated for Basconi et al., 2023	Basconi et al., 2023
Mussel aquaculture capacity	Tons of mussel producible/Km2/ Year	Assessed through the eco-physiological model (R package RAC, Baldan et al. 2018) calibrated for *Mytilus galloprovincialis*	Tons of mussel producible/Km2/ Year	Calculated for Basconi et al., 2023	Basconi et al., 2023

Industrial fishery flow	Measurement of fishing efforts	Spatial explicit fishing effort was estimated by using the Automatic Identification System (AIS)	Trawls fishing effort/km2/year	Extracted from Russo, et al. 2020	Basconi et al., 2023
Ess total capacity	The capacity of marine habitats to provide marine ecosystem services	ESs have been measured from EUNIS seabed habitats (EmodNet website)	Unitless	Modeled by a matrix approach	[16]
Supporting ESs sea bottom	Quantification of the supporting ESs at the sea bottom	ESs delivery was mapped starting from spatial explicit marine components specific to the sea bottom	Unitless	Modeled by richness and hot spot analysis	[5]
Supporting ESs water column	Quantification of the supporting ESs in the water column	ESs delivery was mapped starting from spatial explicit marine components specific in the water column	Unitless	Modeled by richness and hot spot analysis	[5]
Supporting ESs sea surface	Quantification of the supporting ESs at the surface	ESs delivery was mapped starting from spatial explicit marine components specific to the surface	Unitless	Modeled by richness and hot spot analysis	[5]
Eutrophication	TRIX	Trophic index (considering dissolved oxygen, ChlA, total Phosphorous and Nitrogen)	Unitless	TRIX modeled for the Adriatic (~ 2Km)	[43]

Table 1: Indicators of Ecosystem Functioning (EF) and Ecosystem Services (ESs) measured or modeled in the Adriatic Sea, and gathered in the spatial explicit analysis.

Ecosystem Functioning Indicators

Spatial explicit EF indicators have been gathered from different sources (Table 4). Pelagic bottom-up control has been extracted from the POLCOM-ERSEM model as the concentration of Chlorophyll-A (mg/cm3), using it as a proxy of primary productivity. Top-down control has been measured by the biomass of the 100 high trophic-level species modeled by OSMOSE-MED [42]. Transfer of energy and matter across trophic levels namely trophodynamics has been measured by Efficiency Cumulated Indicator (ECI) and, Biomass Residency Time (BRT) [44]. Biodiversity even if more measure of structure is complementary to EF; therefore, it has been included here. Biodiversity has been calculated after a climate suitability approach based on the 579 fish species endemic or if aliens established in the Mediterranean Sea, Basconi et al.

Ecosystem Services Indicators

Spatial explicit ES indicators have been extracted from three different assessments carried out in the Adriatic Sea [5,16] Basconi et al., 2023 . The whole set of assessments approached with snapshot representations of Adriatic marine ESs, using among them different approaches, data sources, and analysis (reported briefly in Table 1). Used ESs have been, three maps of supporting ESs specifically related to the marine domains (i.e., surface, water column, bottom) [5], a general ability of the Adriatic marine area to deliver ESs [16], and two provisioning services (i.e, mussel aquaculture, fishery), two cultural services (i.e., tourism and recreational boating), and one regulating services (i.e., carbon sequestration). Furthermore, the disservice of eutrophication measured by the TRIX regional index was included [43].

Results

Many are the direct or indirect theoretical connections found by the author through expert opinion (Figure 1) among EF and ESs indicators. However, they do not seem to subsist in the spatial analysis results (Figure 2). Correlation co-efficient of the pairwise comparisons for all the indicators considered can be found in Table 1, Supplementary materials.

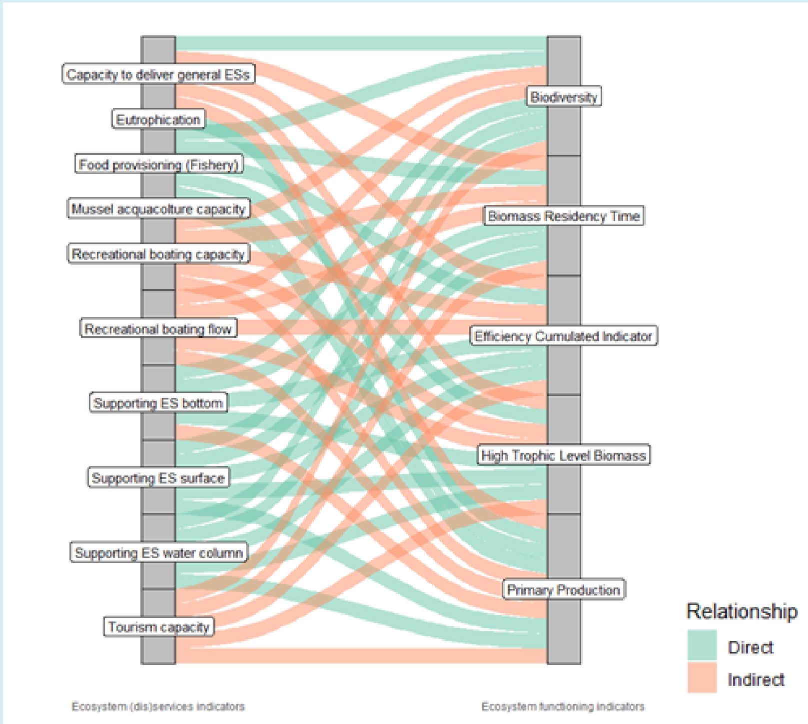

Figure 1: Theoretical links between ecosystem services and functioning indicators.

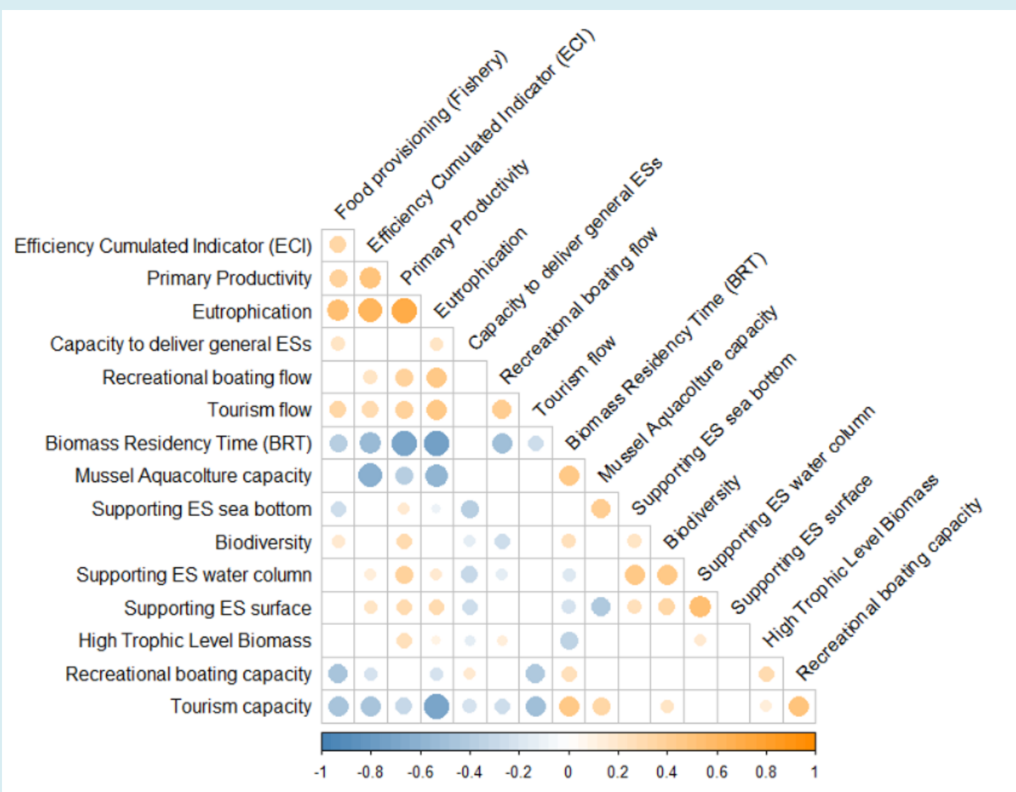

Figure 2: Spatial relationships (alpha=0.05) between eleven ecosystem services and five ecosystem functioning indicators, measured in the Adriatic Sea.

Overall, there is not a unique strictly positive or strictly negative trend describing the spatial dependency of ESs on EF indicators in the Adriatic Sea (Figure 2). To effectively find the bigger picture of the spatial relationship between ESs and EF indicators solely strong correlations (i.e., higher than 0.5 or lower than – 0.5) have been reported as results. Among them, BRT negatively links with primary productivity (corr= - 0.71) and accordingly with eutrophication (corr= - 0.74). On the contrary, ECI positively correlates with primary production (corr= 0.51) and eutrophication (corr= 0.63). ECI negatively correlates with the capacity of mussel aquaculture (corr= - 0.73). The disservice of eutrophicated water is negatively correlated with both capacities of tourism (corr= - 0.70) and mussel aquaculture (corr= - 0.57) while possibly positively correlated (corr= 0.55) with the provisioning service of the fishery. There is even a correlation among services with positive correlations between supporting ESs in the water column and supporting ESs at the surface (corr= 0.53).

Discussion

Rarely have the ecosystem processes and functions been empirically linked to human well-being and activities. According to the cascade framework [17,20] high values of ecosystem functioning correspond to high values of ecosystem services. Theoretically, without ecosystems that function well, ESs is not delivered but still, the spatial relationship can be highly non-linear or even disappear in certain contexts. Notwithstanding the static linkages made for crafting Figure 1, the correlations between ESs and EF are highly dynamic and context-dependent as the marine system is. There are examples in which these two facets of ecology could exist even in opposite trends in the same spatial unit. For instance, in the study area considered for the present work (i.e., the Adriatic Sea) together with other authors a survey was prepared for users of the Adriatic marine space. 250 questionnaires were answered by recreational boaters and around half of them were showing a low interest in the health of the marine ecosystem. In fact, to the question “How many boat trips will you do in detrimental water quality?” (Explaining what ecologically is meant for it) 50% of respondents replied with an “unchanged number of trips”.

A second instance, include the present and future condition of Ocean warming. In fact, the Mediterranean has been projected to tropicalize over time [45,46]. The opening of the Suez Canal is and will further allow species to migrate to the Mediterranean Sea. Whether the Mediterranean Sea assumes tropical abiotic conditions, tropical species will settle in the empty ecological niches (e.g., see species reported by CIESM Atlas, Moschella, et al. [47]). Besides invasive species that could disrupt native ecosystems, the species adaptable to new climate change-driven conditions are the one that functions in those peculiar environmental conditions. In other words, ecological communities always adapt to physicochemical conditions as the “red queen hypothesis” states [48]. The real caveat is how much the market will be adaptable to these new species. It has been already proven that alien or invasive species could be a problem for the Blue Economy in the Mediterranean Sea [49].

Moreover, straightforward examples deal with the ‘anthropization’ of ESs which are linked to nature (as described by ES definition itself, Costanza [1] but for which socio-economic drivers are strong enough to maintain the services even when ecosystems are detrimental conditions. Examples in the coastal and marine ecosystem are coastal erosion prevention by artificial protections as well as tourism by the creation of nature surrogates to maintain the delivery of ESs, Basconi et al., 2023 [50,51]. These are examples of ESs that might be largely independent of the level of functioning of ecosystems and therefore remain high (at least in the short term) even when EF is low. These instances are important examples of spatial detachment between ecosystem functioning and certain services (i.e., cultural service – recreational boating and tourism, provisioning service – fishery supply, regulating service – coastal erosion prevention) which should be always kept in mind by ES assessment practitioners.

Accordingly, the results of the present paper do not show any evident (i.e., correlation coefficent>0.5 or < - 0.5) spatial correlation between the used ESs and EF indicators. Whether they could maintain the relationship will be non-linear and therefore not detected by the coefficients of correlation used. The only presented evident correlation between EF and ESs indicators is the Efficiency Cumulated Indicator and the capacity of the ecosystem to produce mussels in aquaculture farming but it is negative. All the other relevant correlations are among EF indicators (e.g., between primary productivity and Efficiency Cumulated Indicator). From an ecosystem functioning point of view, Biomass Residency Time shows the opposite correlation of the Efficiency Cumulated Indicator. The former represents the inverse of trophic transfer speed and it is stated in the literature [44] that ecosystem functions well when both trophic transfer efficiency and speed are high. In other words, this is the reason behind the opposite correlations between the two in a snapshot analysis such as the one reported in the present paper.

Some correlations shown in Figure 2 serve to possibly prove that the analysis is sensitive in representing ecologically known spatial patterns in the marine realm. For instance, the positive relationship between primary productivity (extracted from a biogeochemical model) and eutrophication (coastally measured through the TRIX indicators by ARPAs and modeled at the whole basin scale). It could prove that the present analysis can show spatial relationships whether present.

The reported results challenge the assumption that a high level of biodiversity and a high rate of ecosystem functioning will always promote high ESs or that these high values will enhance ES supply in the same space. Other research carried out globally [52] and in the terrestrial realm [14] has proven EF and ESs indicators to be spatially uncorrelated. The present paper's results support the explicit use of ESs as discreet and incomplete aspects of EF enables the social and political changes required to ensure the use ESs metric in an ecologically meaningful manner [23]. A critical step in sustainable strategies is to not only agree on indicators that are compelling, intuitive, understandable, and defensible to all stakeholders but also capture the whole complexity of the system. Measuring critical states and processes that underlie the complexity of the ecosystem dynamics (i.e., Functioning-energy flows, Resilience-ability to recover from perturbation, Structure-species organization) is essential to understand the status of conservation or management. An agreement exists about the need to move towards more holistic but not simplistic indicators that recognize the full array of interactions within an ecosystem while measuring ecosystem services [53-56]. This is particularly true in a fast-changing benchmark as in the climate change era, in an already multiple stressors scenarios impacting the marine biodiversity and EF [57-60]. Whilst the spatial relationships between EF and ESs should be further confirmed with studies in other marine areas as well as in long-term studies, a precautionary approach to ecosystem conservation would seem prudent in the meanwhile including EF metrics in multiple ESs assessments.

Conclusion

Empirical knowledge demonstrating the spatial relationships among ecosystem functioning and services is rare. The current study presents for the first time in the marine realm a lack of spatial coherence between ecosystem functioning and services paving the road for a new coming branch of research seeking a better understanding between EF and ESs spatial relationships.

The present results suggest an urgent need to fuel interdisciplinary science bridging together the different metrics of (i) ecosystem structure (e.g., species richness, abundance, biomass), (ii) ecosystem functioning (e.g., primary productivity, tropho-dynamics, high trophic level top-down control and, (iii) ecosystem services (e.g., biophysical measurements, quantitative measurements, stakeholder preferences). De-structuring complex system into complicated ones, avoiding the pitfall of oversimplification, is the way forward for both natural resource management and conservation.

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