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Managing marine aquaculture by assessing its contribution to ecosystem services provision: The case of Mediterranean mussel, *Mytilus galloprovincialis*

Andrea Mattia Pacifico [a,*], Daniele Brigolin [b], Luca Mulazzani [a], Mara Semeraro [c], Giulio Malorgio [a]

[a] Department of Agricultural and Food Sciences, University of Bologna, Viale Fanin 50, 40127, Bologna, Italy
[b] Department of Architecture and Arts, Università Iuav di Venezia, Dorsoduro 2206, 30123, Venezia, Italy
[c] Mediterranean Agronomic Institute of Bari (CIHEAM), Via Ceglie 9, 70010, Valenzano, Italy

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ABSTRACT

Assessing the ecosystem services (ESs) provided by marine aquaculture is a promising approach to support policymakers in planning and management processes. Among the different types of marine aquaculture, mussel farming holds the potential to address the dual challenges of delivering food security and providing multiple ESs, emerging as a sustainable human activity and animal protein production. This paper employed a Total Economic Value (TEV) approach to quantify four ESs that were expected to be influenced by Mediterranean mussel, *Mytilus galloprovincialis*, aquaculture in the Mar Piccolo of Taranto (Ionian Sea), including (i) food provision, (ii) carbon sequestration, (iii) nutrient removal, and (iv) local identity. The findings provided valuable data regarding the multifunctionality of mussel aquaculture in providing non-commodity outputs, supporting policy recommendations. Specifically, the results revealed that mussel aquaculture enhances the flow of regulating services, thus demonstrating the overall sustainability of the practices. Local identity emerged as the greatest contributor to the TEV, due to the activity's longstanding tradition in the study area. Economic values per unit of the assessed ESs were provided for implementation in real-world scenarios at the policy level, enabling the transferability of the study's results in a broader international context. The study advocated for integrating the estimated ESs values into decision-making tools and during marine spatial planning processes to operationalize economic valuations. Overall, the findings can be framed within ongoing research efforts aimed at developing innovative methodologies to support the implementation of the Ecosystem Approach to Aquaculture (EAA) and to inform decision-making in the context of marine spatial planning.

1. Introduction

The expansion of marine aquaculture as a viable alternative to meet gaps in seafood supply has the potential to increase protein production, thus contributing to improve the health of Earth's ever-growing population (Luo et al., 2022; Golden et al., 2021; Clavelle et al., 2019). Within the EU context, aquaculture represents a prioritized maritime economic sector under the Blue Growth Strategy (European Commission, 2017), and its development is supported by the Marine Spatial Planning Directive (2014/89/EU), which provides the legal basis to implement an integrated management approach to reduce conflicts and environmental impacts (Lester et al., 2018). These impacts are induced by cumulative pressures, originated by multiple overlapping sectors currently present in coastal systems (Ahmad et al., 2022; Zhou et al., 2022; Chen et al., 2021a; Gentry et al., 2020). The Ecosystem Approach to Aquaculture (EAA) (Aguilar-Manjarrez et al., 2017) is one of the interesting examples of policies promoted to strike a balance between the sustainable development of maritime activities and ecosystem health (Galparsoro et al., 2020). The EAA supports stakeholder involvement in decision processes and promotes environmental, socio-economic, and governance goals in sustainable aquaculture planning (Brugère et al., 2019), taking into account the ecosystem services (ESs) framework for more integrated management and accountable decision-making (Basconi et al., 2023; Weitzman, 2019). Marine aquaculture requires specific environmental

* Corresponding author.
E-mail address: andreamattia.pacifico@unibo.it (A.M. Pacifico).

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and water quality conditions, including current intensity, temperature, salinity, pH, and Chlorophyll-a concentration (Petrosillo et al., 2023; Sanchez-Jerez et al., 2016). Additionally, it requires substantial space resources, which are increasingly constrained by competing coastal and marine activities (Weitzman, 2019). Therefore, considering aquaculture as an activity that provides a wide range of ESs represents a strategic approach for addressing environmental and socio-economic challenges, such as water quality, climate change mitigation and sustainable food production (Van den Burg et al., 2022; Willot et al., 2019). In this perspective, assessing the ESs provided by aquaculture has the potential to support policymakers and practitioners in planning processes, e.g., supporting strategic environmental assessment procedures (Directive, 2001/42/EC) and the preparation of plans for Allocated Zones for Aquaculture (Sanchez-Jerez et al., 2016). ESs valuations reveal trade-offs under different management options (e.g., aquaculture extension scenarios), providing a more accurate forecast of the environmental and socio-economic impacts of aquaculture development (Custódio et al., 2020). Furthermore, assigning monetary values to ESs encourages the adoption of a systematic approach to evaluate the costs and benefits arising from aquaculture-environment interactions (Barrett et al., 2022).

According to Weitzman (2019), the benefits of aquaculture have not been extensively explored in the literature. Furthermore, a scarcity of attention has been paid to empirical studies on the process that integrates values of ESs into decision-making for management purposes (Su and Peng, 2021) due to a lack of biophysical, quantitative, and geo-referenced data (Galparsoro et al., 2021) and biases in the development of tools and methods for improved valuation of ESs (Carrasco De La Cruz, 2021). In order to address these deficiencies, this study quantified the contribution of Mediterranean mussel, *Mytilus galloprovincialis* farming in the Mar Piccolo of Taranto (Ionian Sea, Italy), to ESs provision through a Total Economic Value (TEV) approach. Four ESs that are considered to be controlled by mussel aquaculture, including (i) food provision, (ii) carbon sequestration, (iii) nutrient removal, and (iv) local identity, were quantified in monetary terms.

The paper is therefore providing an in-depth analysis of the ecological and socio-economic interactions of mussel farming along multiple dimensions and with respect to the above-mentioned services. This effort targets the objective of addressing the data gap in the research field by providing a comprehensive assessment of the benefits of mussel aquaculture in a context in which this activity has a long-standing tradition and economic relevance. This goes in the direction of informing management decisions within the study area and providing unit values in monetary terms for implementation in real-world scenarios at the policy level. In this way, this paper also provides valuable insights for ecosystem-based management planning processes involving the EAA and contributes to informed decision-making in the context of marine spatial planning.

2. Background

Mussel aquaculture is widely recognized as a sustainable practice and has been identified as one of the most promising sectors to meet the nutritional needs of a growing human population while also contributing to the provision of many ESs (Suplicy, 2020; FAO, 2020; Smaal et al., 2019). Europe accounts for about 410 thousand metric tons of mussel production, approximately 21% of the global output, with Spain, France, and Italy as leading producers (FAO, 2024; FAO, 2022). Operating at lower trophic levels, mussels exhibit efficient filter feeding behavior (Bayne, 2017) without requiring artificial feeding, thereby serving as an environmentally and energetically efficient source of animal proteins (SAPEA, 2017). Moreover, mussels are nutrient-rich seafood that yields other commercially valuable by-products with a lower carbon and ecological footprint compared to alternatives (Iribarren et al., 2010). Mussel shells find extensive industrial applications, notably in the fields of wastewater treatment, cosmetics, traditional medicines, calcium supplements in animal feed, handicrafts, and jewelry (FAO, 2022). Beyond their role in biomass provision, mussels support a wide range of other ESs in society. Mussel farming enhances biodiversity by providing microhabitats through farm structures, ropes, and shells, supporting many other epibenthic species (AAC, 2021). Key among the ESs provided by mussels is the regulation of water quality, associated with nutrient removal (Cranford, 2019; Jansen et al., 2019; Ferreira and Bricker, 2019). Through filtering, ingestion, and assimilation of organic particles present in the water, mussels remove significant quantities of nitrogen (N) and phosphorus (P), thus mitigating coastal eutrophication (Petersen et al., 2014, 2019; Nizzoli et al., 2005; Lindahl et al., 2005). More recently, attention has focused on the potential of bivalve aquaculture to act as a sink for atmospheric CO_2 (Feng et al., 2023; Martini et al., 2022; Tamburini et al., 2022; Alonso et al., 2021; Aubin et al., 2018; Filgueira et al., 2015; Tang et al., 2011), a topic that is still highly debated without a general consensus on the components to include in the carbon budget (Bertolini et al., 2023). Finally, mussel aquaculture may act as an important key activity for local cultural identity and tourism, promoting local food culture and fostering opportunities for ecotourism and farm-to-table experiences (Barrett et al., 2022; Krause et al., 2019; SAPEA, 2017).

Assessing these ESs aids in informed decision-making and sustainable management practices, leveraging the ES framework to integrate ecological and socio-economic considerations (Boerema et al., 2016). Different decision-making tools have the potential to prioritize and incorporate ESs values, including cost-benefit analysis (CBA) and multicriteria analysis (MCA) (Carrilho and de Almeida Sinisgalli, 2018). Selecting the appropriate decision-making tool requires a thorough analysis of the ecosystem under investigation, particularly its environmental condition. For instance, in cases of environmental degradation requiring conservation action, other approaches going beyond mere cost comparisons are required. Cost-effectiveness analysis (CEA) emerges as being more suitable for such purposes. CEA focuses on identifying the most efficient strategies to address environmental challenges at the least possible cost, especially when combined with financial restrictions (Boerema et al., 2018). However, despite efforts to mainstream ESs values into decision-making, challenges persist due to insufficient institutional arrangements that do not make policymakers consider ESs values in their decisions (Su and Peng, 2021). Furthermore, most peer-reviewed scientific literature lacks explicit contextualization or analysis of the application of ESs valuations in decision-making (Laurans et al., 2013). Nevertheless, previous studies focusing on ESs provided by aquaculture have provided concrete examples and analyses, ranging from comparing alternative farmed species (Baek et al., 2024) to developing payment for ecosystem services (PES) schemes (Van den Burg et al., 2022; Chen et al., 2021b). These efforts represent a step forward in informing ecosystem-based marine spatial planning, thus supporting business cases for marine aquaculture (Ansong et al., 2017; Börger et al., 2014).

3. Material and methods

3.1. Study area

The Mar Piccolo of Taranto is a 21 km^2 semi-enclosed basin exhibiting lagoon characteristics (Fig. 1). It consists of two sub-basins (First Inlet and Second Inlet), with maximum depths of 12 and 8 m, respectively. Two inlet channels connect the Mar Piccolo to a larger bay (Mar Grande), which opens into the Gulf of Taranto (Ionian Sea). The hydrodynamic regime is affected by 34 submarine freshwater springs, locally known as “citri”, that ensure temperature regulation and control salinity gradients (Cecere and Petrocelli, 2009). Mar Piccolo is widely recognized as a production place for Mediterranean mussel, *M. galloprovincialis,* in the Mediterranean Sea context (Massarelli et al., 2021; Caroppo et al., 2012). The study area has a longstanding tradition of mussel farming dating back to the late 19th century. In 2022, “Cozza

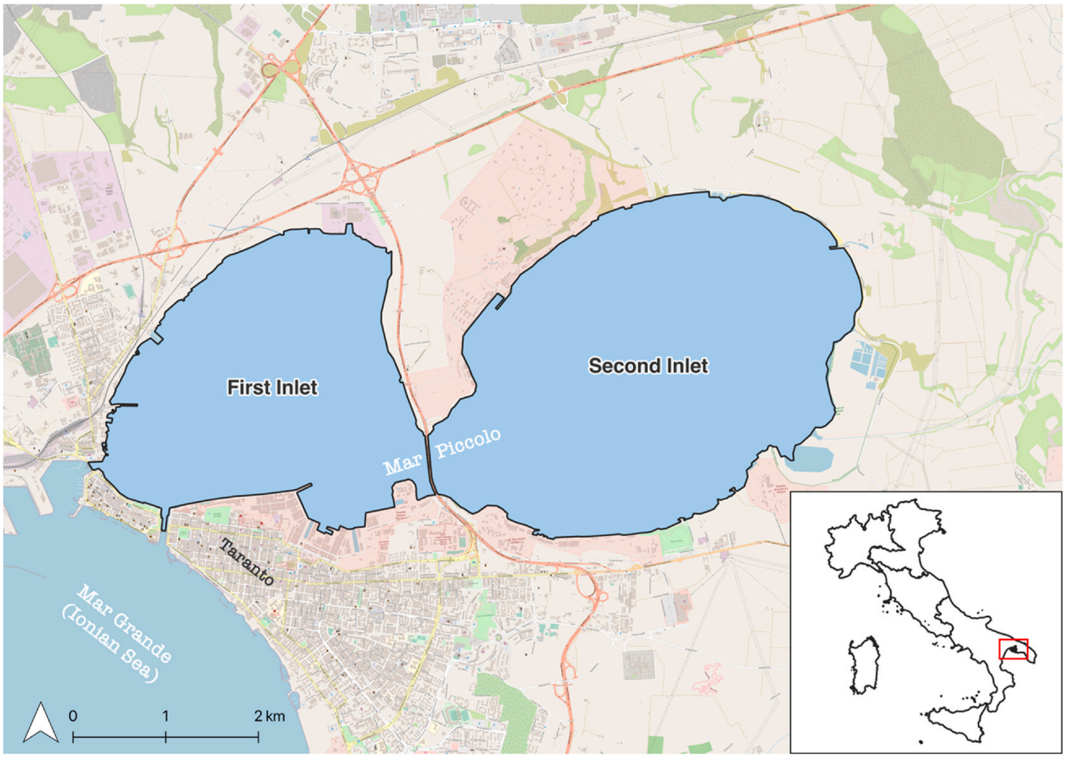

Fig. 1. Study area, Mar Piccolo di Taranto (Italy).

nera di Taranto" received recognition as a local presidium (https://www.fondazioneslowfood.com/it/presidi-slow-food/cozza-nera-di-taranto/) to protect traditional food products. Traditionally, farmers are organized in cooperatives or individual firms, often family-run, without a formalized management collaboration plan. A typical mussel plant consists of several basic units, known as "camera" (i.e., rooms), constructed with stakes driven into the bottom, bound and crossed by "lines". Each line suspends socks containing mussels. The longlines system (polyethylene floats), an adaptation of the traditional system, has recently replaced this culture method and is now the standard in other Italian locations (Gulf of Trieste, Gulf of Olbia).

In terms of the mussel life cycle, farmers begin collecting seeds in November and gather juveniles from May to June. The juvenile mussel phase spans from May to November, concluding the first growth stage. The initial generation reaches commercial size (>50 mm) by May of the subsequent year, with harvesting starting during the summer months, from June through the end of August (Giordano et al., 2019). Due to the high levels of priority contaminants (e.g., heavy metals and organic pollutants) caused by the high urbanization and extensive industrialization of the city of Taranto (Cardellicchio et al., 2007), current regulations in Mar Piccolo limit the First Inlet to seed collection only, designating the Second Inlet for the growing phase (Regione Puglia, 2018).

3.2. Identification of ecosystem services and economic valuation methods

The ESs were identified according to the TEV approach, based on their relevance to the local context, data availability, and previous studies (Zieritz et al., 2022; van der Schatte Olivier et al., 2020; Vaughn, 2018). The TEV of a natural resource, which is equal to the sum of its use and non-use values (Teh et al., 2018), helps to avoid double counting (Sharma et al., 2015) and informs decision-making (De Valck et al., 2023). Table 1 outlines the identified ESs, their value type, and the economic valuation methods used, in accordance with TEEB and Kumar (2010). The ESs were classified according to the Common International Classification of Ecosystem Services (CICES) V5.1, developed by the

Table 1
Identified ESs, value type and economic valuation methods.

CICES V5.1 framework				TEEB (2010) framework	
Division	Group	Class	Goods and benefits	Value type	Economic valuation method
Biomass	Reared aquatic animals for nutrition, materials or energy	Animals reared by in-situ aquaculture for nutritional purposes	Food provision	Direct use value	Market price[a]
Transformation of biochemical or physical inputs to ecosystems	Mediation of wastes or toxic substances of anthropogenic origin by living processes	Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals	Carbon sequestration	Indirect use value	Market price[a]
		Bio-remediation by micro-organisms, algae, plants, and animals	Nutrient removal	Indirect use value	Replacement cost[a]
Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	Intellectual and representative interactions with natural environment	Characteristics of living systems that are resonant in terms of culture or heritage	Local identity	Non-use value	Contingent valuation[b]

[a] Direct market valuation approach.
[b] Stated preference approach.

European Environment Agency (EEA, 2016).

Food provision was identified as a direct use value, while carbon sequestration and nutrient removal were identified as indirect use values. Local identity was identified as a non-use value. Considering the economic valuation methods, market price and replacement cost were used within direct market valuation approaches. The market price method estimates the value of goods and services that are traded in regular markets (TEEB and Kumar, 2010), while the replacement cost method assesses the cost of replacing the ESs with man-made systems (Farber et al., 2002). The market price method was used to estimate both food provision and carbon sequestration, while the replacement cost method was employed to estimate nutrient removal.

Finally, the contingent valuation method was used to elicit the households' willingness to pay (WTP) in the study area for preserving mussel-related traditions contributing to local identity. Contingent valuation is a survey-based technique where respondents are questioned about their willingness to pay (WTP) for a hypothetical change in the level of service provision (United Nations, 2021).

3.3. Data collection

To conduct the valuations, the main operational and economic indicators associated with mussel farming enterprises were gathered to estimate the mussel biomass and the production costs. Data relating to the extension of mussel farming facilities and the number of enterprises were derived from the Apulia Regional Authority, considering enterprises that received regional funding in 2021. Data on enterprise characteristics and the key aggregate economic parameters were collected through a survey involving 5 farmers and 5 local stakeholders, i.e., representatives of mussel farming associations, researchers, and experts in fishery and aquaculture. Table 2 provides a detailed overview of the key operational and economic data of the mussel farming area in 2023, categorized by capacity, landings, businesses, employment, effort, expenses, capital, and profitability.

Table 2
Key operational and economic data for the mussel farming area in 2023.

Parameter	Value
Capacity	
Mussel farming facilities [b]	141.52 ha. (whole area) 55,752 m (linear meters)
Number of vessels [a]	24 (No.)
Landings	
Yield [a]	70 kg m^{-1}
Enterprises	
Number of enterprises [b]	12 (No.)
Employment	
Workers onboard [a]	36 (No.)
Daily working hours [a]	8 h day^{-1}
Hourly wage [a]	12€ h^{-1}
Effort	
Days at sea [a]	280 days yr^{-1}
Expenses: Variable costs per *year (% of revenues)*	
Fuel [a]	2%
Lubricants [a]	0.2%
Stockings [a]	2%
Vessels and facility maintenance (excluding labor) [a]	4%
Utilities [a]	2%
Consumables [a]	1%
General expenses [a]	2%
Public land concession fees [a]	0.1%
Capital	
Facilities value [a]	50 € m^{-1}
Vessels and equipment value [a]	1,440,000 €
Profitability	
Average wholesale market price [a]	0.8 € kg^{-1}

[a] Focus group.
[b] Apulia Region data.

As shown in Table 2, the mussel farming area extends for 141.52 ha (equal to 55,752 linear meters), with an average productivity of 70 kg of mussels (wet weight including shell) per linear meter. The estimated overall annual yield is 3902.64 tons per year. There are 12 regularly operating enterprises, each running two vessels with three full-time workers per vessel. Each worker spends 8 h per day, for a total of 280 days at sea per year. The expenses for carrying out the activity amount to 11.5% of the annual revenue. The facilities are valued at €50 per linear meter, and the combined value of the 24 operating vessels and equipment is €1,440,000. The average wholesale market price in 2023 was 0.8 € kg^{-1}. Additionally, physico-chemical and water quality data were used to assess the quantities of N and P removed from *M. galloprovincialis* in the Mar Piccolo of Taranto and to perform the CO_2 budgets. Data from water quality monitoring in the Mar Piccolo of Taranto by the Regional Environmental Protection Agency, ARPA Puglia (ARPA, 2022), were used as inputs for mussel individual-based models (Brigolin et al., 2009; Bertolini et al., 2023). Parameters include Chlorophyll-a concentration, water temperature, TSS (total suspended solids) concentration, pH, salinity, and total alkalinity. Missing data were integrated with data from operational oceanography, derived from the Copernicus Marine Service, CMS (https://marine.copernicus.eu), following a methodology similar to the one adopted in Bertolini et al. (2023).

3.4. Economic valuation of ecosystem services

3.4.1. Food provision

The economic value of the food provision was determined using the market price method, considering the market value of the mussel meat (van der Schatte Olivier et al., 2020). Aquaculture provisioning services refer to the ecosystem's role in supporting animal growth in aquaculture facilities, which are then harvested by economic units (United Nations, 2021). Market prices include production costs (e.g., the cost of vessels, fuel, nets, and labor) that do not form part of the value of the ESs (UNEP-WCMC, 2011). Therefore, the latter were excluded from the wholesale market value to assess the ecosystem's direct contribution to food provision (Eq. (1)).

$$FP = (W \times MP) - PC \tag{1}$$

Where *FP* indicates the value of food provision (€ yr^{-1}), *W* refers to the mussel biomass (Kg yr^{-1}), *MP* indicates the average wholesale market price (€ Kg^{-1}), and *PC* represents the production costs (€ yr^{-1}). The production costs were determined taking into account the expenses incurred in conducting the activity (e.g., labor, fuel, energy, etc.), social burden, financial burden, and equipment depreciation (da Silva et al., 2022). The computation of expenses involved considering variable costs, expressed as a percentage of the revenues outlined in Table 2. Labor costs were determined by multiplying the number of workers onboard, days at sea, daily working hours, and hourly wage. To determine the financial burden, an interest rate of 4.5% established by the European Central Bank was considered as a factor influencing the overall cost structure and contributing to the formation of the cash flow. According to da Silva et al. (2022), the social burden, which includes the work benefits paid to each employee, was estimated at 40% of labor costs, while the financial burden was computed considering the interest rate of the expenses added to social burdens. The depreciation of investment items was calculated, taking into account a 10-year lifespan for facilities and a 20-year lifespan for vessels and equipment.

3.4.2. Carbon sequestration

The estimation of CO_2 budgets of mussel farms was based on the meta-modeling approach proposed by Bertolini et al. (2023), accounting for CO_2 released due to shell calcification, and respiration processes related to soft tissues and the organic fraction of the shell. This work derived general predictive models based on multiple regression, starting from the outputs of individual-based mathematical models of the mussels, which were forced by operational oceanography data from Copernicus Marine Service (https://marine.copernicus.eu). Models were run at 12 representative mussel farming sites for 12 years. Net fluxes for soft tissues were estimated based on two predictors, chlorophyll-a concentration and water temperature, while those related to shell were based on chlorophyll-a concentration, water temperature, pH and total alkalinity. Reference values for these independent variables were estimated from ARPA Puglia data.

The carbon sequestered by mussels generates carbon credits, which can be implemented within existing carbon credit programs (Van den Burg et al., 2022). In this study, the economic value of carbon sequestration was estimated by assuming that carbon credits from mussels may be sold in the carbon markets at prevailing carbon prices. According to previous studies (Krzemień et al., 2022; Marcelli et al., 2018; O'Donnell et al., 2013), the reference carbon price considered is the European Union Allowance (EUA), the official carbon credit under the European Union Emission Trading Scheme (EU ETS). The EU ETS is a cap-and-trade scheme that was implemented in 2005 (Directive, 2003/87/EC) as the main European regulatory tool for achieving emission reduction targets in a cost-effective and economically efficient way (Lutz et al., 2013) by explicitly pricing carbon (Dewaelheyns et al., 2023). The EUA is a tradable unit that entitles its holder to emit one ton of carbon (European Union, 2003). EUA prices are influenced by demand-side factors, such as economic activity and fuel switching. Due to the high short-term price fluctuations (Rudnik et al., 2023), the valuation was based on the mean of the daily EUA prices covering the period 01/01/2023–1/06/2023, accessed from EMBER (2023).

3.4.3. Nutrient removal

The amounts of N and P removed by the mussels were estimated based on the model by Brigolin et al. (2009), recently modified by Bertolini et al. (2023), accounting for a 12-month fattening period. The model was forced with a daily time series of data derived from the interpolation of the observed values from the ARPA Puglia monitoring campaigns, and operational oceanography data from CMS. Flows associated with ingestion, assimilation, and excretion were integrated throughout the 12 months in order to draw a complete picture of the farm-environment interactions. Integral fluxes were computed in accordance with Brigolin et al. (2009). The economic value was estimated using the replacement cost method, which determined the unit value of nutrient removal by considering the cost of applying the least-cost alternative mitigation option that is suitable for the local context (Barrett et al., 2022). The analysis entailed estimating the cost of removing an equivalent quantity of nutrients fixed by mussels in the Mar Piccolo of Taranto using wastewater treatment plants. This study followed Marcelli et al. (2018) and relied on data from Provolo et al. (2008) to derive the costs and performance of the wastewater treatment plants. Table 3 shows the shares of the overall cost related to the plant's removal of N and P, as well as the nutrient removal rate for each wastewater plant considered (Appendix A).

The quantity of nutrients fixed by mussels (Fv) was compared with wastewater treatment plants data using Eq. (2), in order to determine the mean cost of replacing the ES provided by mussels with man-made alternatives.

Table 3
Wastewater treatment plants costs and nutrient removal rates (based on Provolo et al., 2008).

Plant	Cost (€ 2008 m^{-3})		Nutrient removal rate (g m^{-3})	
	$Cost_N$	$Cost_P$	Rv_N	Rv_P
Coarse solid separation	0.37	0.33	373.33	337.50
Coarse and fine solids separation	0.97	0.80	1155	898.44
Biological nitrogen removal	4.08	0.57	2966.67	416.67
Nitrogen extraction as mineral fertilizer	9.75	3.58	2666.67	958.33

$$Replacement\ cost = \frac{\sum_{i=1}^{n} \frac{Cost_N \times Fv_N}{Rv_N}}{n} + \frac{\sum_{i=1}^{n} \frac{Cost_P \times Fv_P}{Rv_P}}{n} \tag{2}$$

Where $Cost_{N,P}$ indicates the shares of the overall cost related to the plant's removal of N and P, in € m^{-3}; Fv stands for the quantity (g) of nutrients fixed by mussels; $Rv_{N,P}$ denotes the nutrient removal rate of each wastewater treatment plant considered, in g m^{-3}; and n is the number of wastewater treatment plants under consideration, equal to 4.

3.4.4. Local identity

The contingent valuation method was employed to elicit the households' WTP for the preservation of mussel-related traditions. A focus group was held involving ten representatives of relevant local stakeholder groups (i.e., territorial promotion associations, enterprises, fisheries and aquaculture experts, and researchers). The deliberations encompassed an in-depth analysis of the main socio-economic and environmental issues related to mussels, considering their contribution to local meaning-making and their link with the historical traditions of Taranto. Based on the findings of the focus groups, an online questionnaire consisting of 12 questions was developed. The questionnaire was divided into three sections: (i) respondents' perceptions of the benefits provided by mussels; (ii) WTP question; and (iii) respondents' socio-economic profiles.

In Section 1, respondents were asked to indicate on a 1–10 Likert scale their perceptions of regulating (i.e., nutrient removal and carbon sequestration) and cultural services provided by mussels in the area, as well as their level of general knowledge about the ESs provided by mussels.

Section 2 of the questionnaire included a single-bound dichotomous choice question with a closed-ended format to elicit the WTP. The objective of this section was to estimate the households' WTP for the existence of mussels in the Mar Piccolo of Taranto. Following Bishop and Heberlein (1979), respondents were presented with a specific bid and asked to answer positively (accept the bid) or negatively (reject the bid). The bid amount was randomly assigned to each respondent within a vector of ten values ranging from €5 to €50 (i.e., € 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50) based on the findings of the focus group. The payment vehicle proposed was households' annual donations to organizations, ensuring the ongoing protection of the traditions related to mussels.

Section 3 elicited the socio-economic information of respondents, including gender, age, education level, and annual income. Respondents were given the option to provide each information in this section.

The questionnaire was distributed by the Qualtrics platform from May 1st, 2023 to June 26th, 2023 among the residents of the city of Taranto.

The data were analyzed in order to estimate the households' WTP per year. According to Hanemann (1984), the respondents' attitude toward choosing to pay the proposed bid can be described by an indirect random utility function (Eq. (3)):

$$U_i = U(y_i; z_i) + \epsilon_i \tag{3}$$

where U_i is the utility level of the individual i, y_i is the respondent's income level, z_i is a vector of individual's characteristics (e.g., age, education), and ϵ_i is the identically, independently distributed random variable with zero means. Each respondent was confronted with a randomly assigned bid (A) to which could contribute toward the continued existence of the resource. The difference between the probability of agreeing to pay and opting not to pay is the utility difference under two circumstances (ΔU), which is expressed in Eq. (4) (Amirnejad et al., 2006).

$$\Delta U = U(1, y_i - A;\ z_i) - U(0, y_i;\ z_i) + (\epsilon_1 - \epsilon_0) = \alpha + \beta A + \gamma y + \theta z \tag{4}$$

Using the Logit model, it is possible to measure the utility difference (ΔU) between paying the bid and enjoying the utility and not paying and giving up the utility (Lee et al., 2016). Thus, applying the utility theory, the probability of respondents engaging in maintaining mussel tradition may be described as the following logit model (Lee and Han, 2002) (Eq. (5)):

$$F_{\eta}(\Delta V) = \Pr \frac{1}{1 + \exp(-\Delta V)} = \frac{1}{1 + \exp[-(\alpha - \beta A + \gamma y + \theta z)]} \tag{5}$$

Where $F_{\eta}(\Delta V)$ is the cumulative distribution function of a standard logistic variate, and α is the constant, β is the coefficient of the bid, γ is the coefficient of the income, and θ is the coefficient of individuals' characteristic variables. To ensure consistency with theoretical constraints, statistical efficiency, and aggregability, the truncated WTP was calculated by considering the randomly suggested bid (A) from 0 to the maximum amount (Duffield and Patterson, 1991) (Eq. (6)).

$$WTP = \int_{0}^{Max\ A} F_{\eta}(\Delta U) dA = \int_{0}^{Max\ A} \left(\frac{1}{1 + exp[-(\alpha' + \beta A)]} \right) dA \tag{6}$$

Where α' is the adjusted intercept resulting from the inclusion of socio-economic terms in the original term α.

Finally, the truncated WTP per household was then multiplied by the number of families in order to obtain the aggregated benefit.

4. Results

4.1. Food provision

To assess the economic value of food provision, the wholesale market value of the mussels was first calculated by multiplying the average market price of 0.8 € Kg^{-1} by the annual mussel biomass of 3902.64 t yr^{-1} (Table 2). This resulted in a value of 3,122,112 € yr^{-1}, which reflects the expected revenues of the operating enterprises in the study area.

Finally, production costs totaling 2,141,676 € yr^{-1} (Table 4) were deducted, resulting in a final value of 980,436 € yr^{-1}, which represents the total ecosystem's contribution to food provision.

4.2. Carbon sequestration

The valuation of carbon sequestration was based on the CO_2 budget for *M. galloprovincialis* in the study area. A carbon sequestration of 0.55 g CO_2 eq. per individual mussel specimen per year was estimated for the mussels farmed in the Gulf. Considering a mussel production of 3902.64 tons yr^{-1}, the total net carbon stock sequestered was estimated at 53.64 tons CO_2 eq. yr^{-1}, with a ratio of 0.014 kg CO_2 eq sequestered per kg of mussels produced.

To estimate the economic value, the EUA prices were considered, assuming that the net carbon stock fixed by mussels may be sold as carbon credits within the EU ETS. As the mean daily value of EUA carbon credits traded in the EU ETS during the first half of 2023 was found to be €89.87 $tons^{-1}$ CO_2 (EMBER, 2023), the economic value of carbon sequestration provided by mussels in the study area was estimated at 4820 € yr^{-1}.

4.3. Nutrient removal

The economic valuation of nutrient removal involved computing the costs of building and maintaining wastewater treatment plants required to achieve the same level of N and P removal as provided by mussels. A net removal of 4.05 kg N and 0.39 kg P per ton of mussels produced was estimated for the mussels inhabiting the Mar Piccolo of Taranto. Accounting for the 3902.64 tons yr^{-1} of production, this brings comprehensively to a removal of 15.81 tons N yr^{-1} and 1.82 tons P yr^{-1}.

Table 4
Production costs of mussel aquaculture in the study area (€ yr^{-1}).

Item	Value
Labor	1,415,716
Expenses	375,200
Depreciation of investments items	350,760
Overall total	2,141,676

Table 6 presents the annual costs associated with each wastewater treatment plant considered in this study, computed using Eq. (2). The amounts were adjusted to the 2023 currency using the annual coefficients of monetary revaluation provided by the Italian National Institute of Statistics (ISTAT).

As shown in Table 5, the average costs are 35,041 € yr^{-1} N and 4106 € yr^{-1} P. The cost of N removal, which is 1.71 € Kg^{-1} N, aligns with the results of Gren et al. (2009), falling within the range of 1.7–24.7 € Kg^{-1} N. Considering both the average costs for N and P removal, the total estimated cost is 39,147 € yr^{-1}. The latter is the replacement cost, which corresponds to the projected annual expenditure required to remove the same quantities of N and P as those fixed by mussels. This estimation is based on the assumption that the ES provided by the mussels might no longer be available, necessitating the use of alternative technologies to achieve equivalent nutrient removal.

4.4. Local identity

Table 6 shows the results from the contingent valuation survey. The sample, consisting of 268 respondents aged 18 and above, is well balanced in terms of age, income, and education level. The main age ranges are 51–65 (32%), followed by 36–50 (31%) and 21–35 (22%). The main ranges of income are €20,000–40,000 (51%), <€20,000 (24%), and €40,000–60,000 (17%). The classification of respondents on the basis of their education shows that 34% have a university degree and 19% have a high school diploma.

Fig. 2 shows the results of Section 1 of the questionnaire, reflecting respondents' perceptions of the environmental conditions of the study area and the main ESs provided by mussels. Using a Likert scale, respondents stated their opinions from "very negative" (or "not at all") rated as 1, to very positive (or "very much") rated as 10.

The average participant response indicated a low level of awareness regarding the ESs provided by mussels, rated at 4.8 out of 10. However, the results revealed a higher level of awareness among respondents regarding the importance of mussels in water purification, rated at 5.6 out of 10, compared to their understanding of mussels' carbon sequestration ES (4.9 out of 10). The strongest average rating, 7.7 out of 10, was attributed to the relationship between mussels and the city of Taranto, emphasizing their significance in local meaning-making. Moreover, perceptions regarding the socio-economic impact of mussels were notably positive, averaging around 6.3 out of 10. The assessment of the environmental and health conditions of the Mar Piccolo yielded an average rating of 4.8 out of 10, indicating a relatively low consideration of the state of the area among the sample of respondents. This suggests the need to implement measures to improve and preserve the area's environmental quality. Lastly, respondents indicated a willingness to support measures aimed at safeguarding and enhancing the presence of mussels in the Mar Piccolo, with an average rating of 6.6 out of 10, suggesting a generally positive disposition.

Table 5
Annual costs of wastewater treatment plants for nutrient removal (€ yr^{-1}).

Plant	Cost of N removal	Cost of P removal
Coarse solid separation	20,032	2330
Coarse and fine solids separation	17,239	2098
Biological nitrogen removal	28,135	3202
Extraction of nitrogen as a mineral fertilizer	74,758	8794
Mean value	35,041	4106

Table 6
List of variables and results from the contingent valuation survey.

Acronym	Variable	Categories	Mean	Std. Dev.	Min	Max
Accept	If the respondent is willing to accept the proposed bid	If yes = 1, 0 otherwise	0.548	0.499	0	1
Bid	Bid amount offered in dichotomous choice	[5, 10, 15, 20, 25, 30, 35, 40, 45, 50]	28.224	14.275	5	50
Q_1	If the area's health and environmental conditions are favorable	1-10 Likert Scale	4.798	1.843	1	10
Q_2	If mussels have a positive socio-economic impact	1-10 Likert Scale	6.272	2.117	1	10
Q_3	If mussels are tide to Taranto's historical and cultural traditions	1-10 Likert Scale	7.689	2.240	1	10
Q_4	If mussels contribute to filter sea water	1-10 Likert Scale	5.645	2.528	1	10
Q_5	If mussels contribute to carbon sequestration	1-10 Likert Scale	4.939	2.534	1	10
Q_6	If the respondent is aware of the ecological benefits provided mussels	1-10 Likert Scale	4.846	2.239	1	10
Q_7	If the respondent would support measures to safeguard and enhance the presence of mussels	1-10 Likert Scale	6.623	2.532	1	10
Gender	Gender	Male = 0, Female 1	0.518	0.501	0	1
Age	Age	0-5 scale, where 0 = does not answer	3.167	1.122	0	5
Education	School title	0-4 scale, where 0 = does not answer	2.965	0.947	0	4
Income	Income	0-4 scale, where 0 = does not answer	1.961	0.872	0	4

In order to determine the households' WTP per year, the data were analyzed using a logit model with the maximum likelihood estimation method in STATA 17.00.

As shown in Table 7, the bid, age, income, Q_6, and Q_7 influence households' WTP. The estimated coefficient of the bid was found to be statistically significant at the 1% level with the expected negative sign. This indicates that an increase in the proposed bid is associated with a decrease in the probability of acceptance. Moreover, the coefficient of the age variable was statistically significant at the 5% level with a positive sign, indicating that, on average, the younger the respondents, the greater the probability that the amount will be accepted. The estimated coefficient of the income variable was found to be statistically significant at the 1% level, and the sign was positive as expected.

Furthermore, a higher level of respondents' awareness regarding the ESs provided by mussels (Q_6) and a greater willingness to support measures aimed at safeguarding and enhancing the presence of mussels (Q_7), correspond to an increased probability of accepting the offered bid.

Unexpectedly, the estimated coefficient of Q_4 was found to be statistically significant, with a negative sign at the 10% level. However, this result is considered favorable since it demonstrates that the value of WTP pertains only to the cultural value and does not include the value of the perceived regulating ESs, which were examined independently. After parameters from the Logit model were estimated, the truncated WTP was computed according to Eq. (6). This resulted in a mean WTP equal to 22.83 €/household/year for the local identity provided by mussels. With the population of Taranto including overall 83,462 households (ISTAT, 2021), the aggregate value of the WTP is estimated to be €1.905 million per year.

5. Discussions

Economic valuations can be biased, leading to overestimation or underestimation of ESs values. Despite these limitations, valuation highlights the values of ESs that are typically overlooked or disregarded in decision-making (Costanza et al., 2014). In this study, efforts were made to strengthen the valuation process. The TEV approach was employed to prevent double counting (Sharma et al., 2015). To mitigate potential overestimation when valuing food provision using the market price method, production costs were deducted from the expected revenues. This approach aimed to quantitatively describe the value of the ecosystem's functional processes in providing food (Armoškaitė et al., 2020). For nutrient removal valuation, based on biophysical assessments of N and P fixed by mussels that agree with previous works (e.g., Nizzoli et al., 2005; Petersen et al., 2019), the study followed Shabman and Batie's (1978) least-cost alternative approach. As far as the CO_2 budget is concerned, it is worth remarking that there is still a lack of consensus about the terms to be included in the budget. The methodology adopted in this work for the biophysical estimation leads to a conservative estimate of carbon flows compared to other literature examples (e.g., Martini et al., 2022). Nonetheless, CO_2 budgets for the mussels farmed within the study area were calculated based on the model by Bertolini et al. (2023). In estimating the monetary benefits associated with carbon sequestration, reliability was ensured by adhering to the EU ETS as a systematic framework in compliance with established European standards (Krzemień et al., 2022). Regarding the estimation of local identity, the WTP was found to align with previous assessments for the cultural value of marine activities (Durán et al., 2015). However, potential biases in the WTP estimation can be linked to the low number of respondents and the non-optimal bid design.

Overall, the results of this study provide valuable data to inform management and strategic decision-making processes both in the study area and in a broader international context. Mussel farming was found to play a positive role in regulating services, showing the potential of this human activity for improving water quality. The TEV approach allowed us to identify the relative significance of the estimated ESs, facilitating prioritization in resource allocation and conservation efforts.

As shown in Table 8, cultural and provisioning services emerged as the leading contributors to the TEV. The community of Taranto has a long-standing tradition related to mussels, integral to its cultural heritage. Consequently, management efforts for the study area should prioritize strategies aimed at enhancing the flow of cultural service to support local traditions over time. Additionally, the high value of food provision underscores the importance of mussel farming in the local economy, particularly in terms of its contribution to protein production. This further justifies the need for targeted conservation and sustainable management practices. To achieve this goal, a management strategy could involve implementing PES schemes. PES represents a resource

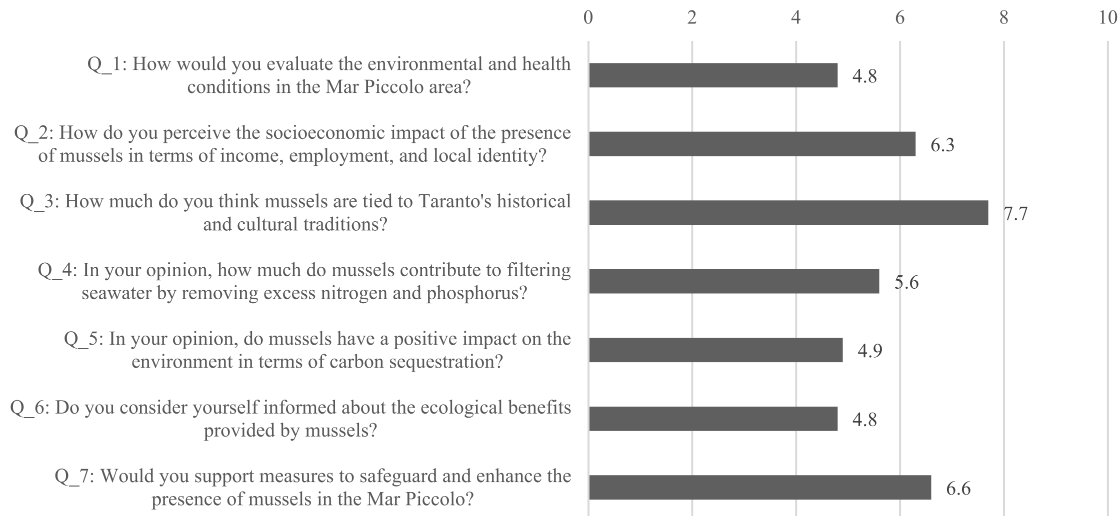

Fig. 2. Results from Section 1 from the contingent valuation survey.

Table 7
Results of the logit model.

Variable	Coefficient	St. Err.	Z-score
Const	–0.760	0.930	–0.82
Bid	–0.058[c]	0.012	–4.73
Gender	0.028	0.325	0.09
Age	–0.277[a]	0.152	–1.82
Education	0.143	0.204	0.70
Income	0.797[c]	0.207	3.86
Q_1	0.052	0.103	0.50
Q_2	0.113	0.108	1.04
Q_3	–0.094	0.101	–0.93
Q_4	–0.192[a]	0.099	–1.94
Q_5	–0.021	0.110	–0.19
Q_6	0.195[b]	0.097	2.02
Q_7	0.232[b]	0.102	2.27
Number of observations: 228			
Percent of right prediction: 77.2			
Log likelihood: 120.690			
McFadden $R^2 = 0.231$			
Maddala $R^2 = 0.148$			

[a] Significance at 10% level.
[b] Significance at 5% level.
[c] Significance at 1% level.

Table 8
Total economic value of ESs provided by mussels in the study area and economic values per unit.

Value type	ES class	ES	Economic value	Economic value per unit
Direct use	Provisioning	Food provision	980,436 € yr^{-1}	6677 € ha^{-1} yr^{-1}
Indirect use	Regulating	Carbon sequestration	4820 € yr^{-1}	34 € ha^{-1} yr^{-1}
Indirect use	Regulating	Nutrient removal	39,147 € yr^{-1}	278 € ha^{-1} yr^{-1}
Non-use	Cultural	Local identity	1.905 million € yr^{-1}	22.83 € $household^{-1}$ yr^{-1}

management tool that incentivizes behavioral changes to increase the flows of ESs (e.g., discouraging habitat degradation through sustainable practices). This is achieved by providing incentives that can be monetary or in-kind, such as infrastructure development (Lau, 2013). PES has demonstrated effectiveness in capturing the value of non-market services, primarily focusing on environmental services (i.e., regulating services) (Lau, 2013), while also acknowledging the value of cultural services (Gaglio et al., 2023; Schirpke et al., 2018).

Given that mussel-mediated ESs result from both natural processes and human intervention, recognizing farmers as ESs providers can lead to the implementation of public PES programs based on the non-market services values (i.e., regulating and cultural services) estimated in this study. This approach marks a shift from conventional command-and-control policies to incentivization strategies, aiming to mitigate the negative externalities of marine aquaculture while improving public welfare (Chen et al., 2021b). PES can target enhancing cultural services by creating ecotourism opportunities that are currently lacking in the area and strengthening the flow of regulating services. For instance, incentives could support the construction of sustainable aquaculture facilities to minimize environmental impact and improve the environmental conditions of the area. Payments could be directed towards nature-based solutions for coastal ecosystem restoration to ensure the long-term resilience of mussel farming activities (Thompson et al., 2023; Reed et al., 2017). Furthermore, recognizing the Protected Designation of Origin (PDO) for the "Cozza tarantina" mussel could strengthen and enhance the value of food provision by promoting its quality and authenticity. The study's results can inform management and policy-making beyond the local context. Table 8 presents unit values of ESs in monetary terms that serve in benefit transfer exercises to estimate the ESs provided by Mediterranean mussels to other sites (i.e., policy sites). Care should be taken when transferring the cultural value per unit, as not all mussel-producing areas share the same cultural traditions. The estimated values at policy sites can be integrated into decision-making tools to compare the economic viability of maintaining mussel farming with shifting to alternative uses of coastal areas. For instance, transferring the estimated unit values at the policy sites allows for the comparison of aquaculture systems when shifting from mussel farming to another species, or vice versa (Baek et al., 2024). Furthermore, ESs values can be integrated into the CBA, CEA, and MCA. According to CBA, the estimated ESs values at the policy site enable the comparison of the monetary values of different management options, including the implementation of coastal development projects or the establishment of marine protected areas, to make the most economically advantageous decision. During the implementation of the CEA, values can be transferred to quantify the effects of management measures on different ESs (Boerema et al., 2018). Finally, in MCA, the estimated ESs values at the policy site are relevant to provide quantitative scores in monetary terms to evaluate scenarios in order to help decision-makers and stakeholders make better-informed decisions (Carrilho and de Almeida Sinisgalli, 2018).

According to Ehler and Douvere (2009), the study's findings provide key implications for marine spatial planning that can be implemented at different stages. The valuation of ESs enables the establishment of PES schemes that can be framed as innovative financing options for ecosystem-based marine spatial planning, thus motivating financial support for planning efforts (Ansong et al., 2017). Furthermore, the ESs values can be employed to assess the current conditions and provide information on the relevance of marine aquaculture as reflected in their economic and social values, highlighting incompatible uses (Börger et al., 2014).

The study's findings can also be used to provide economic insights into how mussel farming can function as a cost-effective nature-based solution, providing a sustainable alternative to human-made solutions for enhancing coastal water quality (Filippelli et al., 2020), and similar considerations were recently applied to climate change mitigation (Maas and Rousseau, 2024). In this perspective, considering the economic values of the ESs provided by marine aquaculture drives scenario plans by providing decision-support data to weigh the economic trade-offs of proposed plans involving changes in the extent of aquaculture operations (Börger et al., 2014).

Finally, the economic valuation of ESs provided by mussel aquaculture represents a significant advancement in the field of ocean accounting. The ocean accounting framework aims to integrate spatial data on marine habitats with enhanced measurements of the marine economy, including the value of ESs in comprehensive accounts (Gacutan et al., 2022). Accounting for the value of non-market services provided by mussel aquaculture in national income calculations aids in quantifying the ocean economy and supports informed marine spatial planning decisions regarding the allocation of space and resources for human activities.

6. Conclusions

This study aimed to fill the gap in the literature by presenting the first economic valuation of multiple ESs provided by Mediterranean mussel aquaculture in the Mar Piccolo of Taranto, where this activity has a long-standing tradition and economic relevance. Using the TEV approach, the research comprehensively accounted for all values (i.e., use and non-use values), avoiding double-accounting and thereby providing better insights for management and policymaking. The economic valuation of the ESs highlighted that *M. galloprovincialis* aquaculture plays a significant ecological role, contributing to the overall sustainability of the activity. Notably, mussel farming is a type of aquaculture that does not require the input of feed by the farmer, thus relying completely on the support of the ecosystem in terms of the trophic resources required. Furthermore, cultural value emerged as the greatest contributor to the TEV. Therefore, the results underscored the multifunctionality of mussel aquaculture, which provides non-commodity outputs (i.e., regulating and cultural services) that function as public goods for society (Mulazzani et al., 2019). As a result, the findings can inform management and strategic decision-making both in the study area and in a broader international context. In the study area, targeted conservation and sustainable management practices were identified as crucial for supporting local identity and enhancing the contribution to protein production, driven by the estimated high value of cultural and provisioning services. This supports the establishment of beneficiary-pays-principles through PES schemes and advocates for careful spatial planning of aquaculture in the area to mitigate environmental interactions (e.g., energy use, emissions, litter, and disease transmission). Furthermore, by providing the economic values of ESs per unit, this study enables further studies and policymakers to conduct benefit transfer exercises and estimate the value of ESs provided by Mediterranean mussels in other locations. These estimations serve as input in decision-making tools to assess the economic impacts of different management options and inform marine spatial planning by evaluating the economic trade-offs of proposed scenario plans involving changes in aquaculture operations. Overall, this study offered a comprehensive economic valuation of the ESs provided by Mediterranean mussels, supplying policymakers with values that can make the economic valuation of ESs operational in management and decision-making. This study can be framed within ongoing research efforts aimed at designing innovative methodologies for supporting the implementation of the EEA (e.g., Chary et al., 2022) and by considering a multi-sectorial perspective within the efforts aimed at sustaining ecosystem-based maritime spatial planning (Frazão Santos et al., 2019). Future works could further explore the implementation of the study's findings in real-world policymaking scenarios.

CRediT authorship contribution statement

Andrea Mattia Pacifico: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Daniele Brigolin:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Luca Mulazzani:** Writing – review & editing, Supervision, Methodology. **Mara Semeraro:** Writing – review & editing, Investigation. **Giulio Malorgio:** Writing – review & editing, Supervision.

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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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Appendix A

Wastewater treatment plants use engineered, controlled processes involving mechanical, chemical, and biological treatments to remove contaminants from water. The costs and performances of the following wastewater treatment plants were collected from Provolo et al. (2008): (i) coarse solids separation, (ii) coarse and fine solids separation, (iii) biological nitrogen removal, and (iv) nitrogen extraction as a mineral fertilizer. Each plant is divided into multiple methods, each corresponding to different types of separators that vary in the way the effluent is conveyed through the filtering system. The total cost (€ 2008) includes depreciation, of structures (20 years) and equipment (10 years), as well as management, maintenance, and additives. To define the nutrient removal rate (g m^{-3}) based on the performance (%) of each method, the concentrations of N and P in cattle farms were considered. In livestock effluents from cattle farms the N concentration is 4 kg m^{-3} (Provolo et al., 2008), and the mean P concentration is 1.25 kg m^{-3} (range 0.2–2.5 kg m^{-3}) (Provolo and Riva, 2008). For each of the methods under consideration, the N and P concentration values of livestock effluents from cattle farming were multiplied by the extreme values of the performance (%) values for N and P removal for each respective method (Table A.1).

Table A.1
Wastewater treatment plants data by types and methods

Plant	Method	Total cost (€ m^{-3})	Performance (%)		Nutrient removal rate (g m^{-3})	
			N	P	Rv_N	Rv_P
Coarse solid separation	*Vagli*	0,3	4–7	8–12	160–280	100–150
	Cilindrico	0,9	8–15	30–42	320–600	375–525
	Elicoidale	0,9	6–16	28–42	240–640	350–525
Coarse and fine solid separation	*Sedimentazione*	0,35	25–35	50–65	1000–1400	625–812,5
	Flottatore	1,6	30–40	70–90	1200–1600	875–1125
	Centrifuga	1,6	20–26	73–87	800–1040	912,5–1087,5
	Nastropressa	3,55	20–35	60–80	800–1400	750–1000
Biological nitrogen removal	*SBR senza separazione*	3,5	50–70	0	2000–2800	0
	SBR con separazione	4,4	70–90	15–75	2800–3600	187,5–937,5
	Processo continuo	6,05	70–95	15–95	2800–3800	187,5–1187,5
Nitrogen extraction as mineral fertilizer	*Strippaggio*	10,5	60–80	30–90	2400–3200	375–1125
	Precipitazione	17,5	80	85	3200	1062,5–1062,5
	Microfiltrazione	12	50	85	2000	1062,5–1062,5

Finally, for each of the methods that were investigated, the mean of the total costs and the mean of the central values of the nutrient removal intervals were computed (Table A.2).

Table A.2
Wastewater treatment plants costs and nutrient removal rate by types

Plant	Total cost (€ m^{-3})	Nutrient removal rate (g m^{-3})	
		Rv_N	Rv_P
Coarse solid separation	0.70	373.33	337.50
Coarse and fine solids separation	1.76	1155	898.44
Biological nitrogen removal	4.65	2966.67	416.67
Nitrogen extraction as mineral fertilizer	13.33	2666.67	958.33

Total costs indicate the expenses for running the wastewater treatment plant and include the sum of the costs for N and P removal. Considering the total cost connected with each wastewater treatment plant as well as their relative N and P removal rates, the share of total plant cost related to their removal was determined using Eq. (A.1) (Table A.3).

$$Cost_{N,P\ i}\left(\frac{€}{m^3}\right)=\frac{Total\ cost_i\left(\frac{€}{m^3}\right)\times Rv_{N,P\ i}\left(\frac{g}{m^3}\right)}{Rv_{N\ i}\left(\frac{g}{m^3}\right)+Rv_{P\ i}\left(\frac{g}{m^3}\right)} \tag{A.1}$$

Table A.3
Wastewater treatment plants data considered for the computation

Plant	Cost (€ m^{-3})		Nutrient removal rate (g m^{-3})	
	$Cost_N$	$Cost_P$	Rv_N	Rv_P
Coarse solid separation	0.37	0.33	373.33	337.50
Coarse and fine solids separation	0.97	0.80	1155	898.44
Biological nitrogen removal	4.08	0.57	2966.67	416.67
Nitrogen extraction as mineral fertilizer	9.75	3.58	2666.67	958.33

Data availability

Data will be made available on request.

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