Donor-side and user-side evaluation of the Atlantic blue crab invasion on a Mediterranean lagoon

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A R T I C L E I N F O

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A B S T R A C T

The recent invasion of *Callinectes sapidus* in the Lesina Lagoon has raised great concern about its potential impacts on the ecosystem and on local fisheries. The effects of the blue crab presence on the receiving ecosystem were evaluated from both a donor-side perspective, through the application of emergy analysis, and a user-side perspective, by means of interviews to the local fishermen. While emergy analysis showed that *C. sapidus* brings to an increase of both natural capital and ecosystem functions values, results from interviews highlighted that the major problem caused by the presence of the blue crab in the lagoon concerned the local economy. As the first quantitative assessment of the ecological and economic impact of *C. sapidus* in invaded habitats, the present investigation provided original and useful information for a comprehensive risk assessment of the species in European waters and in Mediterranean Sea.

1. Introduction

Non-indigenous species (NIS) are species that were introduced outside of their previous or present natural range by human activities (Rotter et al., 2020). In many cases these are able to survive and reproduce in the new environment (CBD, 1993). According to the IUCN (2018), in Europe there are over 12,000 NIS, 15 % of which are invasive. Whenever NIS colonize permanently the new environment, if they aggressively spread in other areas with potential threats to the local biodiversity and/or economic damage, they become invasive species (Molnar et al., 2008). Invasive Alien Species (IAS) can alter the equilibrium between biotic and abiotic components of an ecosystem bringing different effects and changing the ecosystem stability. They can compete with indigenous species, increase diffusion of new diseases, and bring negative effect on the economy of colonized areas. For these reasons, IAS are considered one of the most direct drivers of biodiversity loss and depletion of ecosystem services (Corriero et al., 2016; EEA, 2012). The Mediterranean Sea is among the marine regions most exposed to bioinvasion (Cerri et al., 2020) with recent estimates of >1000 NIS in the basin, 10 % of which being invasive (Zenetos and Galanidi, 2020). Especially crustaceans are emblematic of this ongoing process, accounting for about 1/5 of Mediterranean NIS, and in particular brachyurans (Brockerhoff and McLay, 2011). An emblematic example is the Atlantic blue crab *Callinectes sapidus* (Rathbun, 1986), which is rapidly expanding in the Mediterranean basin, and especially in transitional water systems, finding optimal conditions for their settlement also due to climate change (Mancinelli et al., 2013). *C. sapidus*, is a decapod crustacean belonging to the Portunidae family that inhabits estuaries, lagoons and shallow waters up to 90 m depth. Original from the west coast of the Atlantic Ocean, the blue crab was introduced in Europe at the beginning of the 20th century through ballast water (Nehring, 2011). Thanks to its physiological characteristics, the Atlantic blue crab can tolerate a wide range of temperature and salinity, and it can colonize different environments (Dulčić et al., 2011). In the native habitats, *C. sapidus* is considered a keystone species, because it plays an integral ecological and economic role. For all these reasons, *C. sapidus* has long been recognized to influence the structure and function of benthic food webs, either as a keystone species regulating carbon flows by reducing prey abundance and inducing trophic cascades. As a consequence, as in the native areas (Williams, 1984; Kampouris et al., 2019), the blue crab

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could represent an essential food and income resource (Seafood Watch Consulting Researcher, 2013; Cilenti et al., 2015). Nonetheless, in the areas of recent colonization, *C. sapidus* is considered a threat. In the Mediterranean Sea, negative interactions were recorded with endemic biodiversity and local economy (Olenin et al., 2014; Kampouris et al., 2019) even if scarce information is available on the ecological impact of the species in invaded habitats to date.

The Lesina lagoon (SE Italy, Adriatic Sea) is known as an invaded system in Mediterranean where the abundant presence of the blue crab is reported (Cilenti et al., 2015, 2016; Renzi et al., 2020). This is a lagoon ecosystem largely exploited by humans: fishing and aquaculture activities represent a significant income source for the local economy (Breber et al., 2009). In this study Lesina lagoon was taken into consideration in order to: assess the direct impact of Atlantic blue crab on the local benthic community (with a focus on *Nanozostera noltii* seagrass bed), estimate the effect of the invasion on the natural capital and on the ecosystem functions' provisioning through emergy analysis, evaluate potential outcomes on the local economy. Emergy method is a "donor side" approach that provides a biophysical and monetary evaluation of natural capital and supporting flows. In recent years, the concepts of natural capital, ecosystem functions and ecosystem services become widely known: the great merit of ecosystem services theory is the ability of highlighting the relationships between natural realm and human economy (Sukhdev et al., 2010). Natural capital comprises all natural resources required for the economy and the human development. Ecological functions arise from natural capital components' interaction while ecosystem goods (e.g., energy) and services (e.g., ability to purify water) are the benefits that humans obtain, directly or indirectly, from ecosystem functions. Even when humans do not use some functions or even perceive their existence, our survival and our well-being depend on them. Natural capital value should be then maintained precautionary constant since the modification (in particular the depletion or the compromising) of a function can generate consequences affecting good or services that humans use (Paoli et al., 2022).

The assessment of natural capital must be precise and reliable and, for this reason, it requires scientifically valid environmental accounting methods (Vassallo et al., 2007). In particular, emergy analysis allows to quantify the value and the changes in natural capital stock and in ecosystem functions it generates, providing results easily understandable by policy makers and other stakeholders. In this study, a three-steps approach was developed: (1) realization of a field experiment with a controlled introduction of blue crabs to evaluate the effect of the invasion on the benthic community; (2) estimate of natural capital value and ecosystem functions supporting the lagoon system through emergy analysis application on results from the experiment; (3) questionnaires administration to fishermen working in the lagoon to understand the impact of the Atlantic blue crab on local economy.

2. Materials and methods

2.1. Study area: Lesina Lagoon

Lesina Lagoon (N 41.88°, E 15.45°) is one of the largest wetlands of the central and southern Italy, situated on the southern Adriatic coast in the Apulia region. Lesina lagoon is a semi-closed system influenced by both fresh and marine waters. The lagoon covers a 51.36 km^2 area with a maximum depth of about 1.5 m. The catchment area is about 600 km^2. The lagoon is characterized by shallow waters and limited exchanges with the sea, as many other Mediterranean lagoons, characterized, if compared with Atlantic systems, by a less influence of tides and a lower freshwater input (Breber et al., 2002; Manzo et al., 2016). Due to the limited tidally-driven exchanges between the lagoon and sea, the hydrology of the Lagoon is strongly influenced by precipitation, evaporation and freshwater inputs, which explain also the heterogeneous spatial distributions of several environmental variables (Roselli et al., 2009). The lagoon's main hydrological features, temperature and salinity, follow a seasonal trend, with minimum values in winter and maximum ones in summer. Temperatures range from 3 to 32 °C, salinity from 5 to 38 ppt and an average annual precipitation equal to 400–700 mm (Vignes et al., 2010; Roselli et al., 2009). Lesina lagoon is characterized by an east–west salinity increasing gradient that is the main driver of the distribution patterns of seagrass species and macrobenthic assemblages (Manzo et al., 2016). Lesina lagoon is an important habitat for various plants and animal species, and it plays a major role in the local economy in terms of fisheries and tourism (Ferrarin et al., 2014). The seagrass *Nanozostera noltii* covers most of the Lagoon bed. Seagrasses, in recent years, are suffering from a drastic decline due to the rise of the water turbidity and other anthropogenic causes. In the lagoon there are also numerous species of fish caught by small artisanal fisheries and reared through extensive aquaculture practised for many years, exploiting the migratory movements of the euryhaline marine species between marine and lagoon environments. Lagoon management is, therefore, recognized as the main instrument to preserve the ecological features and prevent the depletion of valuable aquatic resources and degradation of sensitive habitats (Manzo et al., 2016). For these reasons Lesina lagoon, which is part of the Gargano National Park, is designated as both Special Protection Area (SPA-IT9110037) and Site of Community Importance (SC-IT9110015), following the implementation of the Birds and Habitats Directive (2009/147/EC, 92/43/EEC).

However, due to its physical characteristics the lagoon of Lesina, like the other semi closed environment sites such as harbour and brackish water, is more prone to invasion than pristine sites. Indeed, first record of *Callinectes sapidus* in this ecosystem is reported by Florio et al. (2008) in 2007, where five exemplars of blue crab were caught by fyke nets in June, July and October 2007. Moreover, the first record of ovigerous *C. sapidus* was reported in 2015 by Cilenti et al. (2015) where mature female were caught in four sites near the channels during the breeding migration to more saline waters.

2.2. Field experiment

The effect of the introduction of *C. sapidus* on the macrobenthic community of the lagoon was tested carrying out a manipulative field experiment (Fig. 1a). According to the procedure following by Garbary et al. (2014) Four square mesocosms (3 × 3 m) were built within *N. noltii* meadows (Fig. 1b). The mesocosms were made with rigid plastic nets (mesh size of 1.5 cm), attached to long stakes, and firmly buried into the soft substrate. Two mesocosms were assigned as control (without the crab) and two as treatment, where three exemplars of blue crab each were introduced (Fig. 1c, Table 1). The experiment started on the end of July 2018 and ended after 30 days. To analyze the community associated to *N. noltii* and to estimate the impact of the presence of the blue crab on the seagrass bed, both the autotrophic and heterotrophic components have been sampled. Specifically, for macrozoobenthos assemblage three sediment samples per each mesocosm (12 sediment samples in total), were collected in August 2018 using an Ekmann Grab with a surface of 225 cm^2. Once the samples were taken, they were rinsed directly in the lagoon with a sieve with a 1 mm mesh size and stored in a fixing solution (4 % formalin), to preserve macroinvertebrates and the seagrass for the subsequent analysis.

2.3. Laboratory analysis: community assessment

The total number of shoots of *N. noltii* in the samples and their biomass were quantified to assess the eelgrass bed status. In the laboratory the orthotropic rhizomes, with live leaves attached, were rinsed and separated from dead leaves and the macrozoobenthos, and successively counted to obtain the total number of shoots per sample. This led to an evaluation of the *N. noltii* density in each mesocosm. According to Buia (2003), the biomass of the orthotropic rhizomes was estimate as dry weight by weighting the rhizomes, earlier wrapped in foil, and placed in an oven at 60–80 °C for at least 24 h until it reaches a constant

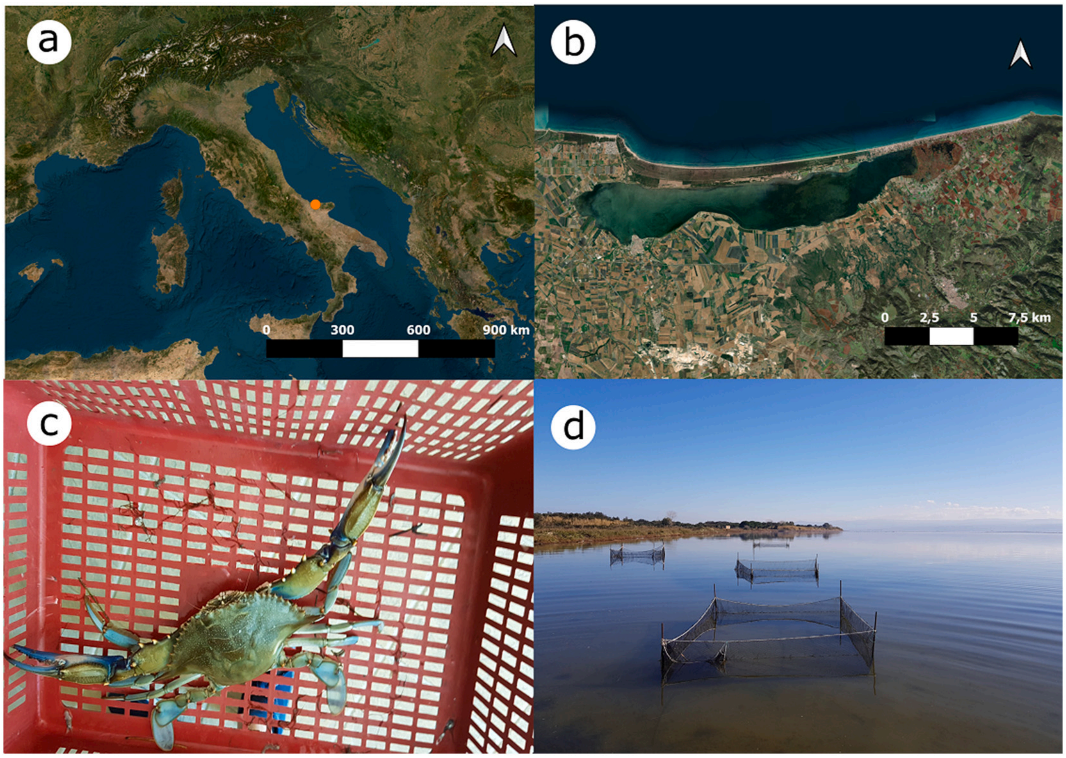

Fig. 1. a) Study site and position of the four mesocosms; b) Lesina lagoon.; c) a specimen of *C. sapidus* used in the experiment; d) detail of the four square mesocosms built on Nanozostera noltii meadows in the Lesina lagoon.

Table 1
Callinectes sapidus body measure, experimental mesocosm 1 and 2. Table shows the gender, carapace width (CW), carapace length (CL) and carapace weight (CWW).

Gender	CW (mm)	CL (mm)	CWW (g)
F	175.00	70.00	223.20
F	160.00	68.00	196.00
F	155.00	70.00	177.00
M	151.00	60.00	170.80
M	115.00	55.00	99.80
M	115.00	55.00	75.00

weight. For the analysis of macrozoobenthic assemblages, samples were sorted separating all benthic organisms from the sediment and from the seagrass leaves. Then, each organism was identified at family level, counted and preserved in a labelled Eppendorf with a solution of 70 % alcohol. Finally, the biomass of macrobenthos, aggregated at class/ phylum level, was estimated as wet weight.

2.4. Data analysis

Data about orthotropic rhizomes, macrozoobenthic biomass and density of shoots of *N. noltii* and benthic fauna were used as response variables to assess the impact caused by the presence of the *C. sapidus*. To verify if the impacted ecosystem is different from the original one, a nested analysis of variance (ANOVA) was performed, using the software R to test for differences in: 1) biomass and abundance of main invertebrate taxa (i.e., Mollusca, Polychaeta, and Crustacea), 2) the total abundance and biomass of macrozoobenthos, and 3) the number and biomass of orthotropic rhizomes. In all cases, the design for the analysis included two factors: Treatment (Tr, two levels, presence and absence of *C. sapidus*, fixed) and Mesocosm (Me, (Tr) two levels, control and experimental, random, nested in Tr).

2.5. Natural capital and ecosystem functions assessment

The investigated lagoon system is characterized by a stock of natural resources that constitutes the natural capital and provides functions and ecological services, required to support life and generate well-being. To assess the value of natural capital and ecosystem functions of the investigated system and to assess the effect of *C. sapidus* introduction, the emergy analysis was applied.

This method, introduced by H.T Odum (1988, 1996), represents a "donor side" approach to measure natural capital and ecosystem functions value. The estimate is realized by assessing the costs of capital and functions production and maintenance in terms of biophysical flows used to support their generation and functioning (Ulgiati et al., 2011).

In this method, all inputs supporting the system are accounted for in terms of their solar emergy, defined as the total amount of solar energy, directly or indirectly, required to make a given product or to support a process, a territory or a population (Paoli et al., 2018), and measured as solar equivalent Joules (sej) (Odum, 1996). Therefore, the more energy is embodied in generating natural resources and ecosystem functions, the greater is their value (Odum, 1988, 1996), since higher was the cost bearded by the nature to maintain them.

The conversion of inputs flows to solar energy is done through a conversion factor named Unit Emergy Value (UEV): the equivalent solar energy needed to obtain a unit of a certain product. UEV unit of measure is sej/unit (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 corresponds the greater the environmental cost to produce it (Brown and Ulgiati, 1997; Franzese et al., 2009). When the UEV is expressed in sej J^{-1} is named transformity. The transformity is a quality and efficiency indicator, indeed high transformities characterize complex processes and high-quality products. The outcomes of an emergy assessment in sej can be translated into currency equivalents values using the emergy-to-money ratio (EMR) (Lou and Ulgiati, 2013). EMR represents the average amount of emergy needed to generate one unit of money in the national economy (Odum, 1996). In this way the importance of natural capital and ecosystem functions could be better understood by policy makers and other stakeholders allowing an effective communication in socio-economic contexts (Turcato et al., 2015; Vassallo et al., 2021). To assess the value of natural capital and ecosystem functions of Lesina lagoon, emergy analysis was applied following the procedure described by Vassallo et al. (2017) and Paoli et al. (2018, 2022).

The biophysical value of resources stock stored in living structures of the system is a proxy of natural capital, whereas the ecosystem functions are measured as annual flow of resources supporting the system (Paoli et al., 2018; Vassallo et al., 2021). Natural capital evaluation is based on the identification of the main benthic trophic groups composing the food web of the studied ecosystem (namely lagoon ecosystem in this study). Once trophic groups were identified, their biomasses were assessed. The benthic biomasses data were obtained by laboratory analysis and transformed in gC/m^2 (the amount of carbon contained in the organisms). Biomasses originate through food network, starting from photosynthesis: all inputs required to initiate and keep going the photosynthetic process must be then assessed (i.e., nutrients and natural resources). The amount of nutrients (carbon, nitrogen and phosphorus) stored in the primary biomass together with the flows of natural resources (i.e., solar radiation, wind, chemical energy of rain, geothermal flow and freshwater) involved in the process of primary biomass accumulation were calculated by means of the formulas expressed in Table 2. Similarly, the flows of nutrients and natural resources exploited on a yearly base by the biomass itself were accounted to estimate the ecosystem functions (Paoli et al., 2018). Formulas for functions assessment are similar but referred to a yearly basis. For the sake of clarity, the results of the experimental mesocosms are reported both considering and excluding the contribution due to the blue crab. This means that in the first case the community performances are assessed considering the biomass of the crab while in the second this biomass is removed from calculations. Finally, the assessment of the ecosystem functions made also possible the assessment of the system's self-sufficiency (Paoli et al., 2018). This is made comparing the intensity of flows consumed by the system with the flows generated by the system itself: accordingly, a system is defined in surplus when available flows are greater than exploited (time of stock formation is lower than one year) and in deficit when the system is expected to entirely exploit the internal flows and it gets missing resources from other, external systems.

All these inputs have been then converted into emergy units by using specific UEVs (Odum, 1996), reported in Table 3 and finally added up to obtain the total emergy value of the system.

The obtained biophysical values have been then converted into monetary terms applying the EMR, here corresponding to 9.60E+11 sej/€ (Pereira et al., 2013). Monetary equivalents of biophysical values have been expressed in emergy-euros (em€).

Table 2
Formulas for the calculation of nutrients and natural resources flows that support the natural capital generation.

Items	Formula	Unit	References
Carbon	Benthic biomass	g	This work
Nitrogen	Benthic biomass·7/41	g	This work
Phosphorus	Benthic biomass/41	g	This work
Solar radiation	Annual solar radiation per unit area area·(1-albedo)·area·time for stocks formation	J	This work
Rain (chemical energy)	Annual rainfall·Gibbs free energy·water density·area·time for stocks formation	J	Odum (1996)
Wind	Air density·drag coeff.·(wind speed·geostrophic wind velocity)^3·area·seconds per year·time for stocks formation	J	Odum (1996)
Geothermal heat	Area·geothermal flux·time for stocks formation	J	Odum (2000)
Fresh water	Annual fresh water·Gibbs free energy·water density·area·time for stocks formation	J	Odum et al. (2000)

Table 3
UEVs employed for emergy analysis based on 15.20E+24 sej/year emergy baseline (Brown and Ulgiati, 2010).

Items	UEV	References
Carbon	1.02E+08 sej/g	Campbell and Tilley (2014)
Nitrogen	7.40E+09 sej/g	Odum (1996)
Phosphorus	2.86E+10 sej/g	Odum (1996)
Solar radiation	1.00E+00 sej/J	Odum (1996)
Rain (chemical energy)	2.93E+04 sej/J	Odum (1996)
Wind	2.41E+03 sej/J	Odum (1996)
Geothermal heat	5.53E+04 sej/J	Odum (1996)
Fresh water	7.81E+04 sej/J	Odum et al. (2000)

2.6. *Impact of Callinectes sapidus on local economy*

In recent decades, community participation has acquired a crucial role in the context of environmental management. This means that, apart from the results gathered from the analytical studies, social and cultural values, economic realities and political factors are also important (Gutrich et al., 2005). For this reason, human perception is a key factor that needs to be considered during the decision-making process (Petrosillo et al., 2010). To assess the damage caused by the presence of the Atlantic blue crab on local economy, data were collected by means of questionnaires administered to a sample of 20 among the 70 fishermen working in Lesina lagoon, through face-to-face interviews from April to August 2018. Each interview lasted between 20 and 30 min and each question was read to interviewees by interviewers who recorded the answer. Questions were structured to collect data on the fisherman's perception and awareness about the damaged caused by the presence of *C. sapidus* in the lagoon ecosystem, and to estimate the economic loss due to blue crab invasion. The questionnaires were articulated in three main sections:

1. Characterization of fishing activity in Lesina lagoon: hours and workdays, main species withdrawn in the lagoon;
2. Fishermen's knowledge about *C. sapidus*: where is it from, how it reached the lagoon and economic value;
3. Damage caused by *C. sapidus*: damage on ecosystem and on human activities, decrease of hours and days of work after the invasion.

3. Results

3.1. *Community assessment*

ANOVA did not detect a significant effect of the presence of *Callinectes sapidus* on the biomass of *Nanozostera noltii* beds (Table 4), although inspection of the graph in Fig. 2 suggests a reduction of biomass in treated mesocosms. In contrast, ANOVA detected a significant decline in the shoot's density of seagrass in mesocosms where *C. sapidus* was added with respect to controls (Table 4).

Macrobenthic assemblages (abundance and biomass of the main taxa founded are reported in Appendix A) were dominated by Polychaeta that are the 56 % of the associated community, in particular Nereididae, followed by Mollusca (25 %), mainly belonging to Semelidae family (20 %), meanwhile Crustacea represent only a 1 % of the macrobenthic assemblage (Fig. 3). ANOVA shows that there were no significant differences between the control and the treated mesocosms (with the blue crab) 1) in the abundance and biomass of the main macrozoobenthic groups and 2) the abundance and biomass of the whole macrozoobenthic community (Table 5).

3.2. *Natural capital and ecosystem functions assessment*

The emergy system diagrams of the Lesina lagoon before and after

Table 4
Nested ANOVA results for both abundance and biomass data of orthotropic rhizomes in all the mesocosms.

	Density (n/m^2)					Biomass (g/m^2)				
	Df	SS	MS	F	P	Df	SS	MS	F	P
Tr	1	5896.000	5896.000	13.196	0.006**	1	18.330	18.250	0.290	0.605
Me(Tr)	2	1822.000	911.000	2.038	0.193	2	36.800	18.380	0.292	0.755
Residuals	8	3575.000	447.000			8	504.00	63.010		

** $P < 0.001$.

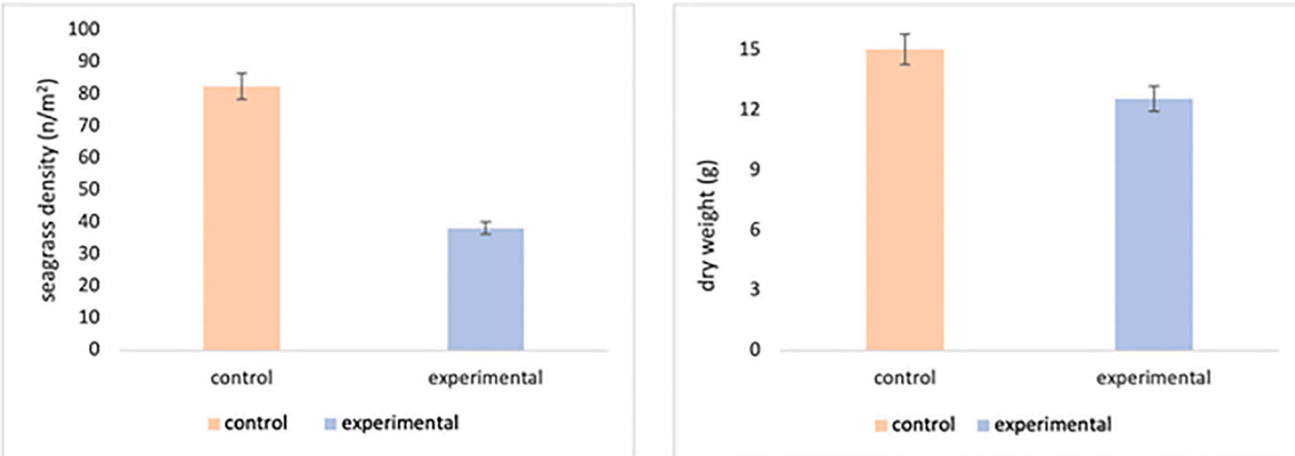

Fig. 2. *Nanozostera noltii* study. Data of abundance and biomass of orthotropic rhizomes were used to produce measures of eelgrass bed decline.

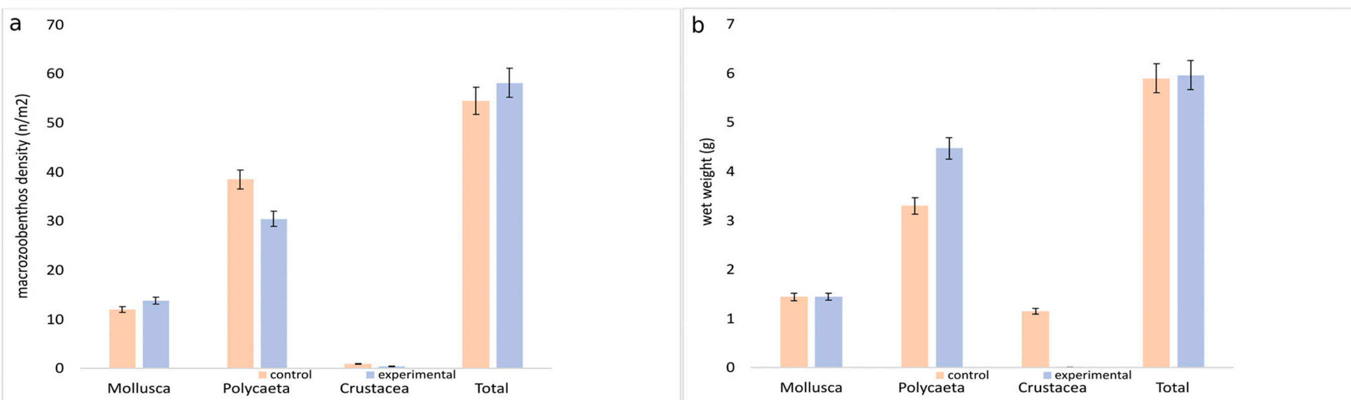

Fig. 3. *Nanozostera noltii* study. Data of abundance and biomass of orthotropic rhizomes were used to produce measures of eelgrass bed decline.

the *Callinectes sapidus* introduction are reported in Fig. 4. They show the external sources feeding the system (depicted as circles around the main box), the internal processes (within the main box) and the provided services (as output).

The emergy associated to flows of energy and matter identified in the diagrams in 3 is presented in Tables 6 and 7.

Freshwater contribution always plays a major role in the lagoon ecosystem in terms of both natural capital and yearly functions flows that were respectively: 84.72 % and 87.17 % in the control mesocosm; 62.41 % and 52.96 % in the experimental mesocosms including crab; 83.82 % and 85.58 % in the experimental ones excluding crab.

In control ecosystem, the second main contribution is due to geothermal heat (6.20 % for the natural capital and 6.38 % for the functions flows). When the experimental system is considered, the second main contribution is represented by nitrogen if the crab is included in calculations (29.96 % for natural capital and 40.84 % for functions flows) and by rain if the crab is excluded (7.23 % for natural capital and 7.41 % for functions flows).

Both natural capital and functions flows showed an increase (equal to about three times and two times respectively) after the crab invasion. On the contrary, when the experimental system is analyzed excluding the blue crab biomass, natural capital and flows decreased. Moreover, Table 8 shows the results about the system's self-sufficiency including and excluding the blue crab: in the first condition the lagoon system reported a deficit condition and the carrying capacity of the ecosystem was exceeded by about 33 %, thus exploiting resources from outside; on the contrary, excluding the blue crab presence the system was able to maintain itself and the quantity of resources exploited did not exceed the carrying capacity of the ecosystem.

The results obtained through the emergy evaluation and the corresponding conversion into monetary terms are reported in Table 9.

3.3. Indirect impact of Callinectes sapidus on local economy

Questionnaires given to local fishermen for the assessment of indirect damage caused by *C. sapidus* in the Lesina lagoon reported that all

Table 5
ANOVA results on abundance and biomass of macrozoobenthic community. The design for the analysis included two factors: Treatment (Tr, two levels, presence and absence of *C. sapidus*, fixed) and Mesocosm (Me, two levels, random, nested in Tr). Table shows degree of freedom (Df), sum of squares (SS), mean of squares (MS), f-value (F) and *p*-value (P).

	Abundance (n/m^2)					Biomass (g/m^2)				
	Df	SS	MS	F	P	Df	SS	MS	F	P
Mollusca										
Tr	1	10.100	10.100	0.200	0.700	1	4.100	4.100	1.900	0.200
MesocosmM(Tr)	2	206.800	103.400	1.900	0.200	2	13.900	6.900	3.100	0.100
Residuals	8	428.000	53.500			8	13.900	2.200		
Polychaeta										
Tr	1	192.000	192.000	1.300	0.300	1	0.000	0.000	0.000	1.000
Me(Tr)	2	40.300	20.200	0.100	0.900	2	0.200	0.100	0.100	0.600
Residuals	8	1210.700	151.300			8	1.300	0.200		
Crustacea										
Tr	1	0.750	0.800	0.500	0.500	1	3.900	3.900	0.900	0.300
Me(Tr)	2	2.800	1.400	0.900	0.400	2	7.900	3.900	1.000	0.400
Residuals	8	12.700	1.600			8	3.900	3.900		
Total										
Tr	1	40.300	40.300	0.200	0.700	1	0.000	0.000	0.000	0.900
Me(Tr)	2	365.700	182.800	0.800	0.500	2	14.100	7.000	1.400	0.300
Residuals	8	1826.700	228.330			8	40.700	5.100		

fishermen consistently catch eel (*Anguilla anguilla*) and sea bream (*Sparus aurata*), followed by the big-scale sand smelt (*Atherina boyeri*) (95 % of fishermen) and the sea bass (*Dicentrarchus labrax*) (75 % of fishermen) (Fig. 5). Instead, blue crab is caught by only the 25 % of the anglers. The time spent working by the anglers decreased by about 30 % after the invasion of *C. sapidus*. Questions about the knowledge of the blue crab and its origin highlighted that only six fishermen, over the interviewed twenty, know where the blue crab is from and how it reached Lesina lagoon. Nonetheless, many of them declared to be aware of the possible damage caused by *C. sapidus* to the lagoon ecosystem. Indeed, thirteen over twenty anglers claimed that, after the invasion of the blue crab, other fish species declined because of the aggressive behavior of the crab. In addition, for the 75 % of the fishermen the major damage imposed by blue crab is on the fishing equipment. Moreover, 45 % of the fishermen said that, after the invasion, the catches decreased too. Using the data obtained from the questionnaires and ascribing sample results to entire fishermen population operating in the lagoon, it was possible to estimate the invasion of *C. sapidus* in Lesina lagoon led to an income decrease of about the 30 %, that could be express in a total economic loss equal to about 200,000 € per year (Fig. 6).

4. Discussion

4.1. Community assessment

ANOVA results showed that there was a significant change regarding the abundance of the *Nanozostera noltii* seagrass rhizome in the experimental cages (with the blue crab). This is because the crab, with its sifting feeding strategy focused on the consumption of epiphytic invertebrates on seagrass leaves, could have a potential role in the decline of the seagrass (Kampouris et al., 2019). On the long term this behavior might have negative effects on the system functioning and on the *Callinectes sapidus* population itself due to the habitat loss. Seagrass meadows represent a potential nursery and feeding area for *C. sapidus*, offering a suitable habitat especially for the early blue crab life stages (post-larvae stages) (Read, 2011; Bilkovic et al., 2021). Further research should be performed after longer period.

The benthos compartment is a major sub-system within the marine system and whose structure and composition represent a reliable indicator of the biological and environmental status (Fabiano et al., 2004; Paoli et al., 2016). In particular, the presence of bivalves of the Semelidae family in the experimental mesocosms highlights a good environmental status: these species are totally sedentary and then more sensitive to disturbances (Cilenti et al., 2002). The results of the experimental manipulation, aiming to assess the ecological impact derived from the invasion of the blue crab, showed that there are no significant differences in the whole macrozoobenthic community between the control mesocosms and the experimental one, regarding both abundance and biomass data. This was confirmed by the analysis of variance (ANOVA) where biomass and abundance of the main invertebrate groups (i.e., Mollusca, Polychaeta and Crustacea) were used as response variable dependent by the presence of the blue crab. This is somehow unexpected because the *C. sapidus* invasion is usually assumed to have impact on the abundance of organisms in the receiving system even if a general lack of ecological information may be the cause of an incorrect interpretation (Mancinelli et al., 2017a). Furthermore, a possible future improvement of the assessment might consider the biomass of detrital material and to carry out the field experiment on multiple seasons in order to assess variability that could be due to the *C. sapidus* feeding on *Zostera* seeds as already demonstrated (Fishman and Orth, 1996).

4.2. Natural capital and environmental flows assessment

The European Union, with a dedicated action under the EU Biodiversity Strategy to 2020 (COM/2011/0244), calls Member States to 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 natural capital stocks and environmental flows (Vassallo et al., 2007). For these reasons, in this study, a biophysical approach for the assessment of the natural capital and the ecosystem functions of the system was applied to quantify the effects due to the blue crab colonization of a Mediterranean coastal system. Both natural capital and ecosystem functions increased in the mesocosms impacted by the introduction of *C sapidus*. This is caused by the biomass increase due to the blue crab and to its complexity (in terms of energy requirement) characterized by a higher trophic level than other benthic organisms. In fact, if the experimental system is analyzed: 1) natural capital is more than three times greater when the contribution of the crab is considered in comparison with values excluding crab 2) functions value is more than two times greater when the contribution of the crab is considered in comparison with values excluding crab 3) both stock and flows values become very similar to the control system when the crab biomass is excluded from calculations. Instead, both considering the control system and the experimental system without the blue crab it is evident a natural capital and flows decrease, highlighting the burden suffered by the system to support the

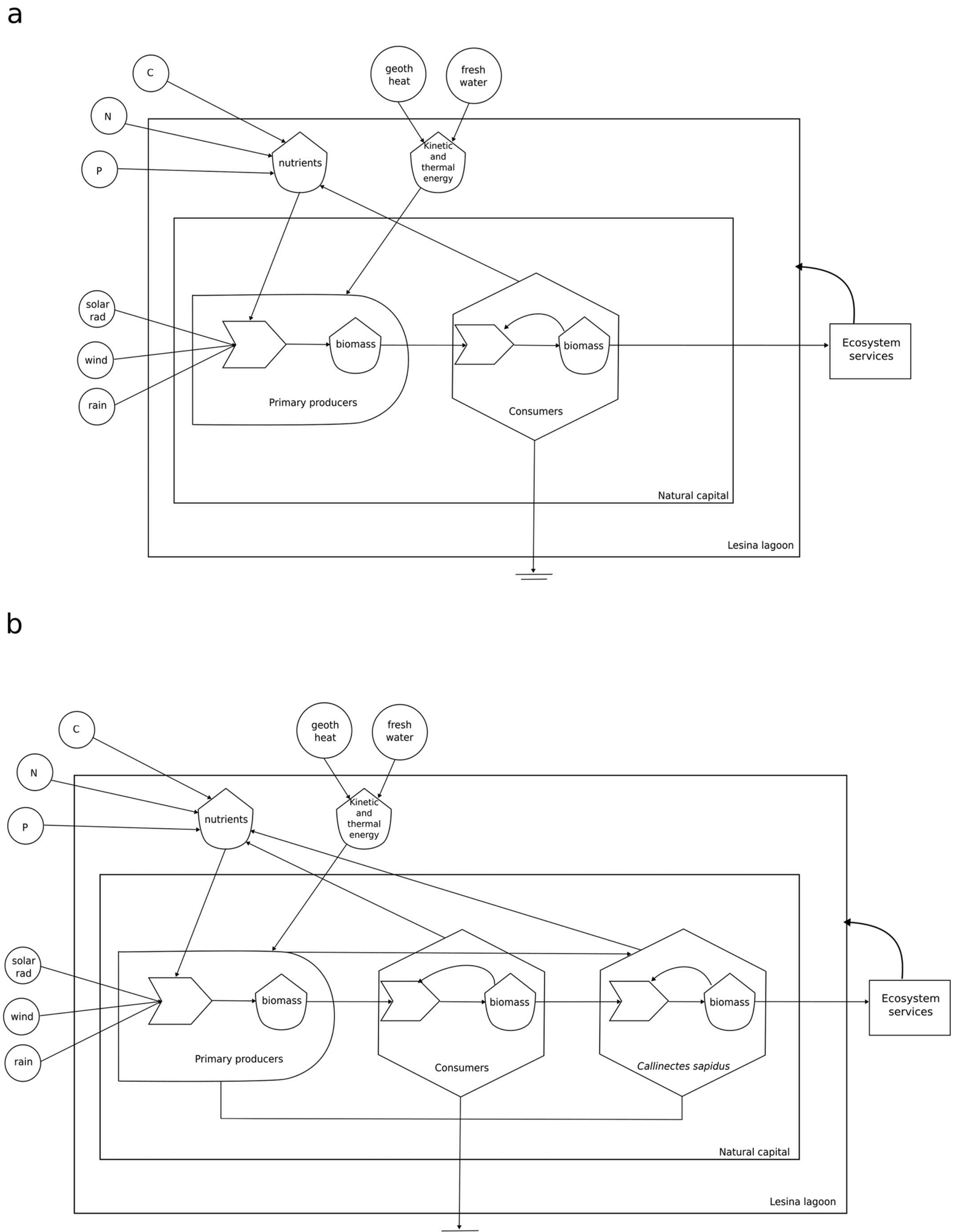

Fig. 4. Density and abundance of the main macrozoobenthic community groups associated to Nanozostera Noltii in Lesina Lagoon.

Table 6
Conversion in emergy units of the flows required to create the natural capital stored in the Lesina lagoon. UEVs are reported in Table 3.

Input	Quantity				Emergy (sej)		
	Unit of measure	Control	Experimental (considering crab)	Experimental (excluding crab)	Control	Experimental (considering crab)	Experimental (excluding crab)
Carbon	g/m^2	2.24E+01	4.60E+02	1.26E+01	2.29E+09	4.71E+10	1.29E+09
Nitrogen	g/m^2	3.83E+00	7.86E+01	2.15E+00	2.83E+10	5.82E+11	1.59E+10
Phosphorus	g/m^2	5.47E-01	1.12E+01	3.08E-01	1.57E+10	3.22E+11	8.81E+09
Solar radiation	J/m^2	6.30E+08	1.56E+09	6.10E+08	6.30E+08	1.56E+09	6.10E+08
Rain	J/m^2	7.33E+05	1.82E+06	1.39E+06	2.15E+10	5.33E+10	4.08E+10
Wind	J/m^2	9.92E+06	2.46E+07	9.62E+06	2.39E+10	5.95E+10	2.32E+10
Geothermal heat	J/m^2	6.25E+06	1.55E+07	6.26E+05	3.57E+10	8.87E+10	3.46E+10
Fresh water	J/m^2	6.46E+05	1.60E+06	6.06E+06	4.88E+11	1.21E+12	4.73E+11
Total					5.76E+11	1.94E+12	5.64E+11

Table 7
Conversion in emergy units of the functions flows yearly exploited in the Lesina lagoon.

Input	Quantity				Emergy (sej/year)		
	Unit of measure	Control	Experimental (considering crab)	Experimental (excluding crab)	Control	Experimental (considering crab)	Experimental (excluding crab)
Carbon	g/year/m^2	2.55E+01	8.73E+02	8.90E+00	2.61E+09	8.93E+10	9.10E+08
Nitrogen	g/year/m^2	4.35E+00	1.49E+02	1.52E+00	3.22E+10	1.10E+12	1.12E+10
Phosphorus	g/year/m^2	6.22E-01	2.13E+01	2.17E-01	1.78E+10	6.10E+11	6.21E+09
Solar radiation	J/year/m^2	1.38E+09	1.85E+09	1.38E+09	1.38E+09	1.85E+09	1.38E+09
Rain	J/year/m^2	1.61E+06	2.15E+06	3.16E+06	4.72E+10	6.30E+10	9.26E+10
Wind	J/year/m^2	1.93E+06	2.57E+06	1.93E+06	4.65E+09	6.20E+09	4.65E+09
Geothermal heat	J/year/m^2	1.42E+06	1.89E+06	1.42E+06	7.85E+10	1.05E+11	7.85E+10
Fresh water	J/year/m^2	1.37E+07	1.83E+07	1.37E+07	1.07E+12	1.43E+12	1.07E+12
Total					1.23E+12	2.70E+12	1.25E+12

Table 8
Results about the lagoon system's self-sufficiency.

	Unit of measure	Control	Experimental (considering crab)	Experimental (excluding crab)
Surface exceeding the ecosystem capacity	m^2	0.00	0.33	0.00
Total surface needed to maintain the lagoon system	m^2	1.00	1.33	1.00
Lagoon system condition	–	Surplus	Deficit	Surplus

Table 9
Natural capital and flows values expressed in biophysical (sej/m^2) and monetary terms (em€/m^2) before and after the blue crab insertion.

	Control	Experimental		Unit of measure
		Considering crab	Excluding crab	
Natural capital stock	5.76E+11	1.94E+12	5.64E+11	sej/m^2
	6.00E-01	2.02E+00	5.88E-01	em€/m^2
Functions flows	1.28E+12	2.70E+12	1.25E+12	sej/m^2 year
	1.33E+00	2.81E+00	1.31E+00	em€/m^2 year

invasion. In other terms, the introduction of a non-indigenous invasive species asks for a toll to the receiving system but plays a pivotal role increasing the system's ability to convey, store and exchange energy. This might be read as a manifestation of the maximum empower principle theorized by Odum in its early research (Odum and Pinkerton, 1955; Odum, 1996). This is an interpretation of the general functioning of self-organizing systems (especially biological systems) far from the equilibrium. Formerly the principle was proposed by Lotka in the early 1920s (maximum power principle - Lotka, 1922), and it states that self-organizing systems capture and use energy to develop network designs that maximize the energy flux through a system that is compatible with its environment, and the systems prevailing on the long run are those that maximize power (Odum and Pinkerton, 1955; Odum, 1988, 1995, 1996; Cai et al., 2004; Hall, 2004; DeLong, 2008). Lotka (1922, 1925) defined the maximum power principle as the fourth law of thermodynamics that constrains and guides the self-organization of open systems (Odum, 1995).

From this perspective, the introduction of a non-indigenous species is expected to be successful (invasive) if it can maximize the flow of energy maintaining the system. It is the case of the blue crab in the Lesina lagoon, that had triggered an increase of the natural capital and ecosystem functions. The experimental mesocosms are young ecosystems: ecosystems evolve through time following a strategy of development (succession). If, according to the "fourth law" the maximum empower principle is assumed to drive succession, self-organization will evolve into structures more and more able to utilize energy in the new condition. Holling (1986) depicted the ecosystems developmental behavior drawing a lazy eight figure eight characterized by four primary ecological states: 1) resources exploitation 2) resources conservation 3) creative destruction of stored resources 4) recharge of available resource energy and material to build another ecosystem and start a new cycle. Odum (1999) showed that these four stages produce a pattern of resources cycling. Succession is then a pulsing than a linear process. When a pulsing cycle has been established, it occurs in all levels of nature hierarchical organization: if a system is maximizing empower this means that its subsystems are maximizing resources use alike. A level of larger organization is then maintained by the pulsing of smaller scale subsystems. A sudden variation in energy sources intensity (like blue crab introduction) is then reflected at all hierarchical levels, even if, probably, with less strength at smaller scale (Campbell, 2000). The analyzed

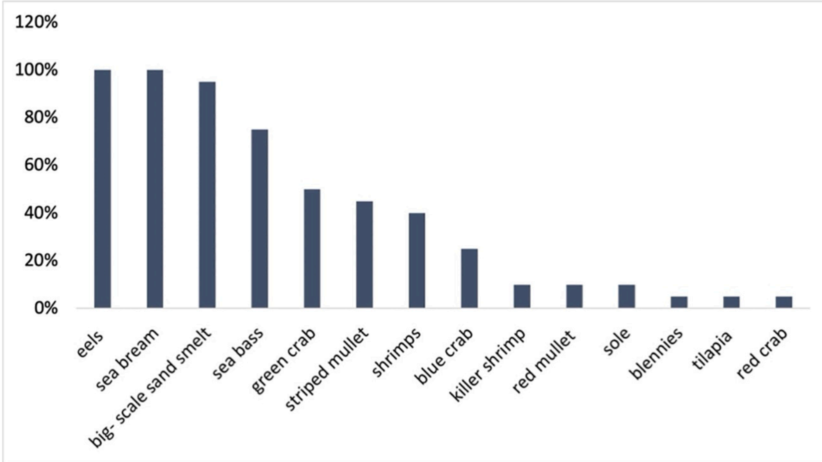

Fig. 5. System diagram of Lesina lagoon; respectively without (a) and with (b) the presence of the blue crab.

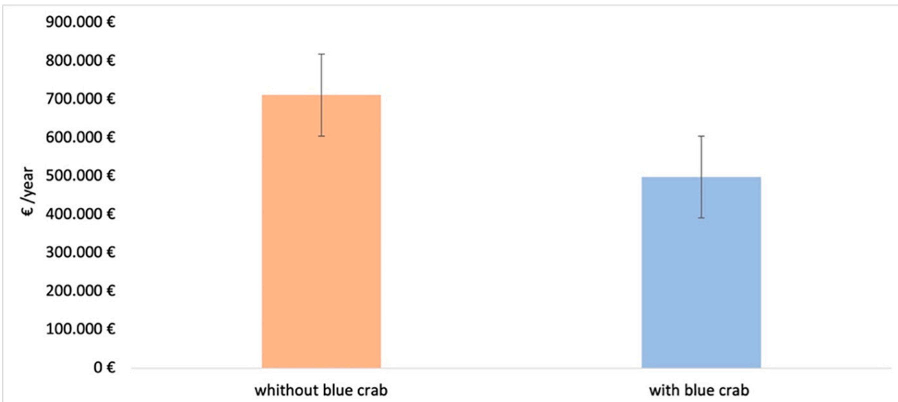

Fig. 6. Main fish species, expressed as percentage, fished in Lesina lagoon.

system, namely experimental mesocosm, perfectly fits this pattern, with greater changes shown at higher level than at lower ones. Currently it is not possible to assess the development stage of the system and other potential modifications could happen. This evaluation would require an indefinite, probably very long, period of time and will be the object of future researches.

As final appraisal it can be highlighted that the increased emergy budget due to the invasion resulted in a deficit condition of the system, in fact, the natural ecosystem functions maintained in the lagoon system require resources not locally available and yielded in external systems (Paoli et al., 2018). This might be dependent on the very high density of blue crab forced in the mesocosms, but it provides an indication of the limits of the system to support a new, energy demanding species whose development must cope with local resources availability.

4.3. *Effect on the local fisheries*

Questionnaires survey is nowadays a powerful tool for investigating the distribution and for gathering key information about stakeholder's knowledge and perception. According with results, after the invasion of the blue crab, the economy of the lagoon seemed to suffer a great damage. Many fishermen declared that the fish available to be caught in the lagoon decreased of about 45 % after the invasion of the crab. Such findings confirmed what occurred in other areas of the Mediterranean Sea where blue crab populations have reached high abundances and has led to considerable negative effects on fishing activities (Mancinelli et al., 2017a). This could be correlated to the predatory behavior of the blue crab actively feeding on economically important fish species, like the Mediterranean seabream and seabass and flatfish, even when they are trapped in the net, prawns or mussel in farming areas (Kampouris et al., 2019). A small fraction of fishermen also claimed that, after the invasion of the blue crab, the hours of work per day increased of about 30 % to fix the damaged equipment. With its strong claws, *C. sapidus* can easily cut the mesh of deployed nets, highlighting that the nets used in the lagoon are not suitable for the blue crab in comparison to the effectiveness of the wire traps used in native counties (Glamuzina et al., 2021). Also, the blue crab fishing has not developed in the lagoon probably because of the low demand and low price (about 3 €/kg) of this species in the local market. On the contrary the blue crab in its native country is considered a valuable seafood and supports an important fishery (Mancinelli et al., 2017b). Indeed, it represents the most important fishery in Chesapeake Bay, providing livelihood and incomes for more fishermen that any other species (EBFM report, Green, 2012). The analysis of questionnaires suggested that there is not enough knowledge about the origin of the *C. sapidus* and its potential as seafood. Management actions tailored to promote the exploitation of the blue crab and improving fishing tools will be therefore essential to increase the resilience of the socio-economic system to the invasion and to control *C. sapidus* populations in the lagoon.

5. Conclusion and future directions

In its native geographic range, *Callinectes sapidus* is considered a valuable seafood, providing livelihood and more incomes for fishermen that any other species (Mancinelli et al., 2017b). On the contrary in the areas of recent invasion it is consider a treat and a problem to be solved. In this study, the statistical results, where data about the abundance and biomass of the macrozoobenthic assemblage and the orthotropic rhizomes were used as response variables to evaluate the ecological impact derived from the presence of *C. sapidus* (considered as explanatory variables), revealed no significant differences between the control and experimental mesocosms for the macrozoobenthic assemblage, but highlighted a significant change in the abundance of the seagrass rhizomes in the experimental mesocosms. Emergy analysis, which allowed to assess the value of natural capital and functions flows that characterized the investigated system, showed that both obtained values grew of about three times and two times respectively after the invasion of the blue crab in the Lesina lagoon. However, with *C. sapidus* the system resulted in deficit, that means that the primary productivity needed for maintaining this organism is yielded out form the studying system boundaries (Paoli et al., 2018). On the contrary, the questionnaires administered to the local fishermen highlighted that in Lesina lagoon *C. sapidus* is considered a problem because, with its aggressive behavior can harm other fish species of commercial value and damage the fishing equipment bringing to huge economic losses.

This work highlights the major problem caused by the presence of the blue crab in the lagoon regarding the local economy. Results of the emergy analysis show that the blue crab brings to an increase of the overall value of ecosystem. This suggests the ability of the crab to be turned into a profitable resource. Consequently, the current invasion of the blue crab could offer the possibility of identifying new policies aiming to control the crab population increase and to revert it into profits for local fishermen. For example, in his work Cilenti et al. (2015) proposed a targeted fishery of the mature female during the breeding migration to more saline water. In addition, the correct engagement of stakeholders is imperative to reach that aim. Indeed, for ensuring long-term partnership and provide valuable assets to bridge the gap between science, policy and stakeholders the increase of knowledge is essential (Rölfer et al., 2022). Moreover, promoting *C. sapidus* as valuable seafood and providing fishermen with appropriate equipment, could be the first step for identifying successful policies and management strategies.

CRediT authorship contribution statement

Laura Cannarozzi: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Chiara Paoli:** Conceptualization, Methodology, Software, Formal analysis, Writing – review & editing, Supervision. **Paolo Vassallo:** Conceptualization, Methodology, Software, Formal analysis, Writing – review & editing, Supervision. **Lucrezia Cilenti:** Conceptualization, Methodology, Software, Resources, Validation, Writing – review & editing, Supervision, Funding acquisition. **Stanislao Bevilacqua:** Formal analysis, Writing – review & editing, Visualization. **Nicola Lago:** Writing – review & editing. **Tommaso Scirocco:** Investigation. **Ilaria Rigo:** Conceptualization, Methodology, Software, Formal analysis, Visualization, Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Table A.1
Composition of the macrozoobenthic community. Abundance and biomass (wet weight): data are reported as average values of the samples from each mesocosm.

	Abundance (n/m^2)				Biomass (g/m^2)			
	Average		Standard deviation		Average		Standard deviation	
	Control	Experimental	Control	Experimental	Control	Experimental	Control	Experimental
Mollusca	4.00E+00	4.61E+00	4.95E+00	4.63E+00	1.10E+00	1.49E+00	9.71E-01	1.59E+00
Militidae	6.67E-01	5.17E+00	1.21E+00	4.79E+00	3.93E-01	2.17E+00	6.66E-01	2.06E+00
Semelidae	8.83E+00	6.67E+00	6.05E+00	5.85E+00	1.44E+00	9.56E-01	1.06E+00	1.30E+00
Cardiidae	2.50E+00	2.00E+00	1.05E+00	1.41E+00	1.46E+00	1.34E+00	8.54E-01	1.33E+00
Polychaeta	9.63E+00	7.63E+00	1.24E+01	8.93E+00	3.61E-01	3.61E-01	5.99E-01	5.30E-01
Nereidi	2.63E+01	1.97E+01	1.04E+01	5.82E+00	1.31E+00	1.22E+00	4.47E-01	2.71E-01
Harmothoe	0.00E+00	1.67E-01	0.00E+00	4.08E-01	0.00E+00	6.00E-03	0.00E+00	1.47E-02
Spionidae	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Others	1.22E+01	1.07E+01	5.56E+00	3.33E+00	1.35E-01	2.22E-01	5.17E-02	8.28E-02
Arthropoda	8.00E-01	2.73E+00	2.09E+00	5.90E+00	2.31E-01	6.37E-03	1.24E+00	1.23E-02
Idoteidae	6.67E-01	0.00E+00	1.21E+00	0.00E+00	1.58E-02	0.00E+00	2.80E-02	0.00E+00
Gnathidae	1.67E-01	5.00E-01	4.08E-01	8.37E-01	2.00E-03	1.00E-02	4.90E-03	1.82E-02
Gammaridae	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Decapoda	1.67E-01	0.00E+00	4.08E-01	0.00E+00	1.13E+00	0.00E+00	2.77E+00	0.00E+00
Chironomidae	3.00E+00	1.32E+01	4.00E+00	6.15E+00	4.17E-03	2.18E-02	5.23E-03	9.68E-03

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