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Ecosystemic health: considerations and insights on a kelp forest in the Strait of Messina (Italy)

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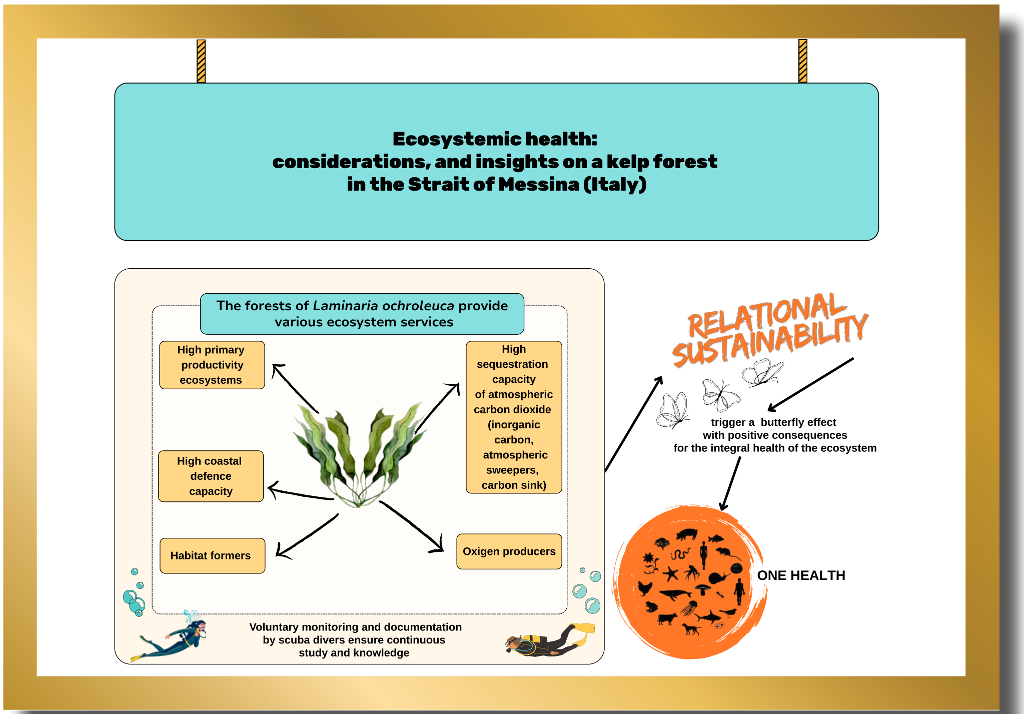
Graphical Abstract



Highlights

- *The forests of Laminaria ochroleuca provide various ecosystem services.*
- *Relational sustainability of these forests triggers the integral health of the ecosystem.*
- *Voluntary monitoring by scuba divers ensures continuous study and knowledge.*
- *Integral well-being of native Mediterranean populations is supported by underwater forests.*

Abstract

The forests of *Laminaria ochroleuca* in the Strait of Messina and the Alboran Sea (Mediterranean Sea) are true Atlantic relict species, probably dating back to the Pliocene or earlier, that have remained isolated in these areas of the Mediterranean Sea due to the presence of chemical and physical conditions similar to those of the temperate Atlantic Ocean from which they originate. They represent a priority habitat, i.e., a natural habitat to which the European Community has assigned conservation priority. These giant kelp forests are resilient and highly relational species, establishing numerous sustainable reciprocal relationships with the biotic and abiotic environment and with the Mediterranean native coastal populations, providing various ecosystem services. The reciprocal and interconnected relationships characterizing the ecosystem services of these forests trigger a domino effect (or butterfly effect), with positive consequences for the integral health of the ecosystem in which native coastal populations are among the many beneficiary species. The well-being of a species inherently reflects the integral well-being of an ecosystem. Mediterranean native coastal populations therefore should develop a new awareness and relational skills. The objectives of this scientific contribution are to provide valuable considerations and insights on the interconnections between ecosystem services of *L. ochroleuca*'s forests, preliminary data, and remarks concerning participatory science and research activities carried out by researchers and divers in the Strait of Messina, as well as the integral health of the marine environment and the native Mediterranean populations living along these shores.

Keywords: Environmental Health. Algae. Mediterranean Sea. Ecosystem. Native Coastal Populations.

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INTRODUCTION

The Mediterranean Sea represents only 0.8% of the surface area of the Global Ocean, yet it is home to about 5% of the world's marine animal biodiversity and about 16% of the world's marine plant biodiversity. There are several reasons for this high plant and animal biodiversity compared to the Global Ocean, including the presence of a variety of nutrients for herbivores, carnivores, and omnivores; the presence of typical and exclusive organisms, as well as organisms capable of tolerating small environmental variations; the overlapping of living spaces within communities; the existence of complex relationships between self-feeding organisms and organisms that are fed by others; and the presence of numerous communities of organisms living in environments with specific characteristics where they successfully reproduce.

A small sea, but with big relationships! These relationships — whether competitive, predatory, or cooperative — are essential for the sea's balance. The interconnectedness of carbon and oxygen atoms between the atmosphere and the sea links marine and terrestrial organisms, minerals, and humans. Relational sustainability, i.e., the creation of sustainable reciprocal relationships, is crucial for harmony at both Mediterranean and planetary levels.

The health of the sea and its organisms reflects the overall health of the planet and the native coastal Mediterranean populations. The "One Ocean, One Health" theme emphasizes the interconnectedness of human, animal, and environmental well-being[1]. By improving these areas collaboratively, it is possible to create a healthier planet. This holistic "One Health" vision is recognized by the Italian Ministry of Health, the European Commission, and international organizations as a key strategy to be implemented across various disciplines. This approach addresses the needs of populations, including the most vulnerable, by considering the intimate relationship between their health and the health of their living environment. It takes into account a wide range of health determinants, such as behavioral, socio-economic, cultural, and environmental factors, as well as living and working conditions. This comprehensive strategy can be applied to disease prevention, treatment and health promotion at both individual and population levels. This holistic view, together with the paradigm of relational sustainability, is demonstrated in nature by the marine and terrestrial coastal ecosystem services provided by the *L. ochroleuca* forests.

L. ochroleuca Bachelot Pylaie 1824 forests are present in the Mediterranean Sea only in the Alboran Sea and in the Strait of Messina[2]. The Laminaria of the Strait of Messina are paleo-endemic species of a biocenosis that continuously covered the seabed of the central basins of the Western Mediterranean Sea during the Neogene, when the warm-temperate currents of the Lusitano-Senegalese region were dominant. The temperate Atlantic region and in particular the Lusitanian-Senegalese area, as well as the Alboran Sea area, are the main area of these brown algae, while those in the Strait of Messina are a secondary area, to be considered a relict probably dating back to the Pliocene or even older, i.e., prior to the closure of the North and South Rifano Straits, which expanded the exchanges between the Atlantic Ocean and the Mediterranean Sea. The peculiarity of this relict area lies in the presence not of single Atlantic species, but of entire plant associations, that share the same composition and structure of those found in the Lusitano-Senegalese area in the Atlantic Ocean[2]. In the Mediterranean Sea, the resilient Laminaria of the Strait of Messina constitute facies within biocenoses that are well characterized by floristic and faunal elements in stable equilibrium with the ecological factors of the biotope that hosts them. The chorology of plants in the Mediterranean area has been strongly determined by the Alpine orogeny, by the tectonics of the still-active micro-plates, and by the climatic phenomena that caused the glaciations. In particular, the algal flora and marine angiosperms of this sea only became firmly established after the evaporitic crisis of the Messinian area in the Miocene. The obscure points in the chorology of the paleo-endemic elements are linked to the lack of palaeobotanical and sedimentological elements documenting the events between the end of the Tethys II basin and the beginning of the Oligocene basin of the Mediterranean Sea[3].

Kelp forests, which include *L. ochroleuca* forests, are habitat-forming species for a wide range of flora and fauna[4]. As habitat formers, a single kelp directly provides three distinct primary habitats: the holdfast, the stipe, and the lamina. In addition, epiphytes (primarily attached to the stipe) provide a secondary habitat for colonization[4]. At spatial scales larger than those of a single kelp plant, multiple individuals form extensive forests that provide three-dimensional habitats for a vast array of marine organisms. Rich understory assemblages of plants and animals persist beneath kelp canopies, mitigating environmental stressors and providing shelter and food[4]. *L. ochroleuca* is a brown alga found in the Strait of Messina, forming dense aggregations at depths of 40-60 meters. It creates two types of habitats: forests with stipitate individuals on rocky substrates and beds with prostrate individuals on mixed substrates[5]. Stipitate individuals have rigid structures to remain upright, while prostrate individuals cover sandy substrates. The prostrate Laminaria bed starts at about 48 meters depth and continues up to 50-52 meters. Beyond 52 meters, the prostrate bed alternates with the stipitate forest, which develops on rocky and bioconstructed elements. *L. ochroleuca* exhibits an alternation of generations, with a large asexual diploid phase (sporophyte) and a microscopic haploid dioecious phase (gametophyte).

At the Porticello site in Scylla, periods between the upstream and downstream currents allow the implantation of reproductive elements (spores and zygotes), while those with intense movement ensure their metabolism[2]. These species is perennial, and their strength lies in its great resilience, allowing for complete regrowth within one to three years[5]. In the Strait of Messina, *L. ochroleuca* is in full reproduction in the sporophytic stage in April-May: extensive sori are found on the upper third of the laciniae[2]. In late autumn, however, the fronds are shorter due to the detachment of fruiting portions. Loss of fronds from entire colonies of Laminaria may instead be attributed to grazing by herbivorous organisms[2]. *L. ochroleuca* forest stands in the Strait of Messina occurs along stretches where there is periodic mixing between the surface waters of the Tyrrhenian Sea (downstream current) and the deep waters of the Ionian Sea (upstream current). This mixing primarily prevents thermal stratification and promoting the disolution of metabolic gases. In addition, the continuous renewal of the “boundary layer” — the thin layer of water in immediate contact with the living surface of these algae — becomes thinner as current speed increases, allowing for a more intense exchange of metabolic gases and a continuous supply of new nutrients that supports considerable heterotrophic nutrition and exuberant development[2]. The Strait currents are of the pulsating type, with periodic pulsations in synchrony with the tidal phases. The expansion or retraction of the species along the European coast appears to be modulated primarily by temperature and anthropogenic disturbance, although nutrient availability is also critical to maintaining optimal physiological performance[5]. The health status of the observed specimens testifies to a clear reversal of the decades-long decline of this population in the Mediterranean Sea.

The biodiversity hosted within these giant kelp forests is proportionally greater than that of terrestrial forests[4]. Indeed, the laminae, stipes, and rhizoids of these algae provide three different types of habitats for numerous planktonic, benthic, and nektonic species. For the European Community, according to protocol SDM/3/6259 of 30 July 2003, the association to *L. ochroleuca* — Cystoseiretum usneoidis (G. Giaccone, 1972); subass. Laminarietosum ochroleucae (G. Giaccone, 1994), represents a habitat of priority interest (IV.3.1.8) and therefore a habitat with priority for conservation, whereas *L. ochroleuca* is a strictly protected species included in Annex I of the Bern Convention on the Conservation of European Wildlife and Natural Habitats. The mapping and study of these priority habitats in the Strait of Messina are mainly attributed to G. Giaccone in the 1960s[6], Drew, Mojo, and Buta in the 1970s[7,8], Di Geronimo and Giacobbe in the 1980s[9], and Zampino and Di Martino[10], Giacobbe and Ratti[11], and T. Giaccone *et al.*[5] in the 2000s.

The objectives of this scientific contribution are to describe the ecosystem services provided by *L. ochroleuca* forests to the biotic and abiotic components of the marine and terrestrial coastal ecosystems, documented in the scientific literature, in relation to the preliminary data and remarks arising from the research activity and participatory science carried out by a group of researchers together with a diving center to study the forest of *L. ochroleuca*[5] in Porticello (Scylla-Strait of Messina) during 2024 (Fig.1). The results of this study offer valuable considerations and insights with a transdisciplinary approach to the interconnections between ecosystem services and the integral health of the marine environment of the Strait of Messina and the native Mediterranean populations living along its shores.

Figure 1 - The forest of *L. ochroleuca* in Porticello (Scylla-Strait of Messina, Italy).

MATERIAL AND METHODS

The research tools used for the description, analysis, and discussion of the ecosystem services of *L. ochroleuca* are bibliographic databases (containing only the bibliographic reference, sometimes a short summary of the content - abstract - or a link to the full text of the publication), full-text databases (containing not only the bibliographic reference but also the full text of the publication) and citation databases (containing not only the bibliographic reference but also the citation list, i.e., references to other publications that cite the publication, such as Scopus or Web of Science). Literature data were also searched and downloaded from search engines and open access archives or networking platforms such as ResearchGate and LinkedIn. This search strategy consists of using all known search terms (author's name, title words, and keywords in general), expanding, redefining, or filtering them based on suggestions made by the tools that have been used (catalogues / discovery, databases, network archives, ...).

Regarding dissemination and scientific communication, the data were taken from the participatory research and science activities that began in January 2023 and are still ongoing. As far as research activities are concerned, qualitative sampling was carried out. Four samples of *L. ochroleuca* - including two with stipitate and two with prostrate habits (four different individuals) - were collected by technical scuba divers. Apical fragments of the lamina of 4 different specimens were placed in silica gel (granules of 0.2–1 mm in diameter) for quick desiccation, for DNA extractions. One specimen was dried to make an algarium. Species identification was conducted using the taxonomic keys found in G. Giaccone (1969). Additional samples, three of hard and three of mobile substrate were also collected during the same dive in view of a preliminary qualitative analysis (sedimentological, morphological, and associated flora/fauna). Photographic documentation was carried out with a Canon G7X Mark II in a Nauticam housing and a Sea

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& Sea YS-D3 flash which allowed for a preliminary qualitative estimate of the associated biodiversity. Genetic analyses are currently underway, and sampling of the associated biodiversity is being planned, to be implemented using quadrats. Approximately fifty divers have participated in the documentation phase of the giant kelp forest so far, and the duration of their engagement has been during the autumn and summer months. Participatory science in this project has used photography and video as the main tools to collect data from divers. All divers had a technical diving training certification and were equipped with underwater cameras and external flashes. Social media, social networking, traditional and digital media, seminars, congresses, scientific journals and newspapers are the means used to convey the results obtained so far to both the scientific community and the general public.

RESULTS

Precious and numerous are the ecosystem services provided free of charge by the underwater forests of *L. ochroleuca* to the marine and terrestrial environments, and consequently to all plant and animal organisms, as well as to the native Mediterranean populations living along the coasts of the Strait of Messina, Morocco, Almeria and Alboran Islands: they are the concretisation of sustainable relationships and reciprocal interconnections.

The submerged forests of these giant algae are ecosystems with high primary productivity, defined as the ability of an ecosystem to produce organic carbon (in the form of glucose, i.e., sugar) from inorganic carbon found in the atmosphere (e.g. CO_2, carbon dioxide). This property is key to maintaining low levels of inorganic carbon in the air we breathe and to allowing plants to grow. They also act as atmospheric sweepers, absorbing carbon from carbon dioxide transferred from the air to seawater, and incorporating it (carbon dioxide sequestration) into organic carbon, i.e., food for other organisms (biomass). Although there are currently no data estimating the sequestration of atmospheric CO_2 or O_2 production by these submerged forests, there is no doubt about their contribution to mitigating the effects of climate change locally and improving the air quality for native Mediterranean populations living along the coastlines.

In particular, the marine environment of the Strait of Messina is a preferential CO_2 sequestration area because, in addition to being characterised by Laminaria forests, it is also influenced by upwelling currents rich in phytoplankton, whose photosynthesis partially lowers CO_2 in the surface water layers, thus facilitating the absorption of CO_2 from the atmosphere. Many phytoplankton and zooplankton organisms are composed of calcium carbonate structures that, at the end of their life cycles, are deposited on the seabed of the Strait, thus contributing to carbon stabilisation at greater depths.

The biomass of Laminaria serves as food for herbivorous fish and some invertebrates, and, through the fragmentation of laminae, for filter-feeding or detritivore organisms, which tend to dominate the volume between the rhizoids and the substrate[12]. However, the composition of the interstitial fauna is sensitive to local environmental factors such as increased turbidity[13], pollution from oil spills[14], and sewage effluents[14]. It can be assumed that these organisms take on the role of environmental indicators of coastal water health.

The habitat provided by Laminaria rhizoids is generally very complex, extensive, and temporally stable for many species. The interstitial space that is created between the hard substrate of the seabed and the rhizoid apterans offers protection to interstitial fauna from possible predators and adverse environmental conditions; in addition, it allows for the accumulation of food sources and increases the area of the substrate and, consequently, the available colonisation area[15]. The fauna associated with Laminaria rhizoids consists of mobile invertebrates, such as harpactocoid copepods, polychaetes, gastropods, and amphipods, as well as sessile fauna such as bryozoans, bivalves, and sponges[15,16,17,18,19,20,21,22,12]. In addition, these giant algae, due to their size of several metres, act as ecosystem engineers, protecting coastal environments from intense wave action: they serve as natural barriers to storm surges and other extreme events. Furthermore, their roots effectively trap and accumulate sediment[23,28], thus limiting detritus removal in highly hydrodynamic areas[12].

The flora associated with Laminaria rhizoids includes both soft-thallus taxa and calcareous-structured taxa, along with a rich microbiota complementing the macrobiota. According to G. Giaccone[6,2], *L. ochroleuca* prefers *Lithophyllum racemus*, *Lithothamnion fruticulosum*, and *Lithothamnion philippi*, while *Laminaria rodriguezii* prefers *Mesophyllum lichenoi-*

des, *Mesophyllum expansum*, and *L. philippi*[6].

Based on monitoring described in his 1969 and 1972 works, G. Giaccone states that the persistence of *L. ochroleuca* and *L. rodriguezii* forests depends on the persistence of these calcareous algae (Rhodophyta phylum). The chemical-physical and biological characteristics of these interspecific relationships have not yet been described but will be studied soon. The stipe can also host various organisms, including epiphytic algae, amphipods, gastropods, and other small mollusks[26]. The composition of epiphytes often varies vertically along the stipe[24] showing marked differentiation along abiotic gradients[25]. The biomass of epiphytes decreases with depth, due to light attenuation in the water column[26,27,24]. Depth, and the associated variations in light levels, also plays a role in the structuring of epiphyte communities, with distinct zonation of different epiphytic algal species along depth gradients. The lamina provides a large surface area for photosynthesis and colonisation by a range of epibionts. It has been observed, however, that heavy epiphyte loading indicate stressful conditions, such as periods of intense warming or high nutrient availability with low light[28,29,30].

The invasive bryozoan *Membranipora membranacea* has been noted as one of the few — and often the only — sessile fauna species associated with Laminaria laminae[31]. This association is likely due to the growth plan of this species, which develops non-calcareous bands of zooids believed to prevent colony cracking on a flexible substrate[32]. The richness of laminar epifauna varies greatly depending on the host species and location. The sessile epifauna of the laminae consists mainly of molluscs, gastropods, and sea urchins that feed on the algal tissue. Although the direct impacts of grazing may be relatively minor and spatially limited to the laminae surface, the indirect effects of tissue weakening may promote canopy defoliation of these algae during intense storms[33]. From the evidence and the examples of ecosystem services, it emerges that the sustainable relationships established by *L. ochroleuca* forests have, on the one hand, various connotations, including predation, competition, and cooperation-based relationships, and, on the other hand, the aim and objectives of health and well-being at the specific, sub-association, biocenosis, and — indirectly — ecosystem levels.

The presence of the forest of *L. ochroleuca* in Scylla (Strait of Messina) was first described by G. Giaccone during his photographic survey carried out in 1969. The re-discovery of the *L. ochroleuca* forest (Fig.2), between 48 and 55 meters deep, in January 2023 by the Scilla Diving Center, represents not only an extraordinary discovery on the Calabrian side of the Strait of Messina (Fig.3), but also a confirmation of the forest's permanence for more than 50 years[5].

Figure 2 - Location of the Forest of *L. ochroleuca* in Porticello (Scylla-Strait of Messina).

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The knowledge of the Strait of Messina, in depth ranges between 0 and 80 metres, by these professional divers goes back many decades and has allowed them to start a valuable collaboration with a team of researchers of the Sicily Marine Centre, the Genoa Marine Centre (Stazione Zoologica A. Dohrn), and the University of Palermo in the aim to produce new scientific knowledge, promote conservation actions, and adopt sustainable lifestyles. The participatory science activity carried out by this team to study the forest of *L. ochroleuca* in Porticello (Scylla-Strait of Messina) started in May 2023 and is still in progress today.

Figure 3 - The forest of *L. ochroleuca* in Porticello (Scylla-Strait of Messina, Italy).

Citizen science or participatory science is a flexible concept that can be adapted and applied to different situations and disciplines. The objective of these scientific research and participatory science activities is to update the scientific studies of this *L. ochroleuca* forest 50 years after it was first reported, in terms of taxonomic update, morphological description, presence/absence of evidence of climate change at a local level, sedimentological characterisation of the seabed, description of the associated fauna and flora, measurement of ecosystem services, and drafting of a document to propose the establishment of protected areas at this site. To answer these research questions, the collaboration with the professionals of the Scilla Diving Center and the citizens who carry out diving activities at their centre was and is of considerable importance and concerns logistical and technical support during the documentation and sampling phases, and during the scientific communication of the results through local events, articles in magazines, newspapers, and social media posts. Collaboration with the Scilla Diving Center and non-professional divers is crucial for logistical and technical support during documentation, sampling, and scientific communication. Since may 2023, the project has published a scientific article, which has been presented at international conferences, has given interviews, and has participated in environmental education events. Ongoing voluntary monitoring and documentation by non-professional divers ensure continuous study and knowledge of the *L. ochroleuca* forest.

DISCUSSION

Threats and Butterfly Effect

Today, *L. ochroleuca* forests in the Mediterranean Sea are threatened mainly by the following factors: local rise in seawater temperatures and changes in pH (widespread heat waves in the underwater environment); variations in salinity of seawater depending on the input of rivers and streams but also due to the intensity of evaporation; cloudiness of the water with consequent reduction of light penetration due to spills in the sea; various sources of pollution and changes in the direction and intensity of currents due to the construction of maritime facilities; the presence of herbivorous alien species that sever the laminae; invasive animals that live close to them and encrust, thus weakening the laminae; and invasive algae that live on the surface of the laminae, thus reducing the surface area suitable for photosynthesis. In the Scylla area, the main threats to the forest of *L. ochroleuca* are related to heat waves in the underwater environment, which in recent years have already produced devastating effects on the gorgonian forests; for example, the change in salinity of seawater due to the presence of streams (Favazzina Stream, Oliveto Stream, Livorno Stream, Monacena Stream ...), water turbidity resulting in reduced light penetration due to spills into the sea (mainly torrential and urban discharges); illegal trawling (causing mechanical destruction, water cloudiness, and dispersal of alien species) and, finally, due to the presence of encrusting epiphytic bryozoan species (reduction of surface area suitable for photosynthesis). The butterfly effect illustrates to what extent everything on our planet is interconnected. It shows that threats to the marine environment or the suffering of certain species can eventually impact the lives of native coastal populations in the Mediterranean Sea. As a cornerstone of chaos theory, it suggests that even a tiny change in a system's initial state can lead to significant alterations in the entire system. This concept is often explained by the idea that a butterfly flapping its wings in the Amazon region can set off a chain reaction, ultimately causing a hurricane in Florida. Such interconnected relationships can have both positive and negative consequences affecting personal and global dimensions. The butterfly effect can trigger a domino effect, where seemingly unrelated events form a chain leading to significant outcomes. Africa, despite contributing the least to climate change, suffers the most from its effects. The Mediterranean area becomes a climate frontier zone, with many environmental migrants crossing it. Even our smallest daily action can contribute to phenomena with substantial social and environmental impacts. Humanity is both the problem and the solution.

Relationship, reciprocity, and interconnection

The standard view, i.e., that the crisis that triggered climate change is only originating from abusing anthropic actions, must be overcome and it is necessary to look at the problem from a different perspective, the one that identifies the real cause of climate change in humanity's inability to establish ties and/or connections with the environment, or in humanity's ability to (very often) create abusing and deviant ties and connections with the environment. The problem of climate change, therefore, is a relational problem: it is a real relational crisis between humanity and the planet, between humanity and the sea. It is therefore more than just an environmental crisis; it is a socio-environmental crisis. Its cure is an issue about relationship, reciprocity, and interconnection, an issue that connects humanity to the sea, that sea where life was born on our planet over 4 billion years ago. High Biodiversity thus becomes synonymous with a great variety of relationships: relationships of predation, competition, and cooperation, or rather relationships of reciprocity possessing an added value of sustainability because they tend towards the pursuit of an integral state of health within a shared common ecosystem. Interspecies and intraspecies relationships that are established beyond chorological affinity and/or biogeographical history; relationships with abiotic elements and with the chemical-physical parameters that characterise the ecosystem: all these relationships build the integral health of the shared common ecosystem - integral health at both an individual and collective level. Defining a particular plant or animal in an ecosystem as a keystone species is one way to help the public opinion understand how important one species can be for the survival of many others. A keystone species is an organism that helps holding the system together. Without keystone species, ecosystems would be very different. Some ecosystems might not be able to adapt to environmental changes if their keystone species disappeared. This could spell the end of the ecosystem, or it could allow an invasive species to take over and drastically shift the ecosystem into a new direction. *L. ochroleuca* has the role of keystone and leads species in the subassociation Laminarietosum ochroleucae (G. Giaccone 1994) The forest of these giant brown algae assumes the role of a relational hub for the integral health of the marine biodiversity of the Strait of Messina and the Alboran Sea, but also for the integral health of the populations of the coastal territories.

The "One Health" approach

One can therefore think of drawing inspiration from and look at the model of relational sustainability implemented by the forests of *L. ochroleuca*, focusing on the sustainable reciprocal relationships that lead to integral wellbeing at the level of species, communities, marine populations but also native Mediterranean people living along the coasts, and propose protocols to raise awareness of the importance of the "One Health" approach; to raise awareness of the local and Mediterranean socio-environmental changes and the urgency to change the relational model between Mediterranean coastal populations and the marine environment; and to disseminate good practices and virtuous actions to mitigate existing anthropogenic impacts, which are the result of unsustainable and abusing relationships. Relational sustainability is the necessary condition for balance and harmony at Mediterranean and planetary levels. The health of the sea and its marine organisms reflects the health of the planet, and that of humanity. The holistic "One Health'" vision together with the paradigm of relational sustainability is demonstrated in nature by the relational evidence of *L. ochroleuca* forests. In fact, these giant kelp forests are sustainable relational hubs that lead to integral well-being at the level of species, communities, and marine populations, but also of abiotic elements and native Mediterranean coastal populations. The ecological skills that Mediterranean coastal native populations need to survive, but above all to live in a healthy world characterised by sustainable relationships, are related to the essential capacities of Theory U, but from a collective and shared perspective. While human intelligence resides in individuals, ecological intelligence is collective by its very nature: it is necessary to learn as a group or community to listen to oneself, to others, to what emerges from the environmental system, i.e., to observe, to suspend judgement in order to move from personal projections towards authentic scientific observation; to feel with an open mind, heart, and will; to be present and to let go of everything that is known, taken for granted, or the result of incorrect information, and contribute to creating networks of people who in turn become instruments of awareness-raising processes and good practices by conveying the new paradigm of relational sustainability. The latter is to be a prototype, on the one hand, to open up and face resistance of thought, emotion, and will, and on the other hand, to integrate thoughts, feelings, and will in the context of new applications, and finally to execute, i.e., to implement actions that bring about short, medium, and long-term environmental restoration thanks to the contribution of various networks of people[34]. To implement the 'One Health' approach in coastal communities, an immersive and interactive sea room at the future Centre of Mediterranean Cultures in Reggio Calabria should be created. This sea room would allow students to virtually experience scuba diving in the *L. ochroleuca* forest using 360° visors, thus fostering an emotional and empathetic connection with marine biodiversity. Educational workshops for students and their families would follow, with the result of promoting sustainable lifestyles. Fishing communities would also be involved to raise awareness about sustainable fishing practices and the economic benefits of protecting the juvenile fish nurseries hosted by the forest. The municipalities and coastal provinces of Sicily and Calabria could stipulate territorial pacts to counter threats to the forest, and to combat coastal building abuse, illegal waste disposal, and malfunctioning water purification systems. Local administrations, the Coast Guard, environmental and diving associations, researchers, and schools could collaborate on beach and seabed clean-ups, monitoring surveys, and participatory science projects. Divers could receive specialized training and certifications in participatory science. The key elements of this approach are co-responsibility, co-participation, and co-activation to achieve sustainability and conservation goals in coastal communities.

CONCLUSION

Future research should therefore aim to implement, on the one hand, ecological studies at a specific and interspecific level, both in the marine and in the terrestrial environment, but also to multiply and deepen studies on the relationships and interconnections between abiotic and biotic elements, in order to propose awareness-raising protocols and good practices to increase awareness in the native Mediterranean coastal populations about the socio-environmental changes taking place locally and in the Mediterranean area, and to suggest virtuous actions to mitigate existing anthropogenic impacts that are the measurable evidence of unsustainable and abusing relationships. Research and participatory science activities are still ongoing. Quantitative study to estimate the extent of the forest, the estimation of values related to carbon sequestration and oxygen production, the estimation of associated fauna and flora, the estimation of grazing and interaction with invasive alien species, trends in biodiversity or ecosystem health, etc. are still being planned and will be implemented soon. International governance regimes and institutions play an important role in addressing threats to marine ecosystems and combatting declines. Kelp forests have largely been invisible in international environmental governance regimes despite expanding and emerging scientific knowledge. If more severe declines are to be avoided, focused effort by the global community is needed[35]. In order to mitigate the threats to the forest of *L. ochroleuca*, through the establishment of protection constraints at the Mediterranean level, it is possible to propose the creation of a Specially Protected Area of Mediterranean Importance, as envisaged in the SPA/BD Protocol (Specially Protected Areas/Biological Diversity), the main implementation instrument of the 1992 Convention on Biological Diversity, with regard to the sustainable in situ management of coastal and marine biodiversity. Natural and social sciences should refine methodologies for measuring sustainability, which reflects the integral well-being of ecosystems. Mediterranean coastal populations should shift from a selfish concept of well-being to the concept of the integral wellbeing of the coastal marine environment. The human mind struggles to recognize the links between human actions and environmental impacts because it is not naturally equipped to detect less visible threats like sea overheating, changes in currents, biodiversity loss, and reduced light penetration due to spills. These anthropogenic dangers are often below the threshold of human perception, like a lighted match in a room full of light[36].

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CRediT author statement

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Declaration of competing interest

The author declares 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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