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Review

The date mussel *Lithophaga lithophaga*: Biology, ecology and the multiple impacts of its illegal fishery

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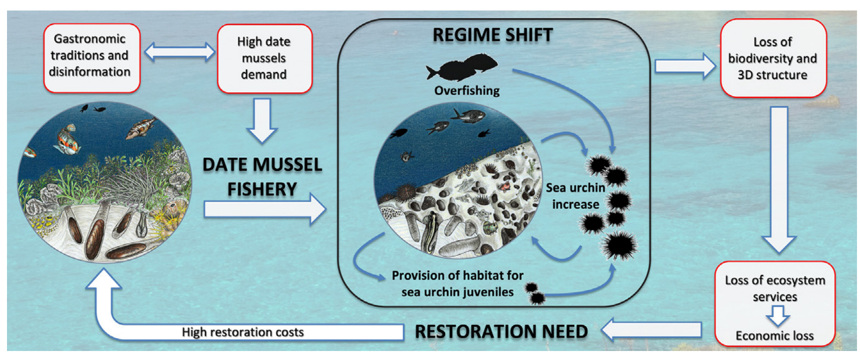
HIGHLIGHTS

- Date-mussel fishery is likely the most impacting practice on marine habitats worldwide.
- Habitat loss can be irreversible (i.e., requires >50 years).
- The active restoration of damaged date-mussel habitats can cost 1–5 KEuros m^{-2}.
- Despite the ban, date mussels are still commercialized and served in restaurants.
- Specific management and educational tools are needed to contrast this phenomenon.

GRAPHICAL ABSTRACT



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ABSTRACT

The date mussel *Lithophaga lithophaga* is an edible endolithic bivalve, protected by the EU Habitats Directive and other international agreements, living inside carbonate rocks. Its illegal harvesting is carried by breaking the rocks where the bivalve grows. The impact has cascade consequences as it causes permanent changes in the substrate characteristics, the removal of benthic species, a shift from highly complex to structurally simplified habitats. As a result, the rich biodiversity of rocky reefs turns into a biological desert, named “barren”. Along with the over exploitation of fish, this practice leads to the increase of sea urchin density and grazing pressure on habitats, hampering the resilience of the associated biodiversity and functions. This paper summarizes the information on date mussel biology, ecology, ecotoxicology, fishery and the legal framework regulating its protection. Evidence indicates that illegal harvesting is still operated and widespread along the Mediterranean and has huge costs in terms of loss of natural capital and ecosystem services, and in terms of active ecological restoration. Two case study areas (the Sorrento and Salento peninsulas) were selected to assess the economic costs of this practice. Tangible economic costs in terms of ecosystems services' loss are huge (from ca. 35,000 to more than 400,000 euros/year in 6.6 km of Sorrento and ca. 1.8 million euros/year along the 69 km of Salento). These costs are, on average, ca. 30 times lower than those of ecosystem restoration. Data mining from websites indicates that date mussels are presently commercialized in hundreds of restaurants in Greece, Balkan countries, Spain and Italy, favoured also by the lack of appropriate consumer information. This practice should be controlled and contrasted

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at local scale, enforced by national legislations, and implemented by transnational initiatives. Social campaigns are needed to increase public awareness of the serious consequences of date-mussel fishery and consumption.

Contents

1. Introduction

The illegal fishery of the date mussel *Lithophaga lithophaga* (Linnaeus, 1758) has been recognized as one of the most destructive practices for shallow rocky reefs. Indeed, fishermen must destroy the rocky substrate in order to reach and capture the bivalve (Guidetti and Boero, 2004). Yet, only fragmentary information is available on the detrimental effects over long temporal scales, spatial extension and ecological costs of the damage of this fishing practice (Fanelli et al., 1994; Gonzalez et al., 2000; Fraschetti et al., 2001). The ecological impact and long-lasting effects of date mussel harvesting have been described in several areas, especially along the Italian coast (Fanelli et al., 1994; Fraschetti et al., 2001; Guidetti et al., 2003). This practice can lead to the desertification of wide stretches of coast (Fanelli et al., 1994; Fraschetti et al., 2001) that, originally dominated by macroalgae, shift to a barren state (Bevilacqua et al., 2006). Once damaged by this illegal fishery, hard substrates can require several decades to recover (Russo and Cicogna, 1992a; Galinou-Mitsoudi and Sinis, 1995), and, at present, there is no evidence of full recovery of the habitat diversity in pre-disturbed conditions. Long-lasting shifts of degraded, alternative states have been observed worldwide in macroalgal beds, which can be replaced by barrens as a result of the overfishing of sea urchins' predators (Ling et al., 2015; Boada et al., 2017), but also in coral reefs, where corals can be replaced by macroalgal beds (Mumby et al., 2007; deYoung et al., 2008).

The date mussel *L. lithophaga* has been an appreciated delicacy since the ancient Greeks and Romans (Bianchi and Morri, 2000; Voultsiadou et al., 2010), and it is still part of the gastronomic tradition in several Mediterranean countries (Russo and Cicogna, 1991; Hrs-Brenko et al., 1991; Voultsiadou et al., 2010). Due to high demand and very high price, date mussels have always been a lucrative good in the seafood market (Fanelli et al., 1994; Fraschetti et al., 2001; FAO, 2004). Despite the ban, the date mussel's consumption occurs because of lack of awareness among consumers on the illegal trade of this species and weak law enforcement (Muscogiuri and Belmonte, 2007; Katsanevakis et al., 2011). As a result, in some Mediterranean areas harvesting and consumption of this mollusc has been, as a matter of facts, largely tolerated (FAO, 2004) or simply not perceived as harmful as it is.

Despite the increasing evidence of the importance of this phenomenon, which is still very active, an updated overview of current knowledge is still lacking. This review, along with additional data presented, provides a comprehensive analysis of the present scientific information of the date mussel biology and ecology in the Mediterranean coast, the impacts of its harvesting, the geographical extent and persistence and the implication in terms of loss of natural capital. Our ultimate goal is to understand how this phenomenon is perceived by the public and to estimate the economic costs associated to this illegal fishery practice either in terms of loss of ecosystem services and of restoration of the damaged habitats.

2. Biology of the date mussel

The bivalve *L. lithophaga* is a mollusc of the family Mytilidae Rafinesque 1815, distributed along the whole Mediterranean coastline (Fisher et al., 1987), throughout the Atlantic Ocean, from Portugal down to Senegal and the northern coast of Angola (Gonzalez et al., 2000), but also reported in the coast of Mozambique (Macnae and Kalk, 1958), albeit Indo-Pacific records of the species should be possibly carefully revised (Huber, 2010). Because of its shell morphology and colour, it is commonly called Mediterranean date mussel. *Lithophaga lithophaga* has an elongate-elliptical shell that can exceed 90 mm in length (Kefi et al., 2014; Peharda et al., 2015). The umbo is located close to the anterior end of the shell, which is lower than the posterior part. The periostracum is mahogany-brown and its sculpture consists of thin growth lines crossed by fine parallel dorso-ventral lirations, which provide a reticulated appearance (Turner and Boss, 1962). A ventral incurrent and a dorsal excurrent siphon come out from the posterior end of the mollusc. They have both respiration and feeding role, canalizing the water flow generated by ciliary gills.

The endolithic behaviour is typical of all species of the genus *Lithophaga*, similarly to other mytilid genera (*Adula*, *Botula*, *Leiosolenus*, *Fungiacava*). They can colonize different hard substrates, such as calcareous sandstones, mudstones, limestones, dead corals and living corals (Goreauand et al., 1972; Owada, 2007). *Lithophaga lithophaga* generally inhabits galleries bored in limestones, by attaching its antero-ventral shell margin to the inner wall of the holes with byssus (Owada, 2007). The absence of erosion marks on the shell of this species excludes any mechanical excavation; galleries are dug with a neutral mucoprotein with calcium-binding ability, which is secreted by pallial glands (Jaccarini et al., 1968). Cavities are typically 1.5 times greater than the individual that excavated it (Galinou-Mitsoudi and Sinis, 1995), and tend to be perpendicular to the rocky surface, in order to minimize the intraspecific competition (Guallart and Templado, 2012). Date mussel boring activity occurs mainly in the autumn-winter season, since during the rest of the year most of the energy is spent for reproduction (Galinou-Mitsoudi and Sinis, 1995). The physiological mechanisms and molecular pathways that enable *L. lithophaga* to bore into calcareous rocks are not fully understood yet. However, transcriptome analysis performed on pallial-gland tissue suggested possible candidate genes involved in chemical boring (Sivka et al., 2018; Sivka, 2019a). Other studies investigated the genome of this species (Giribet and Wheeler, 2002; Martinez-Lage et al., 2005; Vizoso et al., 2011; Nishihara et al., 2016), and investigated the potentially involved genes (i.e., 18S ribosomal RNA, 28S ribosomal RNA, β-actin, α-tubulin, and elongation factor 1-alpha) in mantle, gill, foot, and pallial gland tissue (Sivka, 2019b). These analyses, conducted in different seasons, increased the accuracy of gene expression analysis revealing temporal variation in the expression of the different genes (Sivka, 2019b).

Lithophaga lithophaga has one of the lowest growth rates among bivalves (growth coefficient k: 0.03 $year^{-1}$, Peharda et al., 2015), and has a high longevity since specimens can grow up to 54 years of age (Galinou-Mitsoudi and Sinis, 1994) with some individuals hypothesised to live up to 80 years of age (Kleemann, 1973). Ontogenetic ages determined through stable isotope analysis on a Croatian population varied from 10 to 54 years (30.6–93.6 mm), showing high variations in growth rates between individuals (Peharda et al., 2015). Growth is apparently year-round, but over 95% of the yearly growth of the shells occurs from May to October (Galinou-Mitsoudi and Sinis, 1995). Body wet weight probably decreases in summer due to energy consumption for gonads maturation (Šimunović et al., 1990; Galinou-Mitsoudi and Sinis, 1995). Although further analyses are needed on shells collected from different regions and different temperature regimes to obtain robust insights into the date mussel growth and largest size, it can be expected that higher seawater temperatures can promote higher bivalve growth rates and larger sizes. A precise assessment of individual age is therefore difficult, as growth rate varies according to multiple abiotic (depth, temperature, nutrients and substrate composition) and biotic (age, population density) factors. For example, it was estimated that individuals 5.0 ± 0.2 cm long can range from <18 to >36 years of age (Galinou-Mitsoudi and Sinis, 1995). The age can be successfully determined by the observation of the external accretion rings of the shell, where pairs of annual growth lines are visible, close to each other. One line is deposited annually, while the other is deposited during the reproduction period in differentiated individuals (Galinou-Mitsoudi and Sinis, 1994). Double lines are not observed if reproduction occurs during the period of annual lines formation (Peharda et al., 2015). Young specimens grow faster than older ones: hence individuals less than 1 cm long can be 2 years old, while those 7–8 cm long can exceed 40 years of age (Galinou-Mitsoudi and Sinis, 1995; Peharda et al., 2015).

Lithophaga lithophaga is a gonochoric species, and hermaphroditism has been rarely reported (Kefi et al., 2014). The species reproduces once a year following a decline in sea water temperature and has an unequal sex ratio, with males being dominant at smaller size categories (Galinou-Mitsoudi and Sinis, 1994; Kefi et al., 2014). Sex differentiation can occur from the age of 2 years, when specimens measure nearly 1 cm in length, and sex can be determined by the colour of gonads (orange in females and pearly in males) (Galinou-Mitsoudi and Sinis, 1994; Kefi et al., 2014). In both sexes, the gonad maturation starts yearly during spring, when the average seawater temperature reaches a maximum of 20 °C, while spawning occurs at the end of summer, when the temperature decreases until a minimum of 25 °C (Šimunović et al., 1990; Kefi et al., 2014; Žuljević et al., 2018; Khafage et al., 2019). At that stage, spawning events become visible, since gametes form grey clouds that slowly rise in the water column and concentrate close to the sea surface. It has been observed that spawning starts from few individuals and then spreads among neighbouring conspecifics within a few hours, suggesting a 'gamete to gamete' regulation, possibly depending on gametes concentration in the water column (Žuljević et al., 2018). The veliger can be observed in the water column 32 h after fertilization: it takes >9 days to reach the pediveliger stage (230–250 μm) with shell about 150–200 μm and the foot almost fully developed (Galinou-Mitsoudi and Sinis, 1997a). Metamorphosis is observed when the individuals reach a shell length of 270–350 μm. The process is not size-dependent, rather, it positively depends primarily on the availability of suitable substrates for larval settlement (i.e., hard surface with high $CaCO_3$ concentration, but no or low presence of silicates), as well as on the presence of settled conspecifics, and on the larval lipid content. Settlement usually occurs two months after egg fertilization and it appears to be favoured by high hydrodynamics such as those determined by high-tide currents, which contribute to water oxygenation, food provision and larval dispersal (Galinou-Mitsoudi and Sinis, 1997a).

The sex ratio of young individuals is strongly unbalanced toward males, but their percentage gradually decreases and the ratio becomes more balanced with the increase in shell length (Galinou-Mitsoudi and Sinis, 1994, 1995; Peharda et al., 2015; Kefi et al., 2016), probably because males are less tolerant to fluctuations of environmental conditions (Galinou-Mitsoudi and Sinis, 1994).

3. Ecology of the date mussel

Date mussel usually thrives in sub-vertical to vertical carbonate substrates (Fanelli et al., 1994; Trigui El-Menif et al., 2007), possibly to avoid sedimentation. Yet, the structural complexity of the substrate plays a dominant role in regulating its settlement. In fact, Devescovi and Iveša (2008) reported high abundance of date mussels on vault and stones not exposed to high sedimentation rates, while on vertical and inclined rocks date mussels were absent, possibly due to their very low structural complexity. In addition to the orientation and the structural complexity of substrate, population density depends on the substrate composition, depth range and mean size of individuals (Galinou-Mitsoudi and Sinis, 1997b; Devescovi et al., 2005). Date mussels live between the intertidal down to 25 m depth (Fanelli et al., 1994), both in well-lit areas, dominated by photophilic macroalgal communities, and in shaded areas where coralligenous formations develop (Riedl, 1966). The high biodiversity associated with this species suggests that it may be an important pioneer which facilitates the development of benthic communities (Guallart and Templado, 2012). High abundance is reported within 10 m depth, with a maximum of 1600 individuals/m^2 recorded in the Gulf of Naples (Russo and Cicogna, 1991). Shallow depth (ca. 0–3 m) is less suitable to this species due to hydrodynamics, which limit larval settlement and juvenile growth rate (Galinou-Mitsoudi and Sinis, 1997b; Guallart and Templado, 2012).

Boring habits in bivalves evolved as a defence mechanism against predation and space competition (Morton, 1986). *Lithophaga lithophaga* typically avoids predation sliding its body toward the bottom of the cavity (Owada, 2007). However, some of its natural predators, such as starfishes (*Marthasterias glacialis*, *Echinaster sepositus*, *Coscinasterias tenuispina*, *Ophidiaster ophidianus*) (Guallart and Templado, 2012), can predate these bivalves inside holes everting the stomach (Guidetti, 2004), while some gastropods species (*Muricopsis cristata*, *Stramonita haemastoma*, *Ocenebra erinaceus*, *Euthria cornea*) use long proboscis (Guallart and Templado, 2012).

Endolithic sponges (*Cliona* spp.) and bivalves, such as *Striarca lactea*, *Petricola lithophaga*, *Leiosolenus aristatus* and *Rocellaria dubia*, compete with *L. lithophaga* for food and space (Fraschetti et al., 2001; Trigui El-Menif et al., 2007). However, Šimunović and Grubelić (1992) observed that the boring activity of the sponge *Cliona celata* increases the substrate structural complexity facilitating the settlement of date mussels on artificial structures. Bioerosion activity, in turn, makes sediments available for bioconstructor organisms, that integrate sediment particles into coralligenous formations. Borers therefore provide an important service for epilithic communities (Ballesteros, 2006).

The hard substrates inhabited by date mussels are among the richmost and diverse habitats of the subtidal zone, and are characterized by a huge variety of sessile species (Ballesteros, 2006; Ingrosso et al., 2018). Epilithic organisms build a multilayer structure that increases the spatial complexity (Riedl, 1966). Depending on the environmental characteristics, the basal layer on the rock surface is covered by a very complex community featured by the presence of encrusting algae, sponges, bryozoans. Above this layer, a massive growth of organisms, from erect macroalgae to cnidarians and tunicates is observed (Fraschetti et al., 2001; Guidetti et al., 2003; Seveso, 2005; Bevilacqua et al., 2006; Parravicini et al., 2009). Finally, a layer of arborescent organisms such as macroalgae (*Cystoseira* spp.) might develop in particular environment conditions, providing several microhabitats where invertebrate vagile fauna (Trigui El-Menif et al., 2007) and fishes (Guidetti et al., 2004) thrive, feed and reproduce, increasing the biodiversity of the system (Fig. 1).

4. Habitat loss due to *Lithophaga lithophaga* harvesting

Date mussel fishery, was only occasional in the past, and was conducted by fishermen that incidentally recovered blocks of broken carbonate rocks. Once out of water, the rocks were broken down in small pieces using hammers and chisels, and date mussels were harvested with tweezers (Gonzalez et al., 2000). The development of scuba diving, after the Second World War, enabled the exploitation of this resource in previously unreachable sites (like caves and deep sites). Thereby, the fishing pressure on *L. lithophaga* rapidly increased, causing dramatic impacts over large areas (Hrs-Brenko et al., 1991; Russo and Cicogna, 1991; FAO, 2004). Rocks were broken by scuba divers, manually by hammers, sledgehammers or using specific devices (underwater hammer/diver drillers) and in some cases also underwater vehicles (Guidetti et al., 2002). The use of explosives has been also reported in some areas of the Moroccan and Croatian coastlines (Gonzalez et al., 2000; European Commission, 2002; FAO, 2004). The total removal of the top layer of substrate, together with its rich epibenthic community, allows date mussel harvesting (Fig. 2) and leaves completely bare and smoothed rock, with scattered empty holes (Fig. 1) (Fanelli et al., 1994). In addition, the slow growth rate of *L. lithophaga* contributes to exacerbate the negative impact of date mussel fishery over large spatial scales. Considering the low growth rate, several decades are necessary for date mussels to recover after harvesting (Galinou-Mitsoudi and Sinis, 1995; Russo and Cicogna, 1992a). Consequently, poachers continuously look for unexploited new locations, causing the severe destruction of undisturbed rocky coasts every year. Exploited sites vary in extension from scattered bare patches to several kilometres of completely deserted coast, in the most affected areas where scientific and large scale surveys have been conducted (such as Apulia and Albania) (Fraschetti et al., 2001, 2011; Guidetti et al., 2003).

The destructive harvesting of date mussels causes huge direct impact on benthic communities, resulting in a shift from a multilayer and highly complex community to a simplified habitat structure (Fig. 1). Biodiversity is therefore eradicated from the impacted areas and sharply reduced in the surroundings (Bevilacqua et al., 2006). Beside the biomass loss, communities are indirectly affected by the

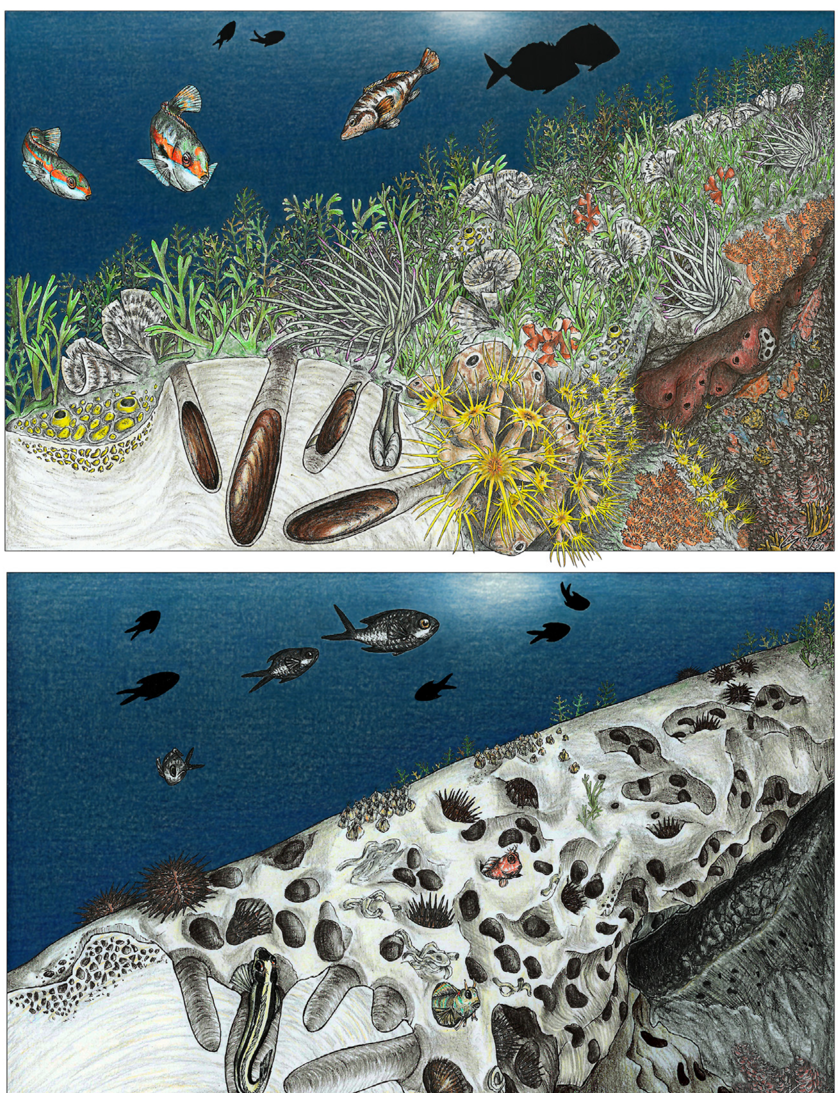

Fig. 1. Illustration of the rocky subtidal benthic community before (upper half) and after date mussel fishery (drawings by Giorgia Di Muzio).

Fig. 2. Example of total removal of the top layer of the rocky substrate showing a date mussel shell in its hole.
(Photo credit Gabriella Luongo)

destruction of the substrate. Mechanical damage alters the geomorphological characteristics of the substrate by reducing the structural complexity of the rocky surface (Parravicini et al., 2006a), and modifying the inclination and roughness of the slope (shadowing effect) (Devescovi et al., 2005). Furthermore, this fishery technique affects the sediment texture by decreasing the roundness of pebbles at the cliff foot (Rovere et al., 2009). Sediments can damage benthic organisms both by burying them on the bottom below broken rocks (Fig. 3), and by physically abrading organisms or hampering the recruitment of juvenile stages due to scouring (Kendrick, 1991; Coelho et al., 2000; Airoldi, 2003).

The removal of epilithic communities induces cascade effects along the trophic web, altering ecosystems functioning (Guidetti et al., 2003). Fanelli et al. (1994) suggested that the depletion of dense benthic cover may facilitate sea urchins unselective grazing on algae and newly settled organisms (Fig. 4). Indeed, several studies reported high density and biomass of sea urchins in areas affected by date mussel fishery (Fanelli et al., 1994; Guidetti et al., 2003; Parravicini et al., 2010; Guidetti, 2011). In particular, the population density of the sea urchin *Arbacia lixula*, a species not abundant in macroalgal beds, increases considerably in impacted areas; instead the species *Paracentrotus lividus* shows a similar density between impacted and non-impacted areas (Guidetti et al., 2003; Agnetta et al., 2013). By preventing the recovery of benthic communities, sea urchins favour the persistence of barrens over the long term, leading to a regime shift from vegetated to barren habitats (Fig. 4) (Fanelli et al., 1994; Guidetti et al., 2003; Guidetti, 2011). Macroalgal forests provide an important refuge, food source (direct or indirect) and nursery areas for several fish species (Cheminée et al., 2013; Thiriet et al., 2016). Consequently, the ichthyofauna commonly associated with the vegetated rocky subtidal suffers from reduced population density and species richness in areas impacted by date mussel fishery (Guidetti et al., 2004; Guidetti and Boero, 2004). In particular, Guidetti et al. (2002) observed that *Symphodus* spp., *Diplodus* spp., *Serranus* spp. and *Coris julis* are less abundant in the resulting barren areas, due to their habitat requirements. As *Diplodus sargus*, *D. vulgaris* and *C. julis* are the main predators of the two most abundant Mediterranean sea urchins *P. lividus* and *A. lixula* (Guidetti, 2004), a reduced density of predators is likely to foster an increase in sea urchin abundance, thus triggering top-down effects through the trophic web (Guidetti, 2006) (Figs. 1, 4 and graphical abstract). The disappearance of fish species associated with vegetated rocky subtidal represents a positive feedback mechanism, together with the depletion of macroalgal canopy, favouring the persistence of barrens after date mussels harvesting, by increasing sea urchin density and grazing pressure. The effect of sea urchins grazing on barrens is so effective and continuous, that the recovery is possible only after the experimental

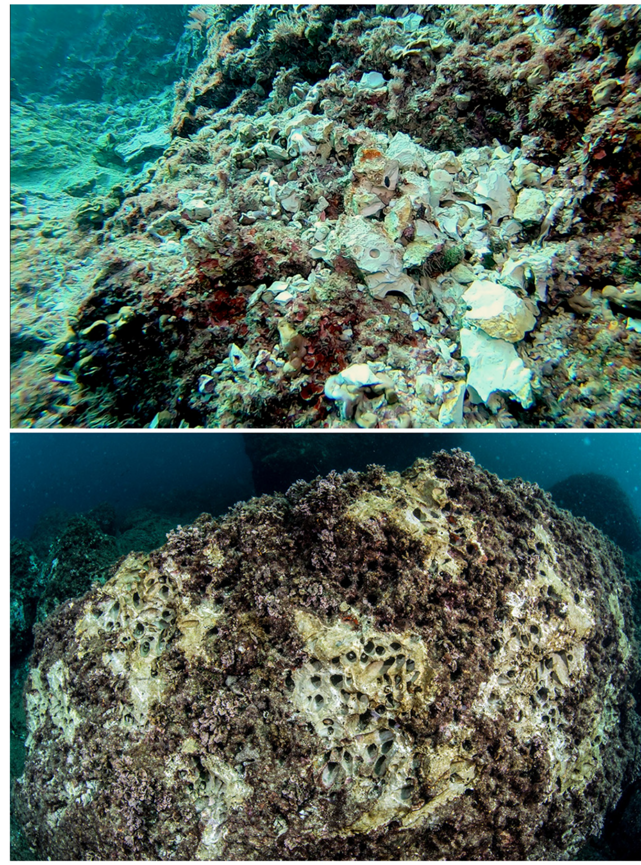

Fig. 3. Examples of the irreversible physical damage caused by date mussel fishery conducted by hammering the concrete carbonate substrate. Reported are: clastic deposit resulting from rocks breaking (upper half); patches of damaged rocks and how they are visible through in situ inspections.

manipulation of the substrate with the removal of all grazers (Guarnieri et al., 2014).

The only epilithic assemblage present on barrens is typically composed by organisms able to resist to sea urchins grazing, such as encrusting and turf-forming algae, sponges, barnacles, vermetids and calcareous tube worms (Fig. 4) (Bevilacqua et al., 2006; Guarnieri et al., 2014). In areas damaged by date mussel fishery, the exposed holes left empty after date mussels extraction are an important refuge for juveniles of *P. lividus* that escape predation (Fig. 1), representing another positive feedback mechanism for the barren persistence (Guidetti, 2011). Others organisms take advantage of empty holes, such as cryptobenthic fishes (e.g. *Aidablennius sphynx*, *Microlipophrys dalmatinus*, *Parablennius zvonimiri*, *P. rouxi*, *P. incognitus*) (Orlando-Bonaca and Lipej, 2008; Parravicini et al., 2008) and bivalves (e.g. *Barbatia barbata*, *Talochlamys multistriata*, *Mimachlamys varia*, *Lima* sp., *Hiatella arctica*, *Thracia distorta*) (Hrs-Brenko and Legac, 2006).

Although the recovery of the community to pre-disturbance conditions is not achieved, a quite rapid cover by encrusting and turf-forming macroalgal species can be observed in areas where sea urchins were less abundant (Bevilacqua et al., 2006). It is therefore evident that local conditions (e.g., sea urchin abundance) can play a key role in driving shift either to a barren state (e.g. the Apulian coast) or to degraded assemblages dominated by turf-forming tolerant/opportunistic species (e.g. the Tyrrhenian Sea; Boada et al., 2017).

Because of its severe detrimental effects, date mussel fishery is considered as one of the most widespread and harmful anthropogenic impacts on temperate subtidal rocky habitats (Guidetti and Boero, 2004). Also, the Encyclopaedia Britannica remarked the importance of this problem, and mentioned date mussel fishery as prime example of fishery disturbance on subtidal hard substrates (Naylor, 1995). To date, the

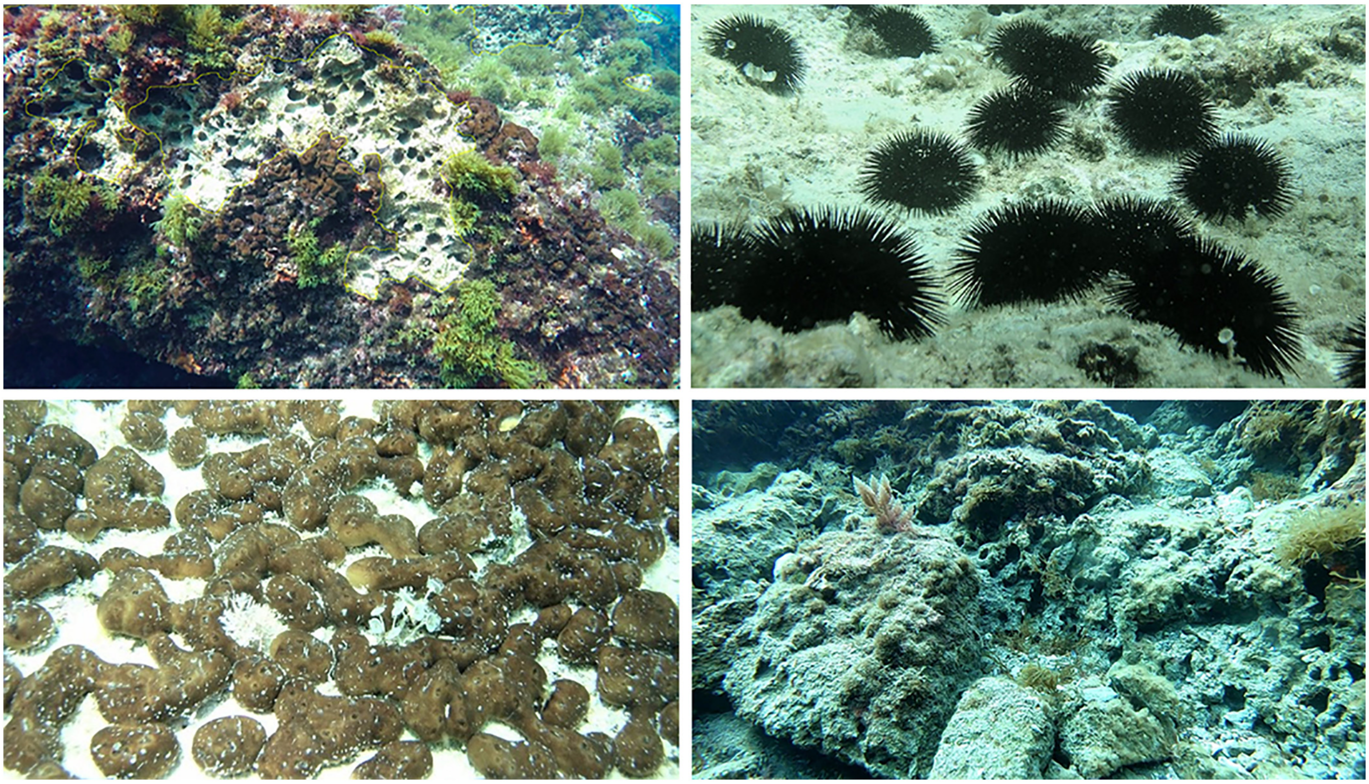

Fig. 4. Subtidal rocky coast affected by date mussel fishery. Recently damaged reef (top left), damaged reef grazed by sea urchins (top right), damaged reef colonized by sponges (*Chondrilla nucula*, bottom left), damaged reef colonized by turf-forming algae (bottom right).

actual spatial extent and distribution of date mussel fishery damage in subtidal rocky habitats throughout the Mediterranean Sea is still largely unknown. Research mainly focused along the Balkan coasts and in Italy, particularly of Liguria, Apulia, Sardinia and the Sorrento-Amalfi Peninsula in the Campania region (Russo and Cicogna, 1992a; Fanelli et al., 1994; Fraschetti et al., 2001; Guidetti and Boero, 2004; Devescovi et al., 2005) (Fig. 5). Russo and Cicogna (1992a) reported the absence of sites free from damage along the 70 km surveyed along the Sorrento-Amalfi Peninsula. 50% of the investigated area showed evidence of severe damage (multiple patches, size >1 m^2), while 35% was moderately affected (scattered patches, size <1 m^2) and 15% was slightly damaged (interspersed patches, size <0.25 m^2). Moreover, recent (i.e., dated less than 12 months) patches of damaged reefs were found in 50% of the investigated areas, indicating that the fishery is a still ongoing problem. An experienced diver operating illegally is estimated to collect 15 up to 25 kg of date mussels in 3–4 h dive, and it has been estimated that 30 fishermen collect from 81 to 135 t of date mussels per year (Russo and Cicogna, 1992b). Evidence of date mussel fishery in Sardinia revealed an intense damage determined by historical harvesting of *L. lithophaga* in the Cagliari Gulf, which decreased since the '90s, whereas this practice was still ongoing in other areas of the region, such as in the Palmas Gulf (Cuccu et al., 1994). Evidence of date mussel fishery was also reported along the Ligurian coast, both in the La Spezia Gulf and in the Bergeggi Island, which are frequently targeted by poachers (Pierotti et al., 1966; Seveso, 2005; Parravicini et al., 2006a, 2006b). In the Bergeggi Island, clear differences were observed among sampling sites, bare rock in 94% of the coast close to Capo Noli, while only 10% of the coast was impacted in Punta Maiolo, probably as a result of the different protection enforcement (Seveso, 2005). Fanelli et al. (1994) investigated the impact of date mussel fishery along the Apulian coasts, from the Ionian to the Adriatic coast. A widespread, though non-homogeneous, damage caused by this illegal practice was observed along 128 out of 206 km monitored in the Salento peninsula. The comparison from a first survey, that took place in 1990, and a second, carried out in 1992, reported an increase of date mussel fishery impact. Due to overexploitation of the Apulian coast, fishermen also started to use small underwater vehicles in order to cover the increasing distance among fishing sites (Fanelli et al., 1994). Fraschetti et al. (2001) confirmed the widespread damage caused by this illegal fishery along Apulian coast observed by Fanelli et al. (1994), and highlighted how this destructive fishery was still carried out intensively after several years. Moreover, poachers started fishing in less exploited areas such as Montenegro, Greece and Albania, where some areas are already highly impacted and degraded to a barren state (e.g. Vlora Bay; Fraschetti et al., 2011). In Montenegro, albeit prohibited, date mussel fishery and date mussel consume are still ongoing, particularly at the Lustica Peninsula, Donji Grbalj, Cape Voluica and Cape Mendra (Macic et al., 2010). In the West Istrian coast, close to Rovinj (Croatia), the damage caused by date mussel fishery on the limestone substrate was investigated over 50 km of the coast, and 47% of the substrate at 6-m depth was damaged (Devescovi et al., 2005). The percentage of impacted surface decreased with increasing water depth, with no evidence of damage below 14 m depth. Date mussel fishery impacted also the Slovenian coast of the Trieste Gulf (Orlando-Bonaca and Lipej, 2008) and the central Adriatic Sea, along the coasts of the "Conero Regional Natural Park" (Cerrano et al., 2014). Here this illegal fishery might have reduced the density of *L. lithophaga*, which was observed only in <3% of the surveyed coast. Date mussels are collected also in Sicily. However, quantitative assessments of the damage extent on the shallow rocky subtidal have never been carried out, even though the high shores and carbonate rocks favour date mussel settlement along a large part of the coasts of the region (Fig. 5) (Fabio Badalamenti and Luigi Musco, personal observation).

5. Assessing the societal costs of date mussel fishery

The assessment of the consequences of habitat damage due to date mussel fishery can be conducted either evaluating the economic loss due to impaired ecosystem services originally provided by the habitat

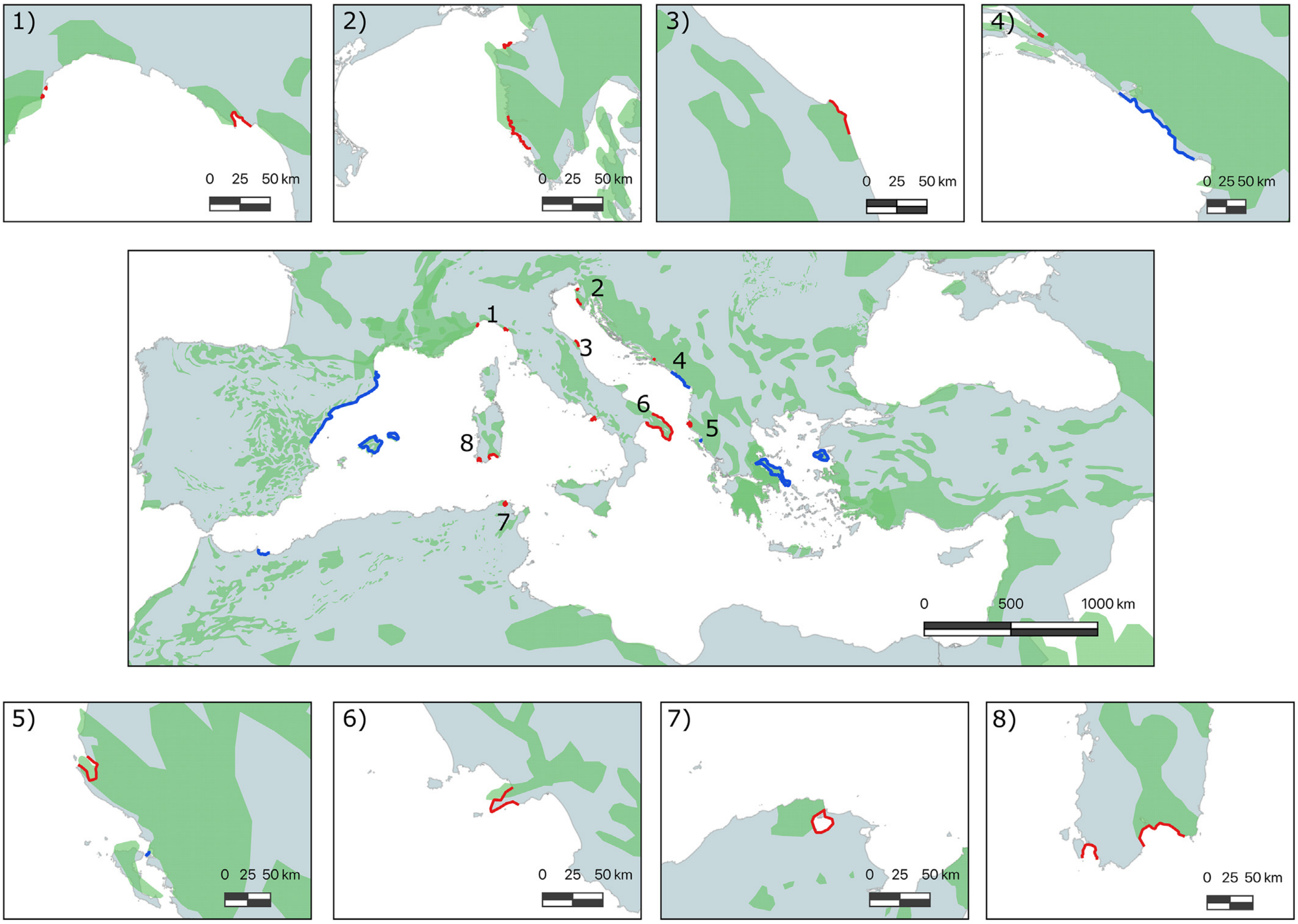

Fig. 5. Distribution of date mussel fishery pressure among Mediterranean countries. Light green areas indicate the main carbonate outcrops: data from Antonioli et al. (2015) and World Map of Carbonate Rock Outcrops V3.0 (2020) (https://crc806db.uni-koeln.de/layer/show/296/). Blue lines depict coasts date mussel fishery is known to be performed but no in situ studies are available, and red lines the coasts where the damage has been quantified by in situ studies. The 8 images, top and down the central one, are a zoomed view of 1 Liguria (Italy), 2 Istria (Croatia), 3 Conero (Italy), 4 Montenegro, 5 Albania, 6 Sorrento Peninsula (Italy), 7, Tunisia, 8 South Sardinia (Italy).

(Bayraktarov et al., 2016; Börger et al., 2014; Wätzold and Schwerdtner, 2005) or by estimating the cost needed to restore the degraded habitat. Herein the economic consequences of date mussel fishery were estimated and compared using both the above mentioned approaches.

Recently, ecosystem restoration, together with other management tools (e.g. implementation of protection actions), has been deemed as critical to counteract environmental degradation due to anthropogenic activities (Bekkby et al., 2020). Albeit marine ecosystem restoration is a relatively new branch of marine ecology, and the mapping of the extension of degraded habitats is not completed yet (Gerovasileiou et al., 2019) noticeable efforts have been made to evaluate the cost of restoration activities, which may be calculated by summing up all costs required to revert a degraded habitat toward its original condition (Bayraktarov et al., 2016). These activities include structural changes of the system undergoing restoration, harvesting of organisms of flora and/or fauna and/or the creation of nursery/farming areas able to produce propagules/specimens to be reintroduced, costs of man-hours for the personnel involved, the use of vessels and equipment, and monitoring of restoration success (de Groot et al., 2013; Blignaut et al., 2014; Bayraktarov et al., 2016; Iftekhar et al., 2017). It should also be acknowledged that the costs of work at sea grow with increasing depth. Attempts to restore long-living species, such as corals, gorgonians, or sponges, may further increase the costs due to the time needed for obtaining propagules/specimens to be reintroduced and for monitoring restoration success. In addition, costs may vary in space and time due to differences in salary, costs of materials, equipment etc. (Wätzold and Schwerdtner, 2005). Active ecosystem restoration aims at providing interventions favouring and accelerating the recovery of the habitats back to pre-disturbance condition. Ecosystem restoration is a process that contributes also to the return of the ecosystem goods and services that have been lost in damaged systems (de Groot et al., 2013). Active restoration becomes a solution once passive restoration is not enough since the disturbance has affected ecosystem resilience, and the return to pre-disturbance conditions can take much longer or be impossible in ecological time spans (as in the case of the barrens created by date mussel fishery).

In the present study, the ecosystem services, in terms of direct or indirect contributions of the ecosystem to human health and wellbeing, were also assessed (de Groot et al., 2010). Ecosystem services include the provision of resources (food, genetic resources, medicines, etc.), regulation services (air purification, climate regulations, protection from coastal erosion, etc.), habitat services (maintenance of life cycles, protection of genetic pools, etc.), aesthetic and cultural services (recreational activities, cultural heritage etc.) (Böhnke-Henrichs et al., 2013). Of course not all services can be converted in economic terms and a large part of them has only intangible values. Here the total economic value of ecosystem services was considered as the value of the tangible assets (Börger et al., 2014).

The economic costs of the impact due to the harvesting of *L. lithophaga* in the Mediterranean area were quantified and compared based on unpublished data (Supplement 1, Table S1) using the case study of the Gulf of Naples, one of the Mediterranean areas most intensively affected by this illegal fishing activity (FAO, 2004). The Sorrento Peninsula, in its southern part, is characterized by calcareous rocky shores particularly suitable for the settlement of the species, thus particularly subjected to illegal fishery (Russo and Cicogna, 1991). The Sorrento Peninsula coast within the Gulf of Naples is about 20 km long. Eleven sites were selected, altogether representing about 6.6 km of the peninsula rocky coast, including the Marine Protected Area of Punta Campanella. At each site, underwater videos were collected. The HD videos were taken at depths ranging from 2 to 15 m (the deepest depth where evidence of date mussel harvesting was detected; please note that the deepest depth changed among sites). From each video at least 3 frames per site were randomly selected (maximum 15), depending on the linear extent of the site (overall 89 frames). Per each frame, the percentage of the impacted area in respect to the total frame area (using ImageJ software) was calculated. The portion of damaged area varied on average from 23 to 68%. Then the total surface of underwater rocky substrates impacted by the illegal harvesting of the date mussel in the considered area was calculated. Overall, along the 6.6 km of investigated coast, the impacted area covered a surface of 13,100 m^2, of which 3700 m^2 of recent impact (as evident for the whither colour, for the complete absence of any significant biological colonization and the signs of broken rocks). It was assumed that the costs of ecosystem services provided by this valuable rocky habitat can be comprised from the values assigned in other studies for vegetated coastal habitats to those of coral reefs (2.66–32 euros/m^2/year; Costanza et al., 2014). Based on our calculation, the loss of ecosystem services caused by the date mussel fishery in the considered area spans from ca. 35,000 to 419,000 euros/year, of which ca. 10,000 to 118,000 euros caused by the recent date mussel fishery activity. The same approach may be applied to the Salento Peninsula (Apulia, SE Italy), the largest Mediterranean area investigated up to date (Fanelli et al., 1994). Following the "weighted index of damage" (D_w) proposed by Fanelli et al. (1994), with D_w ranging from 0 (no damage) to 1 (complete desertification), in that geographic area 128 km of coast appeared damaged ($D_w > 0.15$) and 69 km of them heavily damaged ($D_w > 0.50$). In these last areas damage was evident from the surface to 10 m depth (Fanelli et al., 1994). If the value of ecosystem services is considered at its lower limit (i.e. 2.66 euro/year/m^2) and the calculation is limited to the 69 km of coast of Salento heavily damaged from 0 to 10 m depth, it can be estimated a loss in ecosystem services due to habitat degradation to ca. 1.8 million euros/year. In absence of active restoration interventions, the recovery of the hard bottoms, in presence of overfishing, might require no less than 30 years, causing an economic loss in terms of ecosystem services from ca. 1 up to 12 million euros in the area of the Sorrento Peninsula herein investigated and ca 55 million euros in the Salento Peninsula. These values can be considered conservatives, as the assumption of 30 years is underestimate as so far there are no documented cases of full recovery.

The value of the natural capital associated to the habitat hosting *L. lithophaga* was assessed through a biophysical and trophodynamic environmental accounting model (Picone et al., 2017). The emergy value of both autotrophic and heterotrophic natural capital stocks were converted into monetary units (Emergy-based currency equivalents, ECE) assuming 2,56 euros m^{-2}. Using these equivalents, ca. 1 million euros is lost in the area of the Sorrento Peninsula herein investigated for the last 30 years, and ca. 53 million euros in the Salento Peninsula in the same time span.

Finally, the values above were compared with those of the good associated to these special habitats is quantifying the gain obtained by illegal fisheries. In both case studies, it can be estimated that from 5 to 7 kg m^{-2} of date mussels are present. These are sold at 70–100 euro kg^{-1} to the restaurants or directly to consumers. Thus, it can be calculated that this specific habitat has a value ranging from 350 to 700 euros m^{-2}, which, amounts to 4.6–9.2 million euros in the area of the Sorrento Peninsula and from ca. 240 up to 483 million euros in the 69 km of Salento Peninsula. These values are again an underestimate as they are based uniquely on the illegal market value of the date mussels, without considering the costs of the loss of ecosystem services associated to all other species removed.

If we assume that these latter values are realistic (as they refer to actual market values), then the values calculated using the emergy approach, for this specific habitat type, can underestimate by at least 10 times the values of the goods and services actually provided.

These data were compared with the costs for the active restoration of the pre-existing habitat. To do so, the costs of reintroducing the date mussels sequestered to the fishermen, using scientific divers, were explored. In this case, the cost of restoration depends on costs the scuba diving time and of the supporting vessel/boat, plus the maintenance of the mussels prior to their reintroduction in their original habitat. Considering the data collected in the Sorrento Peninsula, assuming that the average number of individuals is ca. 800 m^{-2} (Russo and Cicogna, 1991) and that 50% of the rock has damaged, the number of date mussel to be reintroduced in holes of adequate size, is approximately 400 m^{-2}. In addition, the mussels have to be appropriately fixed within the empty date holes and require to be protected in order to reduce the risk of date loss or predation. According to these issues, and considering one to two working days at sea depending on work intensity and operational depth of the dive, we estimated that the costs can vary from 1000 to 5000 euros m^{-2}. These values fall within the range of costs for marine habitat restoration calculated by the EU project MERCES (Marine Ecosystem Restoration in Changing European Seas, Deliverable 7.4, http://www.merces-project.eu/) and to other literature data (Bayraktarov et al., 2016). Assuming in our case study a more conservative cost range of 1000–3000 euros m^{-2} the total expenditure of the restoration of the 6.6 km of the coast (13,100 m^2) might be comprised between 13.1 and 19.5 million euros. In this case the return in terms of economic benefits of the restored ecosystem service would take from 33 to 49 years to recover the investment in terms of restoration.

Alternatively or additionally to the reintroduction of sequestered date mussels, restoration of the barrens might be carried out reintroducing the epibenthic flora/fauna usually thriving on temperate rocky reefs of the study area. The cost of such restoration action would be similar to the one calculated for reintroducing of the date mussels considering the average above mentioned restoration costs (1000 to 5000 euros m^{-2}). It has to be stressed that no restoration action can be successful in absence of conservation and/or management initiatives leading also to the recovery of the fish compartment.

This estimate has important implications in terms of investment for the restoration of the Natural Capital, has the efficacy and convenience of ecological restoration must be optimised to be identified as a convenient tool in the future. Of course, the costs of restoration can significantly decrease with the scale up of the field work operation. In order to make convenient the investment in marine ecosystem restoration, the costs of date mussel restoration should decrease to 300 euros per day (which would return the investment in restoration within 10 years).

It is also useful to consider that 1 m^2 of habitat damaged for date mussel fishery, containing on average 5 kg of date mussels, can have an economic return for fishermen of 250 euros and a market value of 500–1000 euros. The loss in terms of ecosystem services of the same square meter, will cause, in 30 years, an economic cost ranging from 80 to 960 euros.

6. Potential effects on human health

Lithophaga lithophaga is a filter-feeder species that feeds on plankton and small organic particles present in the water column and collected by gills. Gills are able to select particles by size and grate the largest ones into ingestible forms, using specialized structures (scabrous blocks) (Akşit and Mutaf, 2014).

As most filter-feeder bivalves, *L. lithophaga* bioaccumulates several pollutants in their tissues (Regoli and Orlando, 1994; Wen-Xiong and Fisher, 1996), and the consumption of this species can lead to potential risks for human health (Stankovic and Jovic, 2012). This problem is largely amplified by the long life span of this species, when compared with the one of most of the edible bivalve species. Since *L. lithophaga* collection and sale is prohibited, there are few studies investigating the dynamics of uptake and loss of pollutants for the species (Ozsuer and Sunlu, 2013). Several field studies evidenced the presence of toxic organic compounds and heavy metals in date mussel tissues (Table 1). Dujmov and Sučević (1990) reported data on the contamination of *L. lithophaga* by polycyclic aromatic hydrocarbons from the Adriatic Sea pointing out the ability of the species to bioaccumulate these compounds and its potential in biomonitoring studies. Deudero et al. (2007a) monitored from 1996 to 2000 the concentration of persistent organic pollutants (POPs) in different benthic species (*L. lithophaga*, *Mytilus galloprovincialis*, *Chamelea gallina*, *Venus verrucosa* and *P. lividus*) in the Balearic Islands (Western Mediterranean). Date mussels showed a non-linear trend in pollutants concentration throughout years and presented the highest mean values among analysed species for γ-hexachlorocyclohexane (γ-HCH) and dichlore diphenyl trichloroethane (ΣDDT), though these concentrations were lower than those established by the EU for human consumption. Total butyltin concentrations varied between 30 and 245 ng g^{-1} dry weight in different bivalve species of the Bizerta Bay (Tunisia), with the highest concentration reported for *L. lithophaga* (Kefi et al., 2011). Omeragić et al. (2016) analysed the POPs presence in *L. lithophaga* samples obtained from the local fish market of Sarajevo (Bosnia Herzegovina), without detecting any correlation between POPs concentration and shell length. The authors recorded an average concentration of organochlorine pesticides below the limits established by the American Food and Drug Administration (FDA, 2002), while PCBs concentration was greater in 2 out of 25 samples analysed (91.31 and 109.44 ng g-1 of wet weight), according to limits established by the Commission Regulation (EU) No 1259 (2011) (75 ng g-1 of wet weight). Thus, the authors evaluated date mussels from the Neum Bay (Bosnia and Herzegovina) as safe for consumption. In bivalves, trace metals uptake is regulated by geochemical factors (e.g. organic carbon, water hardness, temperature, pH, dissolved oxygen concentration, salinity, sediment grain size, hydrologic features of the system), physiology and ecology of the species (e.g. infaunal or epifaunal species), and traits of the single specimens (e.g. age, size, sex, genotype, phenotype, feeding activity, reproductive state) (Boening, 1999). *Lithophaga lithophaga* has been observed to bioaccumulate different heavy metals, with the concentration pattern Zn > Cu > Pb > Cd (Deudero et al., 2007b; Ozsuer and Sunlu, 2013; Kefi et al., 2016). Deudero et al. (2007b) reported a higher Pb and Cd concentration in *L. lithophaga*, in comparison to those detected in *M. galloprovincialis* collected at the same sites (Menorca and Mallorca) and period (April–June). A study on the trace metals accumulated in *L. lithophaga* from Izmir Bay (Aegean Sea) in 2001 and 2011, reported, on average, 7.64 μg Pb g^{-1} dry weight of *L. lithophaga* with values exceeding the limit published in the Turkish Food Codex (2008), and Cd concentrations exceeding the limits of the World Health Organization (1973) (Ozsuer and Sunlu, 2013). Age and sex did not seem to affect the metal uptake, since similar concentrations were found in specimens of different size (Miedico et al., 2016) and in both sexes, with the exception of Pb concentration higher in males (Kefi et al., 2016). Seasonal variability of metal concentration was described by Kefi et al. (2016), who reported an increase of Zn and Cu during winter, suggesting a possible correlation between metals uptake and the variation of several abiotic factors (i.e. temperature and salinity, dissolved oxygen and pH). They also reported higher Pb concentrations in summer, probably correlated to seasonal increase in urban pollution. However, Ozsuer and Sunlu (2013) did not detect a clear trend in metals concentration through seasons. Since *L. lithophaga* can accumulate multiple pollutants in its tissues, sometimes with concentrations higher than the legislative limits, the consumption of this species should be considered hazardous for human health.

Table 1
Summary of contaminants monitored in *Lithophaga lithophaga*. In bold contaminants above national/international limits for human consumption.

Site	Monitored contaminants	References
Croatian coast	Polycyclic aromatic hydrocarbons	Dujmov and Sučević, 1990
Balearic Islands (Spain)	γ-Hexachlorocyclohexane, hexachlorobenzene, dichlore diphenyl trichloroethane, polychlorinated biphenyls (PCB28, PCB52, PCB101, PCB118, PCB138, PCB153, PCB180)	Deudero et al., 2007a
Balearic Islands (Spain)	**Pb**, Cd, Cu, Cr, Hg, Ni, Zn, As, Ag	Deudero et al., 2007b
Bizerta Bay (Tunisia)	Monobutyltin, dibutyltin, tributyltin	Kefi et al., 2011
Izmir Bay (Turkey)	Zn, Cu, **Pb**, **Cd**	Ozsuer and Sunlu, 2013
Gulf of Manfredonia (Italy)	U, Hg, Pb, Cd, Cr, Mo, Co, Ni, Se, As, Cu, V, Sr, Ca, Zn, Mn, Fe, Al	Miedico et al., 2016
Bizerta Bay (Tunisia)	Zn, Cu, Pb, Cd	Kefi et al., 2016
Sarajevo fish market (Bosnia and Herzegovina)	Aldrin, dieldrin, endrin, cis-chlordane, trans-chlordane, oxy-chlordane, PCB118, **Σ(PCB28, PCB52, PCB101, PCB153, PCB138, PCB180)**	Omeragić et al., 2016

7. Efficacy of protection measures and illegal trade of *Lithophaga lithophaga*

Lithophaga lithophaga is strictly protected under international directive and conventions in all Mediterranean countries (Supplement 2, Table S2). Since this *L. lithophaga* is not at risk of extinction, these special conservation measures are designed to prevent damages to the habitat due to the destructive practice.

Despite these regulations, illegal international trade continues to take place, particularly in Mediterranean countries (North-West Africa and South-East European countries). In this regard, FAO (2004) reported that in Serbia and Montenegro almost 30 tons of *L. lithophaga* are exported every year to neighbouring countries (such as Slovenia, Bosnia and Herzegovina). Around 700 kg of date mussels were confiscated between 2000 and 2002 in Croatia. In Slovenia, several violations related to date mussel fishery were recorded in 1999/2000. For example, more than 800 kg of *L. lithophaga* were confiscated in Croatia, Italy and Germany between 2000 and 2004. In Albania this illegal practice is known to be performed mainly along the coast of Ksamili (FAO, 2004). In 2010, a criminal organization responsible for smuggling around 2300 kg of date mussels from Croatia to Slovenia and Italy, with an estimated commercial value of 143,000 euros, was stopped (OECD, 2012). Voultsiadou et al. (2010) reported the presence of an historical and intense exploitation of date mussels along the Greek coast, leading to a decline of the extant population. However, date mussels are still consumed in Greece, particularly in Evvoia and Lesvos islands. Omeragić et al. (2016) reported that along the Bosnia and Herzegovina coast date mussels were frequently harvested in Neum Bay, and they were sold at the Sarajevo seafood market. In Italy date mussel fishery is still of high concern for the environmental impact caused. According to FAO (2004), seizures of 4720 kg of this species were made by different Police bodies from 1999 to 2004. Considering the Levant Mediterranean Basin, in Turkey and Israel, date mussels are not commonly consumed, possibly for local tradition, leading to hypothesize that date mussel fishery may not be common in the two countries (FAO, 2004). Date mussel fishery occurs also in Western Europe: harvesting, trade and consumption of *L. lithophaga* are widespread along the whole Spanish Mediterranean coast, especially in the Balearic Archipelago (mainly at Mallorca and Menorca, where it is traditionally consumed), along the coast of south Catalonia and in the whole province of Castellón. A substantial amount of *L. lithophaga* was also reported to be smuggled to Catalonia or Castellón from Morocco (Gonzalez et al., 2000). Very little information about date mussels harvesting and consumption is available for African countries, except for Morocco, where this illegal practice it is known to occur between Nador e Ras Kebdana (Shafee, 1999; Gonzalez et al., 2000) and Tunisia, where about 5 kg per week were estimated to be harvested only in the bay of Bizerta (Trigui El-Menif et al., 2007).

According to the available literature data on seizure and illegal trade of date mussels, date mussel fishery is carried out in Albania, Bosnia Herzegovina, Serbia, Montenegro, Croatia, Italy, Morocco and Spain. In Fig. 5, are highlighted the areas where date mussel fishery is known to be carried out, which are over-imposed to the map of distribution of carbonate substrates in the Mediterranean area. In all of these countries there is a well-established and profitable market at the base of this illegal trade also involving other European countries, including Germany (FAO, 2004).

8. Public awareness

The main reason of the current illegal date mussel exploitation is the high demand by consumers, who are often unaware that date mussel fishery is illegal and it produces detrimental effects on coastal ecosystems.

Muscogiuri and Belmonte (2007) conducted a study in Apulia (SE Italy), one of the most exploited areas by date mussel poachers (Fanelli et al., 1994; Fraschetti et al., 2001), to assess the perception of this problem among the population. The authors focused their investigation on children from 8 to 13 years old. About 40% of them declared having eaten date mussels. The biology of the date mussel and the impact of its fishery were not well known especially among children receiving information from their family and/or television talks (ca. 20–30%). On the contrary, the children receiving information from schools and the local museum (ca. 5–13%) were aware of the consequences of this activity.

The lack of awareness among consumers is the main driver for the fishery and sale of *L. lithophaga* in local fish markets and restaurants also in other Mediterranean regions, such as in Greece (Katsanevakis et al., 2011). In the Evvoikos Gulfs, date mussels were served in 22.8% of restaurants (i.e., in 65% of the seafood restaurants), also thanks to ineffective controls by the local authority.

To better explore the date mussel consumption in restaurants, an internet research based on cooking websites or personal blogs, was done. The search on Google.com was done using as keywords the common names of the species *L. lithophaga* in different national languages (including Mediterranean languages plus English and German, that are widespread languages among tourists), and "recipe" (again translated in each of the different languages) as it follows: Spanish: *receta dátil de mar*; English: recipe date mussel; Croatian: *recept prstaci*; Italian: *ricetta dattero di mare*; French: *recette datte de mer*; German: *rezept meerdattel/steindattel*; Greek *πετροσωληνες συνταγή*; Slovenian: *recept morski datelj*; Albanian: *recetë shpuesja e shkëmbit*; Turkish: *reçete taş midyesi*; Maltese: *riċetta tamra/tamla*. Webpages reporting date mussel recipes were then divided into those that specify that the species is protected (or that the fishery is prohibited) and those that did not report any warning. The internet survey was repeated replacing the word "recipe" with "TripAdvisor" (a well-known platform for finding and evaluating the restaurants), to investigate the sale of date mussels by restaurants. We then quantified the number of restaurants in which date mussel dishes were reported in pictures or were described in consumer reviews. We excluded from counting the restaurants that denied the consumption of this species by commenting on the consumer's reviews (as we assumed that consumers could have confused date mussels with other bivalves). A total of 126 webpages (i.e. 71 TripAdvisor's restaurants and 55 recipes from other webpages) were found in 13 countries (Fig. 6). Greece was the country with the highest number of webpages (51), followed by Italy (22), Spain (17), and Albania (14). Slovenia, Bosnia and Herzegovina, Montenegro, Malta, Kosovo, and Serbia were reported to sell date mussels only in TripAdvisor-censused restaurants, while the consumption of date mussel in France and Germany was confirmed in Google but not in TripAdvisor. No match was found for Turkey.

The results from TripAdvisor (green columns), indicated that 71 restaurants served date mussels. Greece was still the first country (39 references), followed by Albania (13) and Spain (6). Italy, Croatia, Slovenia, Malta, Kosovo and Serbia had only one reference, while none was found in French, German and Turkish restaurants (Fig. 6). The search for

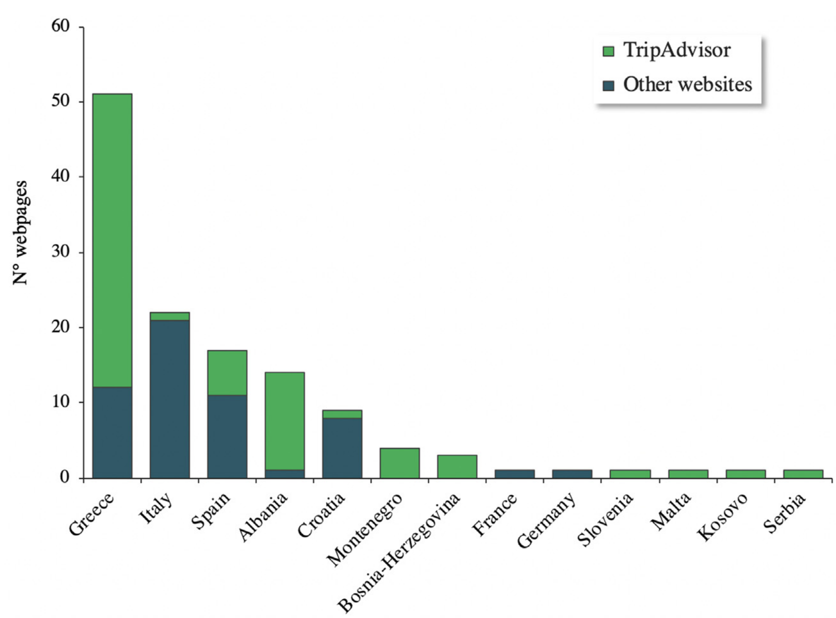

Fig. 6. Number of webpages per country indicating date mussel consume.

recipes from other webpages (blue column) showed 55 total results, mainly distributed in Italy (21), Greece (12), Spain (11) and Croatia (9). France, Germany and Albania had one reference, while other countries none (Fig. 6). Only 21.4% of these webpages informed the readers about the protection status of *L. lithophaga*.

The abundance of date mussel dishes/recipes reported in TripAdvisor webpages highlights the lack of enforcement by local authorities and provides the opportunity to use this tool to enforce the control on restaurants illegally serving to their customers this protected species. Although webpages with recipes do not directly indicate the consumption of the date mussel, the fact that in many cases the customers take pictures of the plates with date mussels is a robust indication of the illegal trade and the lack of information, which creates the demand and promotes the illegal fishery.

9. Conclusions

The illegal harvesting of the date mussel *L. lithophaga* continues to be one of the heaviest forms of human impact on the shallow rocky subtidal. This illegal activity, provokes long-term and partially irreversible impacts on local assemblages, and exacerbates the effects of other sources of impact, with the consequence that recent analysis carried out at EU level defined the Mediterranean shallow rocky subtidal habitats in a vulnerable state (Gubbay et al., 2016; Bevilacqua et al., in press). The data analysis reported in this study points out that this practice is, with limited exceptions, widely widespread among Mediterranean countries, including in marine protected areas. Despite national and international legislations protect this species and rocky reef habitats from this destructive practice, we also report that the consumption of date mussels is far from being ceased.

Urgent measures to contrast this phenomenon should be taken, coupled with restoration actions. Here it is provided the first estimate of the economic impacts, either in terms of ecosystem services, and in terms of costs for the environmental restoration of the impacted habitats. In addition, there are several intangible, aesthetic and recreational values, which are difficult to estimate comprehensively. The present study indicates that the impact of illegal *L. lithophaga* fishery is huge and that the costs for active restoration intervention are also considerable. In addition, the restoration of the damaged rocks is extremely complex, given the complete loss of all species inhabiting the rocks and not only the date mussels.

This problem is surely exacerbated by the limited public awareness on the impact of this illegal fishery. The analysis of TripAdvisor's recensions on restaurants serving date mussels in spite of all prohibitions indicate that there is a need for coordinated, transnational actions promoting educational campaigns on mass media, also using apps aimed at warning that date mussel consumption is illegal. This could contribute to reduce the demand of *L. lithophaga*, especially in touristic areas, thus limiting or stopping its harvesting. Consumers must also be warned about the potential risks for their health associated with the consumption of the date mussels, which bioaccumulate heavy metals and other xenobiotics, often in concentrations above thresholds levels recommended by the WHO (1973). Finally, we also suggest that more investments should be dedicated to the Coast Guard and other institutions to enforce the controls and combat the illegal fishery along the Mediterranean coasts.

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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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