THINKING BEYOND THE DATA

Artificial Marine Micro-Reserves Networks (AMMRNs): an innovative approach to conserve marine littoral biodiversity and protect endangered species

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Artificial Marine Reserve Networks; breakwaters; coastal engineering; endangered and invasive species; harbours and ports; reserve effect.

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Abstract
Coastal engineering works, especially the outer breakwaters of ports where environmental conditions are usually good, often constitute new habitats for marine littoral species. Their potential indirect contribution to the regeneration and conservation of protected species opens up a new perspective in protection of marine biodiversity. This is particularly true when these works harbour, as we show here, important reproductive populations of species that are threatened or even in danger of extinction. We provide integrated data on protected marine species in Southern Iberia established on different substrata (quarried dolomitic rocks, concrete cubic blocks, concrete tetrapods and vertical concrete walls) that are used in the construction of artificial levees that could potentially be Artificial Marine Micro-Reserves (AMMRs). We also present the first evidence of the ‘reserve effect’ in potential AMMRs and we discuss the need for the creation of AMMRs including their effective networking (AMMRNs), supporting data for which has been observed by studying coastal facilities subjected to strict access restrictions (for security reasons, not conservation). These facilities have acted as valuable proxies and, in reality, potentially act as AMMRs, as well as having a role in helping to detect and control invasive species. We discuss the ecological engineering aspects related to the design and type of materials used in coastal constructions with a view to aiding the integration of these into existing coastal ecosystems as well as promoting greater settlement of species and therefore increases in biodiversity. Finally, the environmental implications of AMMRNs within the future implementation strategy of the Water Framework Directive 2000/60 EC are also discussed.

Introduction
Many authors have reported on the increased rates of extinction and depletion of many of the world’s species in historical times (Terborgh 1974; Primack & Ros 2002). The marine sphere, particularly coastal environments, is an area where human impacts are particularly keenly felt, given that a significant proportion of the world’s population live by, and actively use and exploit, the coast (Jackson et al. 2001). There is a growing need for innovative approaches to environmental conservation that integrate the various stakeholders in a synergistic manner to the benefit of all concerned. Such approaches are urgently needed given that anthropic demands on coastlines are expected to increase in the future (Airoldi et al. 2005). Many reasons are given for the conservation of species and habitats (Balmford et al. 2002) involving modern developments in systematic conservation planning and
design of Marine Protected Areas (MPAs) (Beger et al. 2010; Mills et al. 2010; Carvalho et al. 2011; Lester et al. 2013; Portman et al. 2013), considering the connectivity among them (Almany et al. 2009; Beger et al. 2010; Kininmonth et al. 2011; Olds et al. 2012).

Even though many strategies have been proposed for the protection of marine populations (improving of water quality, preventing of overexploitation and spread of exotic species), reserves offer a different type of protection: a spatially explicit form, often permanent, that permits a degree of restriction of human activities (Allison et al. 1998). MPAs represent an efficient way of conserving marine fishing resources, as well as protecting ecosystems from human disturbances (García-Charton et al. 2008). Reserves by themselves cannot guarantee the replenishment of populations of many species. Some authors have argued that there are classes of species for which reserves are of little use, specifically those with planktonic larvae or adults (Kenchington 1990). However, other species with planktonic larvae or large adult ranges may have a stage that is dependent on nursery areas, spawning sites or calving sites. Such species may be protected by reserves if the critical areas can be identified (Allison et al. 1998). In this context, breeding populations of many threatened invertebrates have been detected on artificial substrates in marine environment. They could be effectively protected using different approaches in marine conservation planning.

Many artificial coastal structures such as breakwaters, piers and protective armoury (often referred to as ‘riprap’) can provide habitats for many marine littoral species, particularly along areas exposed to the open sea or otherwise exposed to elevated levels of hydrodynamism (Davis et al. 2002). However, this has usually been considered habitat of secondary importance when compared with natural coastlines and as such has received less attention. García-Gómez et al. (2011) illustrated how such engineering works can benefit conservation efforts indirectly by acting as important small-scale repositories of breeding populations of endangered species, opening up a novel and innovative perspective to the management of these protected species.

The importance of coastal harbour works in the protection, monitoring and conservation of endangered species was initially highlighted for one endangered species, *Patella ferruginea* (Guerra-García et al. 2004a) and subsequently for other protected species (García-Gómez et al. 2011, 2012). This led to the proposal for a new form of environmental protection, the ‘Artificial Marine Micro-Reserve’ (AMMR), defined as an artificial coastal construction which, by mutual agreement between owners and government, is protected due to the environmental value of species or ecosystems that it hosts (García-Gómez et al. 2011). One of the main determinants in the development of the proposal was the massive presence of more than 14,000 specimens of *P. ferruginea* on artificial substrata of port of Ceuta (4000 specimens inside, 10,000 outside) (Rivera-Ingraham et al. 2011a), almost eight times more than the total number (around 1800) recorded for the entirety of the Southern Iberian Peninsula (Arroyo et al. 2011).

García-Gómez et al. (2011) pointed out that due to its intertidal habit, *P. ferruginea* is vulnerable not only to negative impacts such as pollutant spills but also to direct collection by humans as well as other anthropic impacts. Given that natural coastlines are usually publicly accessible, this species cannot be as effectively protected as in artificial habitats, which can be literally fenced off and/or kept under strict surveillance. Moreover, it is easier to develop contingency measures and effective protection of endangered species along artificial coastal facilities, among several other significant benefits of AMMRs which are highlighted by these authors.

In addition, the management of individuals in artificial areas could be facilitated by AMMRs with strictly protected zones (e.g. for programmes to reintroduce the species in areas where it is extinct locally, where new recruits could be installed on artificial plates). In this regard, some experiments have been successfully carried out in the port of Ceuta (Rivera-Ingraham et al. 2011b).

The concept of AMMR exceeds the geographical area of Europe and can be extended to other continents in countries with a coastline where protected species exist (or may need protection in the future), which have a tendency to naturally settle on artificial coastal installations, thus establishing reproductive foci, especially on breakwaters and storm protection jetties. To date there have been no studies focused on the protection of protected species diversity on artificial substrates in order to assess their possible role in conservation.

Networks of reserves have been advocated by numerous researchers (Salm & Clark 1989; Ballantine 1991; Dyer & Holland 1991; Bohnsack 1992; Quinn et al. 1993; Castilla & Fernández 1996) as a potentially effective solution to large-scale reserve coverage while applying restrictions to only a small fraction of exploited areas. Researchers propose that such networks, properly designed, could provide several replicate source populations, reduce region-wide risk of anomalous effects on a single reserve and increase the potential benefits to non-reserve areas by increasing the connectivity between protected and unprotected areas (Allison et al. 1998). Our proposal for the creation of AMMRs and AMMRNs (Artificial Marine Micro-Reserve Networks) strictly follows the philosophy that to protect species, habitats must be protected (OOPEU 2004). In the present case, *P. ferruginea* occur naturally and as effective breeding
populations on artificial coastal installations that come under different forms of ownership.

On a larger scale the creation of AMMRNs should also be supported, as these, properly monitored and managed, would not only aid the conservation of protected species but by safeguarding larger individuals (which contribute disproportionately to fecundity), would facilitate, a priori, gene flow between sub-populations and encourage settlement and colonization of new sites (Alexander & Gladstone 2013). Established networks would aid conservation efforts not only by extending the distribution of these species but also by buffering the effects of any isolated negative impacts to network nodes (such as a localized oil spill at a port) and enhancing the capacity for subsequent recovery.

Finally, AMMRNs can play a particularly important role in the conservation of marine invertebrates, and aid in further research on these, especially as invertebrates are the least protected marine organisms, as shown in the IUCN Red List categories and also CITES. In fact, the number of scientific papers on invertebrate families listed by IUCN is extremely low (e.g. 1000 times lower than for sea turtles) compared with those published for bony fishes, elasmobranchs, reptiles and seabirds (McClenachan et al. 2012). AMMRNs could play an active role in the systematic conservation planning process tailored to complex environments (see Giakoumi et al. 2012). Hence, the main objective of the present study is to analyze and discuss the need for the creation of AMMRNs, based on integrative data.

### Methods

The in situ observations of protected species located on jetty and breakwaters reported in Table 1 were made during monitoring programmes conducted in the Strait of Gibraltar and the Mediterranean coast of Andalucía and Gibraltar (Southern Iberian Peninsula), specifically in Ceuta (35°53.07' N, 5°18'45.90" W; July–August, 1997–1998), Tarifa (36°00'29.05" N, 5°36'03.64" W; July 2009) Algeciras (36°08'25.58" N, 5°25'48.35" W; July–September 1996), La Línea (36°09'20.70" N, 5°21'51.17" W; July–September 2012). Hence, the main objective of the present study is to analyze and discuss the need for the creation of AMMRNs, based on integrative data.

<table>
<thead>
<tr>
<th>Species</th>
<th>Dolomitic quarried rock</th>
<th>Cubic concrete block</th>
<th>Concrete tetrapod</th>
<th>Vertical concrete wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithophyllum byssoides&lt;sup&gt;a&lt;/sup&gt;</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>+</td>
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<tr>
<td>Patella ferruginea&lt;sup&gt;a&lt;/sup&gt;</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Cymbula nigra</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Dendropoma petraeum&lt;sup&gt;a&lt;/sup&gt;</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Tethya aurantium</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Astroclon falcatus&lt;sup&gt;a&lt;/sup&gt;</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>+</td>
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<tr>
<td>Lithophaga lithophaga&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Pinna nobilis&lt;sup&gt;b&lt;/sup&gt;</td>
<td>+</td>
<td>+</td>
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<td>+</td>
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<tr>
<td>Pinna rudis&lt;sup&gt;b&lt;/sup&gt;</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Charonia lampas</td>
<td>+</td>
<td>+</td>
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<tr>
<td>Lurida lurida</td>
<td>+</td>
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<tr>
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<td>+</td>
<td>–</td>
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<td>–</td>
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<tr>
<td>Spongia agaricina</td>
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<td>+</td>
<td>–</td>
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</tr>
<tr>
<td>Homarus gammarus</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Palinurus elephas</td>
<td>+</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Scyllarus arctus</td>
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<td>–</td>
<td>–</td>
<td>+</td>
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<td>Maja squinado</td>
<td>+</td>
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<tr>
<td>Paracentrotus lividus&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>+</td>
<td>–</td>
<td>+</td>
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<tr>
<td>Epinephelus marginatus</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Sciaena umbra</td>
<td>+</td>
<td>–</td>
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</tr>
</tbody>
</table>

<sup>a</sup>Strictly sessile or sedentary species (when adult) frequently found on potential AMMRs with high numbers of reproductive individuals.

<sup>b</sup>Pinna nobilis and Pinna rudis individuals have been found within sediments both between and immediately surrounding artificial reefs and breakwaters. There is evidence that the protection afforded to these and similar soft-bottom species by their close proximity to breakwaters from activities such as sea bed conch raking allows the long-term survival of larger individuals that can contribute disproportionately to the species’ survival prospects, and moreover extends the conservation value of AMMRs to associated substrates (see text).
1996), Gibraltar (36°07′56.61″ N, 5°21′47.27″ W; June–August 2005), La Mamola (36°44′55.20″ N, 3°16′42.12″ W; December, 2007) and Motril (36°43′04.51″ N, 3°31′23.15″ W; October, 2011). We identified four types of artificial substrates: quarried dolomite/limestone boulders, often referred to as ‘riprap’, cubic concrete blocks, concrete tetrapods and vertical concrete walls. Detailed surveys were carried out both along the intertidal and the subtidal (down to 20 m depth) of these four substrate types. We report on the presence or absence of species that are presently under some form of statutory protection (international, national and/or regional). We have avoided in this case any form of quantification given the different characteristics of the various species, with some being strictly sessile in their adult stage (macrophytes, sponges, anthozoans, colonial vermetids, gastropods and bivalve molluscs), partially sessile during low tide (patellids) and vagile (decapod crustaceans, ranellid gastropods and cipreids, echinoid and asteroid echinoderms, and bony fishes).

In the case of *P. ferruginea*, one of the protected species identified as endangered, all breakwaters in the South Bay of Ceuta were surveyed in their entirety between 2006 and 2008. To have a spatial reference for the position of individuals in different areas of the docks, *P. ferruginea* individuals were counted in 10-m-long transects of coastline, measured parallel to the waterline. Each specimen was measured using a vernier calliper. After calculating the density of individuals within each of the transects, we compared the density of individuals between the sides facing the channel exit (see Fig. 1) and those oriented in the opposite direction, using a nonparametric Kruskal–Wallis test. However, to compare the mean sizes of individuals on both sides, every specimen was considered individually.

To establish whether there exists a density decrease at the large biogeographical scale away from the Strait of Gibraltar towards the northeast along the Southern Iberian Peninsula, the breakwaters of the port of Estepona, the breakwaters of the port of Estepona (36°24′44.94″ N, 5°09′24.30″ W, July–August 2009), Marbella–La Bajadilla (36°30′20.28″ N, 4°52′31.00″ W, July–August 2010) and Torremolinos (36°35′38.28″ N, 4°30′39.49″ W; August–September 2011) were surveyed in their entirety. All the breakwaters surveyed were very similar in construction and orientation, which made them readily comparable.

**Results**

**Protected species observed in different types of potential AMMRs substrates**

The protected species observed to be associated with artificial coastal breakwaters and harbour facilities along the south of the Iberian Peninsula and Ceuta in North Africa are detailed in Table 1, specifying the common location of each species on each of the four types of substrates sampled: dolomite rock quarry, cubic blocks of concrete, concrete tetrapods and vertical concrete walls. The majority of intertidal and subtidal protected species referred to in the text are illustrated in Figs 2 and 3.

**Intertidal species and forms of protection**

3. *Cymbula nigra* (Da Costa, 1771): Berne Convention (Annex II: strictly protected fauna species), the Barcelona Convention (Annex II: endangered marine species or threatened species) and Data Book of the Invertebrates of Andalusia (category ‘vulnerable’).

**Sublittoral species and forms of protection**

2. *Astroides calycularis* (Pallas, 1766): Berne Convention (Annex II: strictly protected fauna species), the Barcelona Convention (Annex II marine species endangered or threatened), CITES (Appendix II species are not necessarily endangered, but in which trade must be controlled to avoid utilization incompatible with their survival), Spanish Catalogue of Threatened Species

3 *Lithophaga lithophaga* (Linnaeus, 1758): Berne Convention (Annex II: strictly protected fauna species), the Barcelona Convention (Annex II: endangered marine species or threatened), Habitats Directive (Annex V: animal and plant species of interest whose taking in the wild and exploitation may be subject to management measures), CITES (Appendix II species not necessarily threatened with extinction, but in which trade must be controlled to avoid utilization incompatible with their survival), Red Data Book of the Invertebrates of Andalusia (category 'vulnerable') and Government of Gibraltar Nature Protection Ordinance 1991 (category 'strictly protected').


species of interest whose taking in the wild and exploitation may be subject to management measures), Red Data Book of the Invertebrates of Andalusia (category ‘vulnerable’) and Government of Gibraltar Nature Protection Ordinance 1991 (category ‘strictly protected’).

9 Ophidaster ophiolus (Lamarck, 1816): Berne Convention (Annex II: strictly protected fauna species), the Barcelona Convention (Annex II: endangered marine species or threatened species) and Data Book of the Invertebrates of Andalusia (category ‘vulnerable’).

10 Hippocampus brevirrostris Schinz, 1822: CITES (Appendix II species not necessarily threatened with extinction, but in which trade must be controlled to avoid utilization incompatible with their survival) and Government of Gibraltar Nature Protection Ordinance 1991 (category ‘strictly protected’).

The bivalves P. nobilis and P. rudis were not located directly on the specific substrates under study but were found within soft sediments between the compositional units of the breakwaters or in very close proximity to these (Fa & Finlayson 2008). It is surmised that these specimens derive direct protection from the presence of the breakwaters, due to reduced access but also from the destructive effects of bottom trawlers, a result also observed around wrecks and harbour breakwaters around Gibraltar. These structures also modify water currents which may also contribute to the survival of these species. In fact, P. nobilis has almost completely disappeared from the area studied, except for some isolated specimens detected outside some of the port levees of Gibraltar.

Other species whose exploitation is regulated

Spongia agaricina (Pallas, 1766), Homarus gammarus (Linnaeus, 1758), Palinurus elephas (Fabricius, 1787), Scyllarides arcticus (Linnaeus, 1758), Maja squinado (Herbst, 1788), Paracentrotus lividus (Lamarck, 1816), Epinephelus marginatus (Lowe, 1834), Sciaena umbra Linnaeus, 1758: Barcelona Convention (Annex III), Berne Convention (Appendix III) and/or IUCN Red List. Maja squinado is also strictly protected under the Government of Gibraltar Nature Protection Ordinance 1991.

The ‘reserve effect’ in AMMRs

The Port of Ceuta is exceptional from an environmental point of view because of its two antagonistically located inputs, creating a high-energy hydrodynamic pump which flushes the entire harbour every 6-h tidal cycle (Fig. 1). Due to this unique circumstance, some 4000 specimens of the endangered marine limpet P. ferruginea are established within the Port (Rivera-Ingraham et al. 2011a). We infer that during the reproductive phase, synchronously released gametes from both sexes are trapped for a while within the port, thereby increasing the probability of external fertilization above that expected in the open sea. Moreover, the larvae can only exit via the northern harbour mouth or via the mediaeval moat to the south, locally known as the ‘Foso’, depending on the state of the tide.

An extensive survey and census of the protected species P. ferruginea was carried out by Rivera-Ingraham et al. (2011a) within the southern bay of the Port of Ceuta. We have re-analysed the data presented to test the hypothesis that the ‘reserve effect’ is acting within this harbour, which would therefore be operating as an AMMR. The present study confirms that the breakwaters within this area are heavily colonized by numerous individuals of P. ferruginea, highlighting for the first time significant differences in the spatial distribution of densities. When data are grouped into 10-m-long transects along the breakwaters, the highest densities are obtained along the sides closest to and facing the moat (6.62 ± 5.25 ind.-m⁻¹), with the outward-facing sides presenting significantly lower densities (3.99 ± 4.33 ind. m⁻¹) (K = 3.71, P < 0.05). This observation is best explained via a model of higher viability of successful settlement due to the hydrodynamics of the larval-carrying outflow from the moat. The results are presented graphically in Fig. 1. This significant density differential is evident even on breakwaters very close to the outflow such as the breakwater immediately to the west of the moat, which is essentially a continuation of its western side. We suggest that this is probably due to the great difficulty of forcing the outgoing hydrodynamic tidal current output to loop back on itself, and supports our view that these sub-populations of the South Bay are fed by recruits from reproductive events occurring inside the port. This clearly illustrates the positive effects that AMMRs can have due to their ability to export larvae and encourage recruitment in surrounding areas. However, molecular or equivalent work is necessary to fully assess the possibility that there is genetic flow with populations elsewhere outside the harbour.

Similarly, the observation that the average size of individuals located along the sides of breakwaters facing the moat exit is significantly larger than that of individuals on sides facing in the opposite direction (3.76 ± 1.55 cm versus 3.04 ± 1.50 cm, respectively, K = 261.95, P < 0.001). This finding is of particular interest if we consider that individuals along both sides of any breakwater are exposed to the same probability of collection by humans. This effect further supports the hypothesis that the sides of breakwaters facing the moat channel benefit from not only a higher larval recruitment but also from increased nutrient levels stemming from the interior of the Port, which result in increased algal microfilm...
biomass and turnover, reflected in turn by an increased growth rate in the limpets.

To confirm that the Strait of Gibraltar houses a significant population of *P. ferruginea* (mainly in Ceuta and, to a lesser extent, in Gibraltar and the surrounding coastline) we censused numbers of this species along port structures (Estepona, Marbella and Benalmadena) along the Southern Mediterranean coastline. The results obtained indicate a decreasing number of individuals with increasing distance away from the area of the Strait, regardless of the fact that the general structure and orientation of all the port areas studied were remarkably similar. These results are shown in Table 2 and Fig. 4.

**Applied Ecological/Conservation Aspects and Environmental Implications of AMMRs and AMMRNs: A Discussion**

Protected species and the reserve effect in AMMRs and AMMRNs: principal supporting arguments for their validation as a new form of protection

Espinosa et al. (2009) found that along artificial breakwaters protected by strict security restrictions, such as the rock armoury of the Airport of Gibraltar or the restricted area surrounding the Civil Guard Station in the Port of Ceuta, *P. ferruginea*, the most emblematic species of potential AMMRs in European waters, tends to grow to its maximum size (about 9–10 cm) corresponding mostly to females. This limpet is a protandrous hermaphrodite: when juvenile individuals reach sexual maturity they are all male and over time and with increasing size, become females. A well-distributed range of size classes with correspondingly large individuals favours a more balanced sex ratio in the population (very easily affected by direct extraction of the larger specimens) and increased reproductive output. Figure 5 graphically illustrates how the observed distribution of sizes within the Port of Ceuta varies depending on whether the area is (i) not guarded (the curve tends to be slightly skewed to the left, with the 2–3-cm size category being the most common), (ii) guarded but inconsistently monitored (again, the 2–3-cm category has the highest frequency, but there is a slight extension of the tail to the right, indicating some larger specimens, and (iii) under strict surveillance (here the curve tends to be heavily right-skewed, most the 7–8-cm size category being the most frequent). The latter clearly reflects a positive ‘reserve effect’ within a strictly monitored area.

Reserves can increase the density and average size of individuals (Polunin & Roberts 1993; Roberts 1995). Because larger, older individuals are typically much more important to reproduction in a population than young, small individuals, this change in the population structure can drastically increase the reproductive output of the population protected in reserves (Bohnsack 1992). In fact, Espinosa et al. (2006) reported results which showed that a single female of 8 cm length would release a similar amount of oocytes as 10 females of 6 cm size. This 10-fold increase in reproductive potential with only a 2-cm increase in length means that to avoid the decline of certain endangered species, it is important not only to keep wild populations in a balanced sex ratio but also to maintain high numbers of large females. This is one of the most obvious benefits that future AMMRs could provide. The establishment of the ‘reserve effect’, with balanced sex ratios and large reproductive specimens, could over time lead to long-term viability of these populations, provided that official bodies already implementing security restrictions along certain coastal installations support the initiative, at no additional costs to the relevant authorities.

The efficiency of reproduction within the port can be deduced from the lowered dispersal probability of gametes when compared with open and exposed coastlines. It is known that sperm in such marine species disperses quickly, making fertilization unlikely some distance from the male who released it (Handel 1976; Wilson 1983; Pennington 1985; Denny & Shibata 1989; Okubo & Levin 1989; Grosberg 1991; Levitan 1991; Babcock et al. 1994). This is a limitation that can severely affect reproductive success in marine invertebrates with external fertilization (Levitan & Petersen 1995). This problem, for the reasons outlined above (reduced water movement

Table 2. Reduction in numbers of *Patella ferruginea* individuals along the Southern Mediterranean coastline of Andalucía with increasing distance away from the Strait of Gibraltar (nearest location containing high densities of specimens with a significant proportion of large, actively reproducing individuals).

<table>
<thead>
<tr>
<th>Distance from the Strait of Gibraltar (km)</th>
<th>No. of individuals</th>
<th>Mean (cm)</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estepona Port</td>
<td>38</td>
<td>62</td>
<td>3.35</td>
</tr>
<tr>
<td>Marbella Port</td>
<td>56</td>
<td>27</td>
<td>3.6</td>
</tr>
<tr>
<td>Benalmádena Port</td>
<td>86</td>
<td>4</td>
<td>4.37</td>
</tr>
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</table>
Fig. 4. Location of the studied ports along the Southern Iberian Mediterranean coastline. Distances from the zone of maximum densities of Patella ferruginea at the Eastern end of the Strait of Gibraltar are shown.

Fig. 5. Size-frequency graphs for Patella ferruginea at different stations along artificial breakwaters within the harbour of Ceuta. (A) Not guarded with open access to the public. (B) Guarded but inconsistently monitored. (C) Under strict surveillance (Espinosa et al. 2009).
and wave action, but not stagnant), should be quite diminished in a port such as that of Ceuta and indicates ways in which coastal developments might incorporate design features that maximize fertilization and recruitment.

Many coastal infrastructures are important habitats for protected species, many of which reach very high densities in these sites (García-Gómez et al. 2012). The importance of such structures as potential reserves has already been suggested by Guerra-García et al. (2004b). In this sense, the surveillance of some of these artificial enclaves for security or other similar reasons has reduced the mortality associated with public access such as harvesting for different purposes or trampling, ensuring that many specimens reach the maximum size, thereby exponentially increasing reproductive capacity (Espinosa et al. 2006, 2009). Consequently, these enclaves, which have been under strict surveillance, have become conservation hotspots that export larvae to adjacent areas. The importance of individuals reaching larger sizes is paramount for the future viability of populations, so that eliminating size-based collection of larger individuals is vital to prevent local extinctions. In this regard, population viability analyses (PVA) can be very useful. Rivera-Ingraham et al. (2011c) carried out PVAs for different types of size-based mortality (Fig. 6). A population in which only specimens larger than 5 cm were protected from non-natural mortality (by harvesting or other factors) had a low probability of extinction (Fig. 6A) with a long-term outlook very similar to a population in which all limpets were protected from non-natural sources of mortality (Fig. 6B); populations where non-natural mortality occurs to large-sized individuals led to very rapid population collapse (Fig. 6C).

The preliminary census of *P. ferruginea* in Mediterranean ports near the population hot-spot of the Strait of Gibraltar (the Ceuta Harbour population has been estimated at over 14,000 specimens, Rivera-Ingraham et al. 2011b), indicates a progressive reduction of limpet numbers, despite the favourable dispersing influence of the current loop of the Alboran Sea. In this sense, our observations (see Table 2, Fig. 4) are in agreement with the surface dispersion model formulated by Periánuez (2007) for the Alboran Sea, which predicts the current path (from west to east) in the Southern Iberian Peninsula (eastern coast of Andalusia), from the Northern Straits of Gibraltar to the Alboran Sea. It shows the position of particles 2.5, 12.5 and 27.5 days after instantaneous liberation from the central part of the Gibraltar Strait (10 m s\(^{-1}\) wind blowing from the East is included) and supports the necessary connectivity which must be ensured between the constituent units of a network of AMMRs in Southern Iberian coasts.

We therefore conclude that *P. ferruginea* probably has a low dispersal capacity, which reinforces the need to create networks of AMMRs, each with no more than 30 km distance between its constituent units (ideally even less), and provided that there are no reproductive populations in intermediate natural areas. These multiple population foci can generate genetic bridges, provide stability and encourage growth for the re-establishment of a continuously distributed breeding population. This is consistent

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**Fig. 6.** Results of (1) population viability analyses and (2) extinction probability for each of the three models considered in this study. (A) Protection of only individuals of size larger than 5 cm. (B) Total protection of all individuals taking into account only natural (non-anthropogenic) causes of mortality. (C) Evolution of the number of individuals taking into account both natural and anthropogenic causes of mortality (Rivera-Ingraham et al. 2011c).
with the proposal of Shanks et al. (2003) and Boudouresque et al. (2005), who considered such a scheme of a small network of marine reserves separated by a few tens of km as a particularly suitable model, from a conservation point of view, for the Mediterranean. In the context of MPAs, connectivity must be guaranteed to achieve conservation objectives, for which the size and distance between MPAs is one of the main factors. In this context, there is a reasonable scientific consensus that networks of a high number of small reserves will be more effective than a smaller number of large ones in the marine environment (see Shanks et al. 2003). With regard to distance, some authors (Boudouresque 1996; Shanks et al. 2003) estimated that reserves spaced c. 20 km apart should support long-range dispersing species, by encountering reserves frequently enough to ensure sustainability of populations and stocks. The AMMRNs fit the above-mentioned requirements.

**Artificial habitats: AMMRs versus artificial reefs (ARs) and shipwrecks**

IUCN (1988) defines a MPA as any area of the intertidal of subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part of the enclosed environment. The European Artificial Reef Research Network (EARRN) defines an artificial reef (AR) as a submerged structure placed on the substratum (sea bed) deliberately to mimic some characteristics of a natural reef (see Baine 2001).

According to these definitions, the AMMRs are not MPAs, and AMMRs and shipwrecks are not ARs. However, the MPAs could include AMMRs, ARs and shipwrecks. On the other hand, the concept of AMMR (García-Gómez et al. 2011) could be extended in the future to specific systems of ARs (generally created to enhance coastal fisheries) that may also play an important role in the conservation and connectivity of threatened or endangered species, although they have no commercial value.

In fact, the AMMRs were proposed for previously constructed coastal defence structures (not for biological function) on which stable and breeding populations of marine protected species are established and whose management, environmental surveillance and monitoring could efficiently contribute to their conservation. Therefore, the creation of AMMRs is not intended to promote a new conservation strategy based on *ad hoc* construction of artificial coastal defence structures. On the contrary, the objective is that such structures previously built and later used as new habitats by protected species, can be legally recognized for a better management and conservation of these species.

Many studies have focused on epibiota of man-made coastal defence structures (Connell & Glasby 1999; Davis et al. 2002; Bacchiocchi & Airoldi 2003; Chapman 2003) and such structures have been considered as artificial habitats for marine life (Moschella et al. 2005). However, these structures have not been suggested as AMMRs to enhance the protection, research and conservation of marine protected species that could be found on them.

Comparisons between AMMRs and other artificial habitats will be established in future, especially with ARs designed, funded and submerged *ad hoc* to enhance marine biodiversity and coastal fisheries (Bohnsack & Sutherland 1985; Bohnsack 1991; Baine 2001; García-Gómez 2004). Similarly, shipwrecks (Fagundes-Netto et al. 2001; Arena et al. 2007; Walker et al. 2007) are oases of biodiversity, especially on soft bottoms. However, the AMMRs show the important ecological advantage of including the intertidal zone (absent typically in ARs and shipwrecks), contributing effectively to the protection and conservation of intertidal species, as shown in this paper. Intertidal communities are located at the interface of the land and the sea; they are open ecosystems, with steep environmental gradients and their susceptibility to both terrestrial and marine disturbances makes them more vulnerable than sublittoral and offshore habitats (Thompson et al. 2002).

Although many publications highlight the benefits of ARs in the littoral zone (see review by Baine 2001), neither ARs or AMMRNs can compensate for the negative effects of coastal cities and infrastructure in the littoral zone with loss of biodiversity and important changes in the structure and function of coastal ecosystems and biological interactions (e.g. Underwood & Jernakoff 1984; Estacio et al. 1997; Airoldi 1998, 2003; Guerra-García & García-Gómez 2005a,b; Jonsson et al. 2006; DeLeo et al. 2009; Schlacher et al. 2012). In fact, since the 1960s there has been an unprecedented rate of habitat loss, modification or degradation, with some European countries reporting reductions of over 50% of the original coastal habitat (Airoldi & Beck 2007). In this sense, restoration ecology can contribute to mitigating the problems concerned (Chapman 1999; De Jonge & De Jong 2002; Seaman 2007; Borja et al. 2010). Therefore, AMMRs should only be designed to improve the ecological integration of previously built infrastructure on the coast for non-biological purposes, and never as a pretext for promoting new constructions.

**Towards greater environmental integration in the structural design of coastal structures: implications for AMMRs and AMMRNs**

In previous work, we have emphasized the advantages to marine ecosystems of ‘open’ port works, containing breakwaters with several openings at significantly different
orientations to provide adequate water circulation, as the typical ‘closed’ designs (usually single-opening/same orientation) condemn the water contained within to relative stagnation, with low levels of renewal, increased turbidity and sedimentation as well as having other negative environmental impacts (Estacio et al. 1997; Guerra-García & García-Gómez 2005a,b).

This is an area of increased interest and effort, with renowned research teams and scientific centres actively working on the ecological improvement and optimization of breakwaters and jetties. In this regard, the EICC (Centre for Research on Ecological Impacts on Coastal Cities) from the University of Sydney has developed new lines of research in collaboration with construction companies, to optimize the design of future artificial structures (EICC 2008).

Airoldi et al. (2005) indicate that it is impossible to construct coastal defence structures without causing some impacts on natural habitats. However, they add that it is possible to optimize some of the inevitable consequences of these structures to attain secondary management objectives. In this context, at a European level, the project DELOS (Environmental Design of Low-Relief Coastal Defensive Structures, EVK3-CT-2000-00041) has been implemented. This project aims to promote effective design of low-relief structures (LCS, low-crested structures) for the defence of European coasts while at the same time taking into account specific environmental management objectives, related to the mitigation of impacts on existing habitats or, if advisable, the enhancement of specific natural resources in a sustainable manner. The project involves integrating and valuing the socio-economic and engineering contributions of these low-relief defensive structures with potential ecological impacts over varying spatial (local, regional and European) and temporal (monthly, yearly) scales, including hydrodynamic conditions and environmental relationships. In this context, Bulleri (2006) indicates that, compared with the terrestrial sphere, marine artificial habitats have not received much attention from researchers and therefore our knowledge of their ecological value is scarce.

Some authors have shown the advantages of including environmental criteria in the design and management of these artificial structures (Glasyb & Connell 1999; Davis et al. 2002; Bacchiocchi & Airoldi 2003). Other studies have compared the benthic communities on different types of artificial habitats (Connell & Glasyb 1999; Connell 2001) or have evaluated the suitability of these structures as substitutes for natural rocky substrates, focusing on communities of macrophytes, invertebrates and fishes (Connell & Glasyb 1999; Glasyb & Connell 1999; Davis et al. 2002; Clynick 2006). Some point out that in the future, the construction of such structures will increase for various reasons (population growth, economic factors, climate change). Therefore, it is important that proper management is able to minimize potential environmental impacts on the coast with new design alternatives. The development of structures that allow better circulation of water in enclosed areas and the use of materials and designs that more closely resemble the natural substrates will serve to improve environmental conditions (Vaselli et al. 2008). Moreover, as pointed out by Chapman & Blockley (2009), it is essential to learn how to build coastal urban infrastructures so they can maintain or increase biodiversity, stressing that success depends on the successful union of engineering and ecological understanding.

As previously noted, it is important to highlight that studies such as this one and those reported here do not attempt to justify or encourage civil engineering works and construction of jetties in the coastline, but rather stem from the premise that should these be shown to be necessary, have the relevant legal permits and are going to be deployed, then they should be carried out in an environmentally innovative and integrated manner within the coastal ecosystem.

At present, the philosophy of AMMRs focuses on granting formal protection to already built coastal facilities (or parts thereof) where protected species are found to have settled naturally, confirming both recruitment and growth of these individuals to generate a reproductively viable population. However, for future planned constructions (including formal authorization of amendments to works, extensions of the same or even new constructions) it would be necessary to check that materials and structural designs are environmentally optimized. This will result in an improved integration into the coastal environment, especially if doing so can lead to better recruitment and development of protected species that inhabit the surrounding marine areas. This involves an important challenge for future marine biological research, and in this context, Bulleri & Chapman (2010) point out that improving our understanding of the ecological functioning of marine habitats created by new urban infrastructures, along with the incorporation of ecological coastal engineering criteria, is crucial to preserve marine biodiversity. This is further enhanced by the larger-scale establishment of interconnected networks, which additionally provides a buffering capacity against isolated environmental impacts. The achievement of these objectives depends on close cooperation between engineers, managers and ecologists.

Other environmental contributions of AMMRs and AMMRNs

Monitoring invasive species

Biological invasions occur worldwide and are now considered a major threat to ecosystems (Ruiz et al. 2000;
Hayes & Sliwa 2003; Montelli 2010). In fact, in marine and coastal environments, invasive species have been identified as one of the four greatest threats to the oceans of the world, along with land-based sources of marine pollution, overexploitation of marine resources and physical alteration/destruction of marine habitats. Introduced species are those transported by human activities from their original location, or known geographic range, to another area (Somaio Neves et al. 2007). Such species are considered invasive when they interfere in the establishment and survival of native species, with negative ecological or socio-economic effects (Elliott 2003).

Most introduced species are not invasive, although in many cases environmental factors may favour invasion (Silva et al. 2004). Ballast waters, fouling on boats, and activities associated with aquaculture are considered the main vectors responsible for the introduction of species in the ocean. Meanwhile, ports, especially marinas, can be considered one of the main entry points and subsequent refuges for alien species (Savini et al. 2006). Ports provide suitable habitats for the establishment of species in local fouling communities and may play a role in the spread of invasive species along the coast by recreational vessels (Bulleri & Airoldi 2005; Bulleri & Chapman 2010).

Artificial constructions associated with port facilities often harbour less structured communities at earlier stages of ecological succession when compared with communities on natural substrates. This is usually due to the reduced time since their initial settlement, as many of these structures are only a few years or at most a few tens of years old, with low-levels of disturbance often acting to maintain them. This makes the communities settled on artificial substrates more susceptible to being invaded by alien species (Groom et al. 2006), which gives this type of habitat a key importance in monitoring invasive species.

Before the development of worldwide navigation capabilities, aquatic species dispersed freely through the world’s oceans by natural means, such as ocean currents, weather conditions, winds, ocean surface, and attachment to floating devices. The only barriers to their spread were natural biological and environmental factors such as temperature, salinity, land masses and natural predators. However, current human activities facilitate the circumventing of these natural barriers by many marine and coastal species, allowing them to establish new populations outside their native boundaries and negatively affect native species or cause major ecological and environmental damage, becoming a threat to biodiversity and in many cases an economic problem, too. These invasions have shown a dramatic increase in frequency, extent and damage over the past half century and there is evidence that this trend continues. There is little doubt that this increase is due to the increase of navigation and fishing in the world.

AMMRs can also play a key role in monitoring and preventing the spread of invasive species. The networking of AMMRs in which a monitoring programme of local populations can be conducted, especially with regard to biofouling, would be essential as a tool for active monitoring and control of invasive species. For example, Asparagopsis armata and Asparagopsis taxiformis, typically found in the outer parts of harbours, involve a change in associated macrofaunal communities when compared with native algae in the Strait of Gibraltar (Guerra-García et al. 2012). With regard to the associated macrofauna, we must consider that faunal communities epiphytic on algae, bryozoans and hydroids, are an essential element in port systems. Crustaceans, usually the more diverse group, together with polychaetes and molluscs, play a key role in ecosystem food webs, serving primarily as food for fish. Some invasive species of macrofauna organisms can alter the overall dynamics of the ecosystem and displace native species. This is the case, for example, for the caprellid species Caprella scabra. This species, originally described from Mauritius, Indian Ocean, has invaded the coasts of the Iberian Peninsula during the last decade, spreading throughout the Mediterranean (Guerra-García et al. 2011; Ros et al. 2013a, 2014). This is not only an introduced but also an invasive species which has spread very rapidly, reaching high densities and displacing native species such as Caprella equilibra (Guerra-García et al. 2011). This invasive caprellid reached the Iberian Peninsula through the fouling of ships and initially settled in the marinas. Both marinas and recreational boating play an important role in the occurrence and distribution of exotic invertebrates (Ros et al. 2013b), being a key factor in the secondary spread and range expansion of exotic species (Ros et al. 2014).

Implementing the Water Framework Directive via ecological engineering of coastal works

AMMRs and AMMRNs can also contribute effectively to control and improve the quality of coastal waters. In particular, AMMRs can play a significant role in achieving the objectives of the Water Framework Directive 2000/60/EC (hereafter WFD) (García-Gómez et al. 2012), as, in the near future, they may be an ecological management tool according to the provisions in the Directive, being implemented for each of the water bodies at risk within each River Basin District.

Furthermore, the WFD establishes a framework for water protection in order to prevent, protect and enhance ecological status. However, the Directive recognizes the pressure that some of the uses of the aquatic environment bring to bear and the potential of some of them to compromise compliance with the WFD’s stated environmental objectives. Among these uses are navigation and port
operations. For this reason, water bodies associated with these operations require a specific classification in order to be properly assessed. In Spain, with regard to the implementation of ROM 5.1 (Ley 41 2010), port facilities and their surrounding water bodies are grouped under Port Service Areas, which provides a useful classification to work from:

**Zone I:** Consisting of inland water naturally or artificially sheltered inside the port, which are part of the docks destined for port operations for loading, unloading and transhipment of goods, loading and unloading of passengers, ship building and repair, as well as areas necessary for docking operations.

**Zone II:** Includes the rest of port waters. Its main use is mooring and maritime access.

Ports, including inland water bodies (Zone I) are by necessity areas of very low hydrodynamism, as their main objective is to enable and facilitate navigation and berthing of vessels. This inherent characteristic of the ports hinders the mixing and dispersion of pollutants, contributing to a high concentration in both the water and especially in harbour sediments (Schiff et al. 2007). The WFD considers the waters inside harbours as ‘heavily modified water bodies’ (HMWBs) because they are surface water bodies that have undergone substantial change in their nature as a result of physical and chemical alterations by human activity. The WFD states that by 2015, HMWBs should reach ‘good ecological potential’ and ‘good chemical status’, which would usually require changes to the hydromorphological system which in turn would have significant adverse effects on the area’s specified use or the environment in general (CIS, 2003, 2006). This particular circumstance inherent in internal port waters makes it very difficult to achieve the goal of ‘good ecological potential’ pursued by the WFD, at least for existing ports.

Zone II, which concerns surrounding water bodies outside the port docks, is constituted in most cases of bodies of water that do not require hydromorphological alterations to achieve good ecological status, but the use to which they are usually subjected (anchorage and navigation), their proximity to the Zone I and the absence of quality data on the aquatic environment, warrant their consideration as water bodies at risk of failure to meet quality objectives.

In these cases, the WFD states that specific action programmes and operational controls should be designed to ‘...determine the status of bodies to be considered that may not meet its environmental objectives, and evaluate changes occurring in the status of such bodies resulting from the programs of measures.’ These operational controls are a complementary tool to the inspection system to assess the ecological status of unaltered water bodies (Ondiviela et al. 2007). Within this framework, AMMRs can be a useful tool for the development of systematic checks to assess and determine over time the ecological potential of such bodies of water.

With regard to Zone I, future construction of port facilities should incorporate structural solutions to ensure their functionality, i.e. the reduction of surface hydrodynamics to allow navigation and berthing of vessels efficiently, while maintaining a sufficient water turnover rate in the inner port that enables a level of optimum oxygen concentration for the settlement and functioning of ecological communities that reflect a good ecological status. Renewal also helps maintain moderate levels of oxygen at the sediment–water interface and increases the heterogeneity of the sediments (Guerra-García et al. 2004a). The study of the communities located in ports with different designs allows us to detect a potential solution to the problem. The port of Ceuta, one of the largest in the Strait of Gibraltar, is situated between two bays and has the unique structural feature, as noted above, of two opposing bays that connect through a channel which allows substantial water movement between these two bays. This peculiarity allows the rate of water renovation in some areas within the harbour to increase significantly, which ensures the maintenance of unusual environmental conditions that have contributed to maintain viable populations of endangered species such as the mollusc *Patella ferruginea* Gmelin, 1791 within the inner harbour (Guerra-García et al. 2004b). The presence of this species, usually considered indicative of pristine waters and renewal (Espinosa et al. 2007), can be a very useful indicator of having achieved and/or maintained the ‘good ecological status’ required by the WFD for HMWBs. We believe that, in future, the new harbour breakwaters should consider incorporating linear discontinuities (even if overlapping so as to allow water circulation, but not the entry of waves) or the incorporation of hydrodynamic tunnels located under the water surface, so that, without losing any efficiency of function with regard to protection from wave action, it is possible to increase water turnover and, through that, improve environmental conditions, which can be monitored and controlled via AMMRs.

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