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Human-driven impacts on marine habitats: A regional meta-analysis in the Mediterranean Sea

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ABSTRACT

Habitat destruction is one of the main threats to environmental integrity. Assessing the consequences of human impacts is crucial both to predict and prevent structural and functional changes of habitats. However, to date almost all studies on marine threats, from regional to global scales, have been entirely qualitative and generally based on little more than expert opinion. We have developed a meta-analytical approach to quantify overall effects of various stressors on different Mediterranean habitat types and to compare the relative importance of different impacts across a range of habitats. We first qualitatively reviewed and synthesized 366 experiments (either manipulative or correlative) collected in the literature. After a selection procedure, we finally quantitatively meta-analyzed 158 experiments. We showed that fisheries (destructive or not), species invasion, aquaculture, sedimentation increase, water degradation and urbanization have negative effects on Mediterranean habitats and associated species assemblages. We also explored the overlap between the impacts identified as important in the Mediterranean and those identified by experts as being important globally, highlighting the inadequacies of relying on expert opinion alone. Finally, we drew attention to the critical lack of empirical knowledge about marine systems in many areas of the Mediterranean, which impedes the implementation of effective conservation measures. Our study is the first to synthesize experimental analyses on human-driven impacts on marine habitats across such a broad geographic scale.

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1. Introduction

Just as in terrestrial environments (Sala et al., 2000; Prugh et al., 2008), the world's oceans are subjected to increasing and often unregulated sources of anthropogenic disturbances (Jackson et al., 2001; Lotze et al., 2006; Boero and Bonsdorff, 2007; Hoegh-Guldberg et al., 2007; Halpern et al., 2008). Human activities can lead to homogenization of ecosystems due to reductions in food-web complexity, diversity within functional groups, distribution range, biogenic habitat structure, and size of organisms (Parmesan and Yohe, 2003; Airoldi and Beck, 2007; Airoldi et al., 2008; Dulvy et al., 2008). Entire ecosystems may cease to function in their current form (Hughes, 1994; Hughes et al., 2003; Bellwood et al., 2004; Hoegh-Guldberg et al., 2007), potentially leading to a complete loss of the goods and services derived from those ecosystems by humans (Naeem et al., 1994; Costanza and Mageau, 1999; Chapin et al., 2000; Loreau et al., 2001; Worm et al., 2006). These trends are exacerbated by the growing human populations in coastal areas and increasing need for marine resources (Cardillo et al., 2004; Mora, 2008).

Habitat destruction is considered the most pervasive threat to the diversity, structure, and functioning of marine coastal ecosystems and to the goods and services they provide (Lotze et al., 2006; Hoegh-Guldberg et al., 2007; Airoldi et al., 2008; Halpern et al., 2008; Crain et al., 2009). Destruction of marine habitat has been occurring for at least 150 years (Beck et al., 2009). It is a ubiquitous phenomenon (Pimm et al., 1995; Novacek and Cleland, 2001) occurring at extended spatial scales (thousands of kilometers), which can impair the integrity and functioning of large-scale ecological processes. As such, habitat destruction can decrease population stability and alter patterns of connectivity, thereby isolating populations and communities (Thrush et al., 2006, 2008; Mumby and Steneck, 2008). Habitat loss or fragmentation can also exacerbate overfishing by reducing fishable areas or decreasing productivity of marine environments (Newton et al., 2007), and may worsen the effects of global warming, affecting dispersal capacity of many species (Walther et al., 2002; Thomas et al., 2004). Therefore, assessing the impacts of humans on marine habitats, and protecting habitats from harmful impacts are critical for

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the renewal of resources and the sustainable use of marine biodiversity.

However, a complex suite of interacting factors limits the identification of conservation priorities, implementation of mitigation strategies, and accomplishment of effective restoration plans for marine habitats. Major impediments are related to the general lack of baseline data on marine ecosystems prior to large-scale human impacts and to substantial gaps in knowledge on the current distribution, and even classification, of different habitat types (Fraschetti et al., 2008; Halpern et al., 2008). Because of these impediments, the effects of current and emerging threats to marine habitats are largely unknown. Systematic assessments of the vulnerability and/or sensitivity of habitats to stressors have been based on alternative means, such as expert opinion (Halpern et al., 2007, 2008). Although expert opinion approaches can be used as a proxy for true impacts on habitats, they are not as meaningful as quantitative assessments, which are grossly lacking.

The need for more quantitative assessments of human impacts on habitat is particular pressing in the Mediterranean Sea, due to its specific physiographic and biological characteristics, and because of the high anthropogenic pressure on its habitats, both on land (Myers et al., 2000) and at sea (EEA, 2006). Despite its diminutive size, the Mediterranean Sea contains 7% of the world's marine biodiversity (Bianchi and Morri, 2000). Furthermore, approximately one-quarter of marine species in the Mediterranean are endemic to the region (Boero, 2003; Kallianiotis et al., 2004; Briand and Giuliano, 2007). The Mediterranean Sea also contains a high diversity of habitats (RAC/SPA, 2006a), ranging from bioconstructors and seagrass meadows, to shallow hydrothermal vents and deep sea beds. The Mediterranean is recognized as a hot spot of both terrestrial and marine biodiversity (Myers et al., 2000; Spalding et al., 2007; Abdulla et al., 2009), despite evidence suggesting that the basin, influenced by human settlements for millennia, is now becoming one of the most degraded marine ecosystems worldwide (Bianchi and Morri, 2000; EEA, 2006; Halpern et al., 2008; Hertig and Jacobeit, 2008; Beck et al., 2009; Stergiou et al., 2009).

Due to the pressing need to quantify the effects of human impacts on this economically and ecologically important area of the world, we synthesize the ecological consequences of anthropogenic threats to Mediterranean marine habitats. The specific objectives of this study were to: (1) identify effects of human stressors on marine habitats; (2) quantify and compare magnitudes of effects of different stressors on common habitats and identify potential mechanisms underlying different outcomes; (3) identify gaps in knowledge and possible idiosyncrasies between perceived and assessed human threats; and (4) identify directions for future research agendas. We used a meta-analytical approach at the core of our study to quantitatively synthesize existing information on Mediterranean threats from individual studies since several qualitative reviews on different aspects of Mediterranean biodiversity response to human stressors have already been published (Bianchi and Morri, 2000; Galil, 2009). A meta-analysis is defined as "the quantitative synthesis and analysis of a collection of experimental studies" (Osenberg et al., 1999) or "the formal application of quantitative methods to summarize evidence across studies" (Hedges et al., 1999). We acknowledge that a meta-analysis can present several pitfalls (e.g. inadequate presentation of data summaries) and that our approach will be limited to quantitative studies, even though qualitative research may also contribute to the understanding of habitats response to human and environmental stressors. However, we anticipate that the effort of systematically combining quantitative results of stressor impacts at habitat level will provide crucial conclusions about this body of research and help to guide management actions.

2. Methods

2.1. Literature search

We searched the literature using all databases of *ISI Web of Knowledge* for quantitative studies that assessed the effects of human-driven stressors at habitat level, published until 2008 inclusive. We referred to the RAC/SPA (2006a) classification of benthic coastal marine habitat types, recently revised by Fraschetti et al. (2008), which represents a general classification scheme applicable at Mediterranean scale. This list contains 94 habitats that follow a hierarchical structure and refers to the level on the shore (e.g. high shore), the primary substrate in terms of geological features (e.g. sand), and common assemblages and foundation taxa increasing local complexity (e.g. *Posidonia oceanica*). For each habitat, a specific search was carried out within the "Topic" field, with a factorial combination of key-words "Mediterranean" and "impact". Because some studies used the term "effect" instead of "impact", we additionally ran a second search without "impact" but specifying specific stressors (e.g. "fishery", "trawling", "pollution", "sewage"). Each collected experiment was specific to a habitat, the stressor being investigated, the target species, assemblages or ecological phenomenon potentially affected by the stressor (the "target"), and the response variable, or metric, used to quantify that response (the "response"). Experiments fell into specific "habitat-stressor-target-metric" combinations, nested within "habitat-stressor-target" combinations. These combinations will hereafter be referred to as "metric categories" and "target categories", respectively.

We found 366 experiments (either manipulative or correlative) for eight broad habitat types, extracted from 161 publications, and corresponding to a total of nine stressors for a total of 91 target categories (Table 1, Fig. 1, Supplementary material Tables 1 and 2). This does not include reviews or experiments specifically focusing on habitat recovery trajectories after a simulated disturbance (and not on the impact of the disturbance; e.g. Bevilacqua et al., 2006). In addition, quantitative information available from studies analyzing the effects of impacts on multivariate assemblage structure could not be included (however, within these studies, univariate analyses of single response variables are often coupled to the multivariate analyses and these former experiments were included in our database). We obtained more experiments than publications because some studies focused on different types of habitat, stressors, or response variables.

From this database, we eliminated from the subsequent meta-analysis experiments that did not present controls or were pseudoreplicated (54 experiments from 25 studies). Also, lack of standard deviations and/or sample sizes for the measured metrics prevented the use of 24 experiments from 20 studies. When a given target category was unreplicated (i.e. occurred only once in the database), we could not use the corresponding experiment (57 experiments from 34 studies) in the meta-analysis. Further, we could meta-analyze a given target category only if the metric used to assess the impact of a stressor was studied more than once (unique response categories were found in 63 experiments from 37 studies). Finally, when the same data were used several times with the aim of assessing the effect of the same impact, we kept only the most recent experiments (nine experiments from six studies were excluded). Six habitats were left in the final database, for a total of 158 experiments within 44 response categories (Table 2).

Some of the habitat types of the RAC/SPA list of relevant Mediterranean habitats have never been studied within the *ISI* literature. However, all of the habitats included in the database (Table 1) are common all around the Mediterranean coasts (RAC/

Table 1
Occurrence of target categories found in the 133 collected studies. Those included in the meta-analysis are marked with a cross. For details on the corresponding references, see Supplementary material Table 1.

Habitat	Stressor	Target	Occurrence	Meta-analysis
Coralligenous	Fishery (destructive)	Sessile invertebrates	5	x
Coralligenous	Fishery (non-destructive)	Sessile invertebrates	2	
Coralligenous	Mechanical disturbance	Sessile invertebrates	2	
Coralligenous	Sedimentation	Encrusting algae	1	
Coralligenous	Sedimentation	Erect algae	1	
Coralligenous	Sedimentation	Sessile invertebrates	1	
Coralligenous	Sedimentation	Turf algae	1	
Coralligenous	Species invasion	Sessile invertebrates	1	
Coralligenous	Temperature increase	Sessile invertebrates	14	
Coralligenous	Water degradation	Encrusting algae	1	
Coralligenous	Water degradation	Erect algae	1	
Coralligenous	Water degradation	Sessile invertebrates	2	
Coralligenous	Water degradation	Turf algae	1	
Maerl	Fishery (destructive)	Encrusting algae	2	
Maerl	Fishery (destructive)	Erect algae	2	
Maerl	Fishery (destructive)	Sessile invertebrates	2	
Maerl	Fishery (destructive)	Turf algae	2	
Maerl	Fishery (destructive)	Vagile invertebrates	3	
Mud	Aquaculture	Bacteria	1	
Mud	Aquaculture	Chemical variables	1	
Mud	Fishery (destructive)	Chemical variables	2	
Mud	Fishery (destructive)	Physical variables	1	
Mud	Fishery (destructive)	Vagile invertebrates	21	x
Mud	Mechanical disturbance	Vagile invertebrates	1	
Mud	Sedimentation	Vagile invertebrates	6	x
Mud	Water degradation	Vagile invertebrates	1	
Mytilus spp.	Aquaculture	Chemical variables	1	
Mytilus spp.	Species invasion	Sessile invertebrates	1	
Mytilus spp.	Urbanization	Sessile invertebrates	2	
Mytilus spp.	Water degradation	Sessile invertebrates	1	
Phanerogams	Aquaculture	Bacteria	1	
Phanerogams	Aquaculture	Phanerogams	18	x
Phanerogams	Fishery (destructive)	Phanerogams	3	
Phanerogams	Fishery (non-destructive)	Phanerogams	1	
Phanerogams	Mechanical disturbance	Phanerogams	7	x
Phanerogams	Sedimentation	Phanerogams	18	x
Phanerogams	Species invasion	Encrusting algae	1	
Phanerogams	Species invasion	Erect algae	1	
Phanerogams	Species invasion	Phanerogams	11	x
Phanerogams	Species invasion	Turf algae	1	
Phanerogams	Species invasion	Vagile invertebrates	1	
Phanerogams	Temperature increase	Phanerogams	1	
Phanerogams	Urbanization	Encrusting algae	1	
Phanerogams	Urbanization	Erect algae	1	
Phanerogams	Urbanization	Phanerogams	12	x
Phanerogams	Urbanization	Sessile invertebrates	1	
Phanerogams	Water degradation	Phanerogams	20	x
Rocky intertidal	Aquaculture	Vagile invertebrates	1	
Rocky intertidal	Fishery (destructive)	Encrusting algae	1	
Rocky intertidal	Fishery (non-destructive)	Encrusting algae	1	
Rocky intertidal	Fishery (non-destructive)	Erect algae	1	
Rocky intertidal	Fishery (non-destructive)	Turf algae	1	
Rocky intertidal	Mechanical disturbance	Erect algae	1	
Rocky intertidal	Species invasion	Vagile invertebrates	1	
Rocky intertidal	Urbanization	Encrusting algae	2	
Rocky intertidal	Urbanization	Erect algae	5	x
Rocky intertidal	Urbanization	Sessile invertebrates	2	
Rocky intertidal	Urbanization	Turf algae	3	x
Rocky intertidal	Urbanization	Vagile invertebrates	2	
Rocky intertidal	Water degradation	Erect algae	5	
Rocky intertidal	Water degradation	Vagile invertebrates	1	
Rocky subtidal	Fishery (non-destructive)	Barren	2	x
Rocky subtidal	Fishery (non-destructive)	Erect algae	2	x
Rocky subtidal	Fishery (non-destructive)	Turf algae	1	
Rocky subtidal	Mechanical disturbance	Encrusting algae	1	
Rocky subtidal	Mechanical disturbance	Erect algae	1	
Rocky subtidal	Mechanical disturbance	Turf algae	1	
Rocky subtidal	Sedimentation	Chemical variables	1	
Rocky subtidal	Sedimentation	Encrusting algae	2	x
Rocky subtidal	Sedimentation	Erect algae	2	x
Rocky subtidal	Sedimentation	Turf algae	4	x
Rocky subtidal	Species invasion	Encrusting algae	8	x
Rocky subtidal	Species invasion	Erect algae	9	x

(*continued on next page*)

Table 1 (*continued*)

Habitat	Stressor	Target	Occurrence	Meta-analysis
Rocky subtidal	Species invasion	Sessile invertebrates	1	
Rocky subtidal	Species invasion	Turf algae	8	x
Rocky subtidal	Urbanization	Encrusting algae	1	
Rocky subtidal	Urbanization	Erect algae	1	
Rocky subtidal	Urbanization	Turf algae	1	
Rocky subtidal	Water degradation	Erect algae	1	
Rocky subtidal	Water degradation	Vagile invertebrates	1	
Sand	Aquaculture	Bacteria	6	x
Sand	Aquaculture	Chemical variables	23	x
Sand	Aquaculture	Vagile invertebrates	44	x
Sand	Fishery (destructive)	Vagile invertebrates	5	x
Sand	Sedimentation	Vagile invertebrates	3	
Sand	Species invasion	Vagile invertebrates	1	
Sand	Temperature increase	Vagile invertebrates	2	
Sand	Urbanization	Chemical variables	1	
Sand	Urbanization	Vagile invertebrates	4	
Sand	Water degradation	Chemical variables	4	
Sand	Water degradation	Vagile invertebrates	16	x

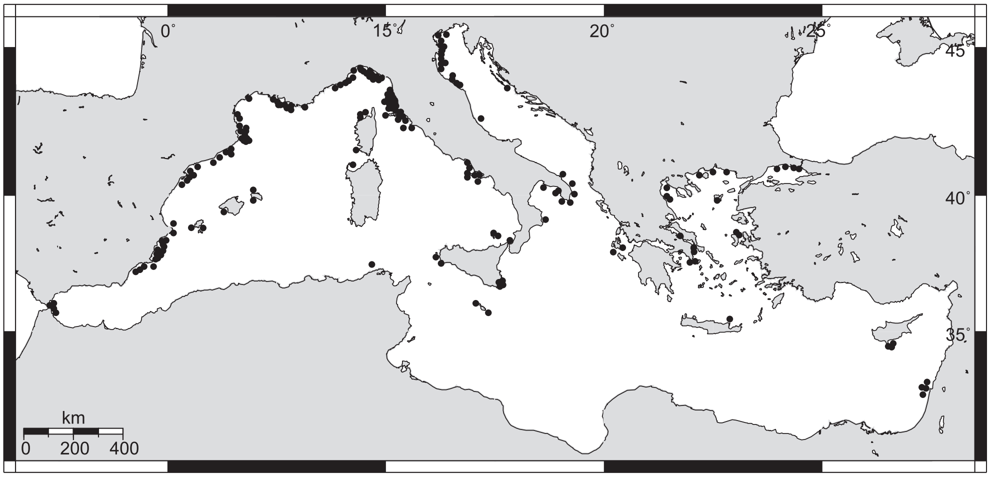

Fig. 1. Geographical distribution of the collected studies on the assessment of the effects of human stressors on marine habitats in the Mediterranean Sea.

SPA, 2006a,b; RAC/SPA, 2009). Seagrasses such as *P. oceanica* can form large meadows from the surface to 40 m depth (Boudouresque et al., 1984). They form highly productive coastal ecosystems, providing habitat for many organisms, including species of commercial value, and providing a significant role as a direct food source for herbivores and also entering detrital food webs (Vizzini, 2009). Intertidal and shallow rocky reefs are among the most productive habitats, sustaining high levels of biodiversity due to their heterogeneity and three-dimensional complexity. They supply food resources, nurseries and shelters for a variety of organisms (Turner et al., 1999). Bioconstructors like coralligenous formations are considered as a typical Mediterranean underwater seascape comprising coralline algal frameworks that grow in dim light conditions and in relatively calm waters (Ballesteros, 2006). This habitat is considered to be of great significance both for fisheries and CO_2 regulation. Due to their vulnerable structure, the formations are destroyed by the operation of various fishing gears. As a result, the recent European Union 1967/2006 Regulation on the management of the Mediterranean fisheries included coralligenous formations in the list of protected habitats (European Commission, 2006). So far, several Mediterranean national initiatives share the aim of mapping the seafloor of the continental margin both for geological and/or biological purposes and for resources management (e.g. http://www.magicproject.it/). However, the lack of maps and georeferenced information on their distribution makes a quantitative evaluation of their extension not feasible at Mediterranean basin scale.

For each habitat, a qualitative review has been undertaken for studies that could not be included in meta-analysis. We considered these qualitative results alongside our quantitative meta-analysis results in order to obtain a more holistic picture of the effects of human impacts on the Mediterranean Sea.

2.2. Data analyses

We used effect sizes to model the differences between impacted and control conditions. We calculated effect sizes with log–response ratios (Hedges et al., 1999) for each response category occurring more than once for a given target category:

$$R_i = \ln(X_{Ii}/X_{Ci})$$

where R_i is the log–response ratio for the response category of the study i, and X_{Ii} and X_{Ci} are the mean values of the metric for study i in impacted (I) and control (C) conditions, respectively.

In addition to obtaining effect sizes for each response category, we also obtained the variances associated with these estimates, which were then used to derive weights in the meta-analysis. Weighted analyses increase the precision of the combined estimates and increase the power of tests (Gurevitch and Hedges, 1999; Osenberg et al., 1999) by giving more weight to the studies

Table 2
Response categories included in the meta-analysis.

Habitat	Stressor	Target	Response	Number of experiments	References
Coralligenous	Fishery (destructive)	Sessile invertebrates	Max basal diameter	2	(Garrabou and Harmelin, 2002; Tsounis et al., 2006)
Coralligenous	Fishery (destructive)	Sessile invertebrates	Max height	2	(Garrabou and Harmelin, 2002; Tsounis et al., 2006)
Mud	Fishery (destructive)	Vagile invertebrates	Biomass	2	(Demestre et al., 2008)
Mud	Fishery (destructive)	Vagile invertebrates	Density	6	(Simboura et al., 1998; De Biasi, 2004; Lampadariou et al., 2005; Munari et al., 2006; Demestre et al., 2008)
Mud	Fishery (destructive)	Vagile invertebrates	Evenness	3	(Simboura et al., 1998; Demestre et al., 2008)
Mud	Fishery (destructive)	Vagile invertebrates	Shannon	3	(Simboura et al., 1998; Demestre et al., 2008)
Mud	Sedimentation	Vagile invertebrates	Density	2	(Simonini et al., 2005, 2007)
Mud	Sedimentation	Vagile invertebrates	Richness	2	(Simonini et al., 2005, 2007)
Mud	Sedimentation	Vagile invertebrates	Shannon	2	(Simonini et al., 2005, 2007)
Phanerogams	Aquaculture	Phanerogams	Leaf density	3	(Delgado et al., 1999; Ruiz et al., 2001; Cancemi et al., 2003)
Phanerogams	Aquaculture	Phanerogams	Rhizome growth rate	4	(Marbà et al., 2006)
Phanerogams	Aquaculture	Phanerogams	Shoot biomass	2	(Delgado et al., 1999; Ruiz et al., 2001)
Phanerogams	Aquaculture	Phanerogams	Shoot density	3	(Delgado et al., 1999; Cancemi et al., 2003; Diaz-Almela et al., 2007)
Phanerogams	Mechanical disturbance	Phanerogams	Shoot density	4	(Ceccherelli et al., 2007)
Phanerogams	Sedimentation	Phanerogams	Production	3	(Guidetti and Fabiano, 2000; Guidetti, 2001; González-Correa et al., 2008)
Phanerogams	Sedimentation	Phanerogams	Rhizome growth rate	3	(Guidetti, 2001; Badalamenti et al., 2006; González-Correa et al., 2008)
Phanerogams	Sedimentation	Phanerogams	Shoot density	2	(Badalamenti et al., 2006; González-Correa et al., 2008)
Phanerogams	Species invasion	Phanerogams	Leaf length	2	(Dumay et al., 2002)
Phanerogams	Species invasion	Phanerogams	Phenol content	2	(Dumay et al., 2004)
Phanerogams	Species invasion	Phanerogams	Production	2	(Dumay et al., 2002)
Phanerogams	Urbanization	Phanerogams	Shoot density	3	(Ruiz and Romero, 2003; Balestri et al., 2004; Montefalcone et al., 2006)
Phanerogams	Water degradation	Phanerogams	Production	2	(Invers et al., 2004; Gacia et al., 2007)
Rocky intertidal	Urbanization	Erect algae	Cover	3	(Benedetti-Cecchi et al., 2001; Guerra-García et al., 2006; Mangialajo et al., 2008)
Rocky intertidal	Urbanization	Turf algae	Cover	2	(Benedetti-Cecchi et al., 2001; Guerra-García et al., 2006)
Rocky subtidal	Fishery (non-destructive)	Barren	Cover	2	(Fraschetti et al., 2005; Guidetti, 2006)
Rocky subtidal	Fishery (non-destructive)	Erect algae	Cover	2	(Fraschetti et al., 2005; Guidetti, 2006)
Rocky subtidal	Sedimentation	Encrusting algae	Cover	2	(Piazzi et al., 2005; Balata et al., 2007)
Rocky subtidal	Sedimentation	Erect algae	Cover	2	(Piazzi et al., 2005; Balata et al., 2007)
Rocky subtidal	Sedimentation	Turf algae	Cover	3	(Airoldi and Virgilio, 1998; Piazzi et al., 2005; Balata et al., 2007)
Rocky subtidal	Species invasion	Encrusting algae	Cover	5	(Piazzi et al., 2001, 2005; Balata et al., 2004; Piazzi and Ceccherelli, 2006; Piazzi and Balata, 2008)
Rocky subtidal	Species invasion	Erect algae	Cover	5	(Piazzi et al., 2001, 2005; Balata et al., 2004; Piazzi and Ceccherelli, 2006; Piazzi and Balata, 2008)
Rocky subtidal	Species invasion	Turf algae	Cover	5	(Piazzi et al., 2001, 2005; Balata et al., 2004; Piazzi and Ceccherelli, 2006; Piazzi and Balata, 2008)
Sand	Aquaculture	Bacteria	Density	4	(Mirto et al., 2000; Danovaro et al., 2004; Bongiorni et al., 2005; Maldonado et al., 2005)
Sand	Aquaculture	Chemical variables	Chlorophyll-a	8	(Karakassis et al., 2000; Mirto et al., 2000; Danovaro et al., 2004; Maldonado et al., 2005; Yucel-Gier et al., 2007; Vezzulli et al., 2008)
Sand	Aquaculture	Chemical variables	Total organic content	8	(Karakassis et al., 2000; Danovaro et al., 2004; Maldonado et al., 2005; Porrello et al., 2005; Vita and Marin, 2007; Yucel-Gier et al., 2007)
Sand	Aquaculture	Chemical variables	Total phosphorus	2	(Aguado-Giménez and García-García, 2004; Porrello et al., 2005)
Sand	Aquaculture	Vagile invertebrates	Biomass	4	(Karakassis et al., 2000; Mirto et al., 2002)
Sand	Aquaculture	Vagile invertebrates	Density	10	(Karakassis et al., 2000; Mirto et al., 2000, 2002; Danovaro et al., 2004; Aguado-Giménez et al., 2007; Apostolaki et al., 2007)
Sand	Aquaculture	Vagile invertebrates	Richness	9	(Karakassis et al., 2000; Danovaro et al., 2004; Aguado-Giménez et al., 2007; Apostolaki et al., 2007; Vita and Marin, 2007)
Sand	Aquaculture	Vagile invertebrates	Shannon	11	(Karakassis et al., 2000; Sanz-Lázaro and Marin, 2006; Aguado-Giménez et al., 2007; Apostolaki et al., 2007; Marin et al., 2007; Vita and Marin, 2007)
Sand	Fishery (destructive)	Vagile invertebrates	Density	3	(Pranovi et al., 2000; Munari et al., 2006; De Biasi and Pacciardi, 2008)
Sand	Water degradation	Vagile invertebrates	Density	4	(Cardell et al., 1999; Guidetti et al., 2000; Raventos et al., 2006; de la Ossa Carretero et al., 2008)
Sand	Water degradation	Vagile invertebrates	Richness	3	(Cardell et al., 1999; Raventos et al., 2006; Espinosa et al., 2007)
Sand	Water degradation	Vagile invertebrates	Shannon	2	(Raventos et al., 2006; Espinosa et al., 2007)

with the most powerful experimental designs (i.e. those with greater and more appropriate replication). Variance of the effect sizes was calculated as:

$$v_i = s_{Ii}^2/\left(N_{Ii}X_{Ii}^2\right) + s_{Ci}^2/\left(N_{Ci}X_{Ci}^2\right)$$

where v_i is the variance associated with the effect size R_i, X_{Ci} and X_{Ii} are defined as above, s_{Ii} and s_{Ci} are the standard deviations associated with X_{Ci} and X_{Ii}, respectively, and N_{Ii} and N_{Ci} are the sample sizes in impacted and control locations, respectively. We then used a meta-analytical framework to incorporate these variances into a weighting scheme:

$$w_i = 1/v_i$$

where w_i is the weight associated with the effect size R_i, and v_i is defined as above. Due to low sample size, we did not include a random component of variation in effect sizes between studies.

For a given response category, weighted cumulative effect sizes were obtained as follows:

$$\bar{R}_k = \frac{\sum_{i=1}^{n_k} w_i R_i}{\sum_{i=1}^{n_k} w_i}$$

where n_k is the number of experiments for the response category k and R_i and w_i are defined as above.

The total heterogeneity was calculated according to Hedges and Olkin (1985):

$$Q_{T_k} = \sum_{i=1}^{n_k} w_i \left(R_i - \bar{R}_k\right)^2$$

and its significance was tested against a χ^2 distributions with $n_k - 1$ degrees of freedom.

All analyses were done using R (R Development Core Team, 2006).

3. Results

3.1. Distribution of the human-driver stressors

Prior to the selection of appropriate studies for meta-analysis (161 studies), the most studied stressors within the 161 collected studies were aquaculture (23%), water degradation (20%), destructive fishery activities (13%), species invasion (12%), urbanization (11%) and sedimentation increase (9%). Other stressors were studied in less than 5% of the cases. The studies were not evenly distributed across the Mediterranean basin. There was a strong disparity in the number of investigations on human-driven impacts between its north-western and north-eastern parts on the one hand, and between its northern and southern parts on the other (Fig. 1). Urbanization has been studied especially in the north-western Mediterranean (Balestri et al., 2004; Mangialajo et al., 2008). Many invasive species have been reported in the Mediterranean Sea, and CIESM recently published an online database of these species, with maps of the distributions at the basin scale (http://www.ciesm.org/online/atlas/intro.htm). However, investigations into the effects of species invasions on habitat are almost entirely limited to the spread of the macroalgae *Caulerpa* through phanerogams and rocky subtidal habitat in the north-western Mediterranean. The effect of aquaculture has been studied across the northern Mediterranean Sea and quantitative studies are available both for the north-western and north-eastern basin (Klaoudatos et al., 2006; Aguado-Giménez et al., 2007). Water degradation is also a large-scale process involving the whole Mediterranean Sea, in both coastal (Herut et al., 1999) and deep sea environments (Kress et al., 1998). From sewage pollution (Soltan et al., 2001; Fraschetti et al., 2006), to mucilage (Giuliani et al., 2005), brine (Gacia et al., 2007) and nutrient enrichment (Arevalo et al., 2007), they all concurred to affect a suite of response variables in all investigated habitats.

After the selection of the 60 studies included in the meta-analysis (158 experiments), we were able to investigate the effects of eight different stressors out of 10. Aquaculture (33% of the studies), sedimentation increase (15%), destructive fisheries (15%), species invasion (12%) and water degradation (12%) were the most investigated stressors, followed by urbanization (10%) non-destructive fishery (3%) and mechanical disturbance (2%). Six habitats could be included in the meta-analysis: coralligenous, mud, phanerogam meadows, rocky intertidal, rocky subtidal, and sand (Table 2).

3.2. Impacts of human-driven stressors on Mediterranean marine habitats

3.2.1. Coralligenous

Fishing activities (Bavestrello et al., 1997; Tsounis et al., 2007), mechanical disturbance (Coma et al., 2004), sedimentation increase (Balata et al., 2005), species invasion (Baldacconi and Corriero, 2009), temperature increase (Garrabou et al., 2001) and water degradation (Giuliani et al., 2005) had all negative effects on species assemblages associated to coralligenous habitats. Those stressors led to a decrease in species density and/or increase in mortality rates.

The quantitative synthesis showed that destructive fishery activities had an overall significant impact on *Corallium rubrum* colonies (sessile invertebrates) (Fig. 2). On average, maximum basal diameter and maximum height were, respectively, 50% and 40% smaller in fished zones than in controls. These cumulative effects were homogeneous ($Q_t = 0.64$, $P = 0.424$, df = 1 and $Q_t = 0.05$, $P = 0.828$, df = 1; respectively).

3.2.2. Mud

Aquaculture had negative impacts on muddy habitats, with pathogenic benthic bacteria density increasing in relation to organic enrichment due to fish farms (Vezzulli et al., 2002). Vagile invertebrates can be unaffected by an increase in sedimentation (Simonini et al., 2005). Following destructive fishing activities, some vagile invertebrate communities can be unaffected (Lampadariou et al., 2005), while some others can present functional changes (de Juan et al., 2007).

The meta-analysis showed that destructive fishing had significant negative effects on biomass and evenness of vagile invertebrates (Fig. 2), whereas no significant negative effects of destructive fishing and sedimentation were detected on density and diversity of vagile invertebrates (Fig. 2). Indeed, diversity increased by 30% in areas subjected to destructive fishing. Biomass was 49% lower in areas subjected to destructive fishing than in unfished control areas and this response was homogeneous across the experiments ($Q_t = 1.68$, $P = 0.194$, df = 1; other effect sizes were heterogeneous).

3.2.3. Mussels

In habitats formed by *Mytilus* spp., spread of the introduced green alga *Codium fragile* increased the recruitment of mussels through the formation of a canopy on which mussel juveniles can more easily settle than on bare rock (Bulleri et al., 2006). Conversely, urbanization (Bocchetti et al., 2008) and decrease in water quality (Porte et al., 1991) had negative effects on the species biology.

3.2.4. Phanerogams

In *P. oceanica* habitats, aquaculture (Díaz-Almela et al., 2008), destructive fishing activities (González-Correa et al., 2005), increase in sedimentation rates (Badalamenti et al., 2006) or invasion

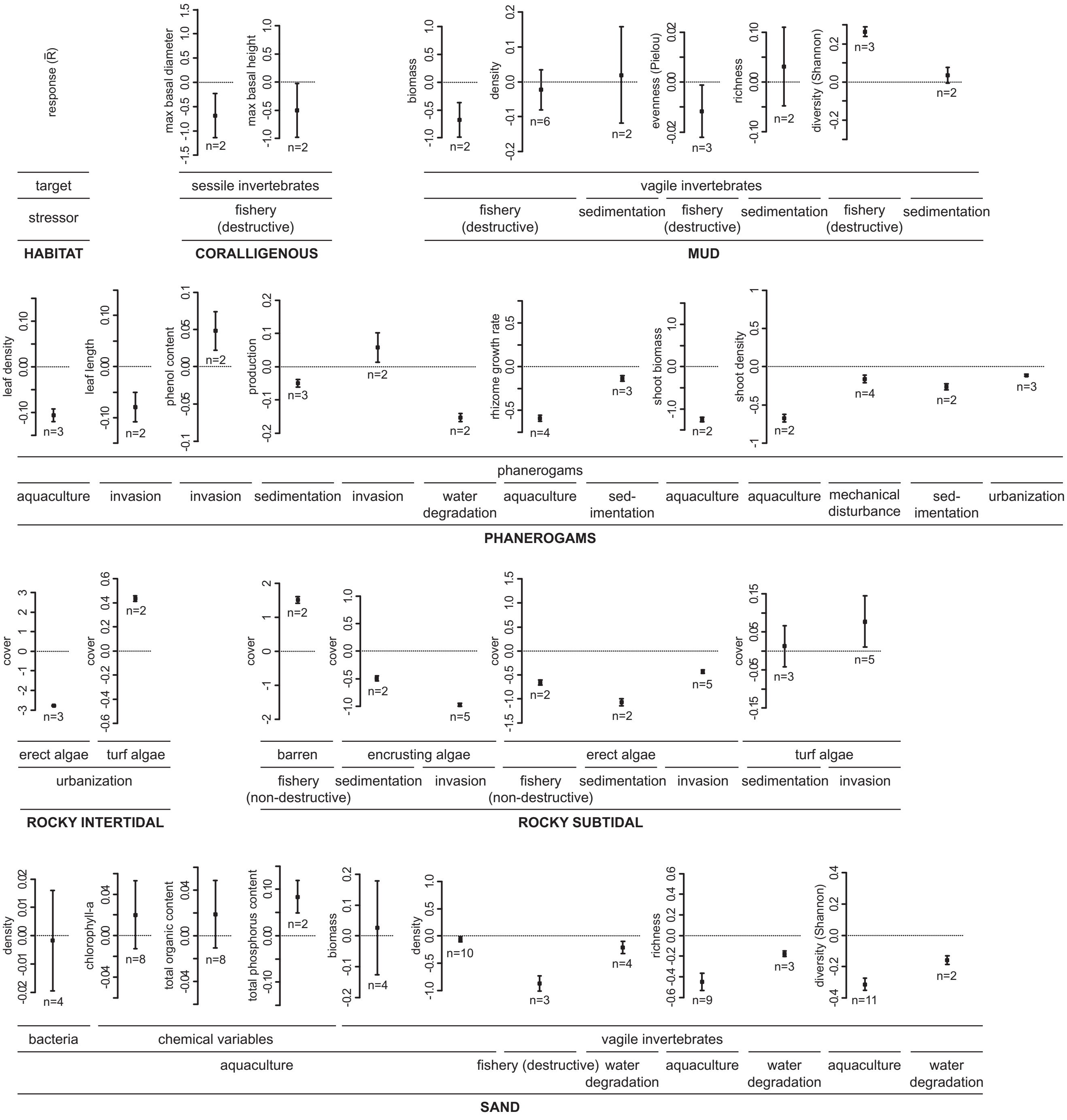

Fig. 2. Cumulative impacts of human-driven stressors (ln–response ration; mean ±95% confidence intervals) in six Mediterranean marine habitats and for different target and response variables. Cumulative effects are significant if confidence intervals do not overlap zero.

by the red alga *Lophocladia lallemandii* (Ballesteros et al., 2007) all led to higher mortality rates and negative effects on phanerogam's morphological variables.

All meta-analyzed morphological variables of the phanerogams were negatively affected by the stressors assessed (Fig. 2). Out of these cumulative effect sizes two effects were homogeneous, with aquaculture reducing shoot biomass by 71% and increases in sedimentation reducing shoot density by 23% ($Q_t = 1.62$, $P = 0.203$, df = 1 and $Q_t = 0.18$, $P = 0.667$, df = 1; respectively). Species invasion increased phanerogams production and phenol content (Fig. 2).

3.2.5. Rocky intertidal

The review of the literature showed that all stressors investigated in rocky intertidal habitats (Table 1) had negative effects on associated species assemblages, often leading to complete shifts in the assemblages composition (Fraschetti et al., 2005; Arevalo et al., 2007; Vazquez-Luis et al., 2008). For instance, a common effect of urbanization is a loss of algal canopies of erect algae of the genus *Cystoseira* and increases of turf forming algae cover (Benedetti-Cecchi et al., 2001; Mangialajo et al., 2008).

The quantitative synthesis showed that average cover of erect algae decreased by 94% in response to multiple stressors related to urbanization while cover of turf algae increased by 54% (Fig. 2). The corresponding effect sizes were heterogeneous among the experiments ($Q_t = 4600.35$, $P < 0.001$, $df = 2$ and $Q_t = 57.07$, $P < 0.001$, $df = 1$; respectively) but the same trajectories were observed in all analyzed experiments (i.e. only the magnitude of the change differed).

3.2.6. Rocky subtidal

Rocky subtidal habitats appeared highly susceptible to invasion by alien macroalgae, with differences among algal assemblages in different locations being reduced in invaded areas through biotic homogenization (Piazzi and Balata, 2008). Besides, the presence of sediments had the potential to enhance the spreading of *Caulerpa* species (Piazzi et al., 2007), suggesting synergies between environmental and human-driven threats in subtidal habitats. One study showed that fish farm derived particulate N waste could be traced in benthic invertebrates over distances of several km from the farm (Dolenec et al., 2007). Many studies showed that deposition of sediments had negative effects on the cover of several species of encrusting and erect algae on rocky subtidal (Airoldi et al., 1996; Airoldi and Virgilio, 1998; Balata et al., 2007). Positive effects have been observed only for filamentous algae (turf), independently of the stage of development, with patterns consistent at different spatial scales. Small-scale spatial variability of the depositional environment may affect the cover and the within-habitat diversity of algal assemblages either through direct effects on individual species or on their propagules, and through indirect effects mediated by competitive outcomes (Airoldi and Virgilio, 1998). As with biological invasions, results showed that sediment increased similarity in assemblages overriding the influence of habitat complexity on beta diversity at small and large spatial scales (Balata et al., 2007).

The meta-analysis showed that average cover of erect and encrusting algae decreased (from 35% to 66%) in response to the stressors analyzed, whereas, in most cases, cover of barren rocks and turf algae significantly increased (Fig. 2). These patterns of change were similar across all the experiments examined but significantly homogeneous only for the effect of sedimentation on encrusting algae ($Q_t = 2.41$, $P = 0.121$, $df = 1$).

3.2.7. Sand

In sandy habitats, single studies showed that sedimentation (Sánchez-Moyano et al., 2004), urbanization (Kourelea et al., 2004) or temperature increase (Lardicci et al., 1999) had no or very limited impacts on vagile invertebrates.

The meta-analysis showed that aquaculture and destructive fishing activities had negative effects on all descriptors of the vagile invertebrate communities (except for invertebrate biomass that was not significantly affected by aquaculture) (Fig. 2). The density decrease of 58% due to destructive fisheries and the 15% reduction in diversity due to a degradation in water quality were homogeneous across the experiments ($Q_t = 0.74$, $P = 0.690$, $df = 2$ and $Q_t = 2.63$, $P = 0.105$, $df = 1$; respectively). On average, aquaculture did not have significant effects on the microbial and chemical compartments of sandy habitats (except for total phosphorus content, which increased with comparison to control areas).

4. Discussion

In the last 40 years, the Mediterranean basin has changed greatly in terms of human pressure and exploitation of marine resources. Several recent studies (UNEP/MAP, 2005; EEA, 2006; Airoldi and Beck, 2007; IUCN, 2007, 2008; Coll et al., 2008; Ferretti et al., 2008) produced large-scale descriptions of anthropogenic drivers of ecological change (such as fishing, climate change, coastal development, and pollution), advocating an urgent need for management and conservation initiatives within the Mediterranean. However, comparative analyses of the magnitude of effects of different stressors were lacking. Our study represents the first systematic assessment of current threats affecting the Mediterranean basin at habitat level. It highlights the fragmented knowledge on the subject, combined with a general lack of manipulative experiments (with few exceptions) and large-scale, long-term coordinated monitoring programs based on robust experimental designs. This assessment warns of the scarcity of quantitative information about how humans are negatively affecting Mediterranean coastal ecosystems and how these threats can be managed.

Despite these limitations, our synthesis revealed that, where assessed properly, human activities had significant negative impacts on all the investigated habitat types. In rocky intertidal and subtidal, and in sandy habitats, urbanization, fisheries, aquaculture and sedimentation led to a shift in associated assemblages. For instance, in fished rocky subtidal habitats, the cover of macroalgae significantly decreased, whereas the cover of barren rocks increased. This shift towards barren habitat due to non-destructive fishing activities in temperate reefs is often a consequence of overfishing of sea urchin predators (e.g. *Diplodus sargus*). Following a decrease in their predators' density, sea urchins increase in density and overgraze erect macroalgae causing formation of barren rock (Fanelli et al., 1994; Sala et al., 1998; Micheli et al., 2005; Guidetti, 2006). This subsequent trophic cascade leads to simplified assemblages in both structure and function, through a process of underwater "desertification". On sand, macrobenthic assemblages affected by aquaculture or water degradation were characterized by significant decreases in density, richness and diversity in comparison to control areas, and by a shift towards populations of few proliferating species (Pearson and Rosenberg, 1978). On mud, although vagile invertebrate density did not respond significantly to destructive fishing activities, biomass and evenness decreased significantly, showing a decrease in species body-size and an increase of the proportion of small individuals (Kaiser et al., 2006). The observed increase in diversity was largely driven by a single experiment (Simboura et al., 1998) where the authors showed it was due to different sediment characteristics in impacted and control areas. Negative effects of destructive fisheries on coralligenous habitats are clear, as are the effect of sedimentation, mechanical disturbance and water degradation on phanerogams. The metrics used for assessing those stressors in these two habitats, which are directly related to the habitat state (Garrabou and Harmelin, 2002; Milazzo et al., 2004), were significantly lower at impacted locations. In the presence of these stressors, both habitats are less complex, leading to potential biotic homogenization with detrimental effects for specific developmental stages of both vertebrates and invertebrates (Gratwicke et al., 2006; Airoldi et al., 2008).

The significant heterogeneity between effect sizes among several of the comparisons carried out was likely a consequence of small sample sizes of our response categories (Table 2), although low sample sizes can be common in meta-analyses based on experiments taken from the literature (Worm et al., 2006). When significant, however, this heterogeneity had only an effect on the average cumulative magnitude of the effect of a given stressor in a given habitat. The directions of the cumulative effect sizes are unlikely to be affected as the great majority of the individual experiments analyzed found negative effects of the stressors investigated. Potential sources of variability among studies, such as connectivity between disturbed and undisturbed habitat patches or interactive stressors that were not accounted for in the original experiments, should be further investigated.

On the other hand, small sample sizes prevented the quantitative comparison of the effects of stressors across habitats when different targets or responses were assessed in the collected studies. Also, a comprehensive quantitative comparison of the magnitudes of effects of stressors within a given habitat was impaired by the impossibility of obtaining comparable observations of all stressors within a given habitat, except for a few response categories. These two pitfalls can have serious implications. A comprehensive comparison among and within habitats of the effects of different human-driven stressors is first critical to developing a framework for understanding and predicting the cumulative impacts at a regional scale. Second, these cross-habitats comparisons are essential to refining our ability to effectively adapt and respond to the growing threats occurring in the Mediterranean Sea.

The greatest global threats on marine environments recently identified by expert opinion surveys (Halpern et al., 2007, 2008), are not completely reflected in the proportion of studied human stressors on Mediterranean habitats. Although the consulted experts identified demersal destructive fishing activities and point source pollution among the most threatening stressors (stressors having also high occurrences in our database), increase in sea temperature was the stressor with the highest score (i.e. with the most negative impact). This global threat is also recognized as a major stressor in the Mediterranean region. The Mediterranean Sea is under a process of "tropicalization" (Bianchi, 2007) and high-temperature conditions are documented to be concurrent with observations of mass mortalities (Garrabou et al., 2001). However, in our database, effects of temperature increase were studied in less than 2% of the cases. These experiments could not be included in our meta-analysis because no observations occurred more than once in a same habitat type, and when they did, experiments did not focus on the same response variable. Rigorously assessing the effect of temperature increase on coastal habitats and associated species and assemblages can lead to very complex experiments in order to have appropriate controls, which may account for the low level of occurrences of such studies in the Mediterranean.

Further, costs, logistic and even ethical constraints virtually preclude experiments at the large spatial and temporal scales that would be necessary to test predictions about some human-driven impacts. When such constraints are present, answers could come from the use of different integrated approaches, which include well designed descriptive studies, quantitative experimental protocols, as well as expert opinions.

In this respect, in the last few years, increased efforts have been dedicated to develop, refine and assess ecological indices. In the northern Mediterranean Sea, following the European Union's Water Framework Directive and Marine Strategy Framework Directive, many biological and physical indices were proposed to monitor the Ecological Quality Status (EcoQS) of coastal areas (Borja et al., 2008). However, monitoring networks are still established at national levels and indices used often vary from place to place (Borja et al., 2009). Furthermore, for a given index, no standardized operational reference conditions exist and the need for control locations is ignored in place of absolute reference conditions. The variability of natural systems cannot be accounted for and indices can therefore vary according to factors independent of the assessed environmental status. These shortcomings impair the use of such indices to assess human-driven stressors on habitats at the Mediterranean level (and elsewhere).

Future research on human-driven impacts in the Mediterranean should consider that threats on habitats do not act in isolation (Crain et al., 2008; Darling and Côté, 2008); they often combine at multiple scales. When coupled with overexploitation and climatic instabilities, localized human perturbations contribute to generate new regimes of disturbances expected to greatly affect the stability, resilience and productivity of marine ecosystems (Hughes, 1994; Dulvy et al., 2008). Quantitative impact assessments of a suite of multiple human threats on marine habitats have rarely been conducted, but the need for solutions for a sustainable resource use and effective conservation strategies should stem from a solid scientific basis.

Current strategies for managing the Mediterranean basin should use more standardized experiments and metrics and investigate more deeply effects of multiple stressors combining at global and local scales. These improved strategies could lead to more appropriate management actions. In spite of this awareness, this information is still largely neglected in the Mediterranean Sea.

5. Conclusions

We used the most rigorous analytical methods – which implied more restrictions regarding the inclusion of the studies – in order to gauge the feasibility of drawing general quantitative conclusions of anthropogenic threats on Mediterranean marine habitats. Less rigorous methods (e.g. vote counting) have already been used but we believe that a combination of different approaches with their respective advantages and limitations should guide management actions.

The present synthesis combining a review and a meta-analysis showed that: (1) the human-driven stressors investigated had negative effects on Mediterranean habitats and associated species assemblages; but that (2) there are few rigorous quantitative evaluations of the effects of current threats on Mediterranean habitats; (3) there are gaps in knowledge on current known distribution of different habitat types; (4) baseline data on coastal conditions prior to large-scale human impacts are lacking; (5) there is a strong disparity in the number of investigations on human-driven impacts between the north-western and north-eastern parts of the Mediterranean basin on the one hand, and between its northern and southern parts on the other (see Fig. 1); (6) standardized metrics allowing proper environmental impact assessments at a regional scale are lacking; and (7) the evaluation of the combined effects of multiple stressors is neglected in the Mediterranean basin. Systematically reducing these gaps would greatly improve current strategies for managing and conserving the Mediterranean Sea.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biocon.2010.06.004.

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