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Designing indicators for assessing the effects of marine protected areas on coral reef ecosystems: A multidisciplinary standpoint

Dominique Pelletier[1,a], Jose A. García-Charton[2], Jocelyne Ferraris[3], Gilbert David[4], Olivier Thébaud[5], Yves Letourneur[6], Joachim Claudet[1,7], Marion Amand[1,8], Michel Kulbicki[3,8] and René Galzin[7]

[1] IFREMER, Laboratoire MAERHA (Mathématiques Appliquées à l'Exploitation des Ressources halieutiques), BP 21105, 44311 Nantes Cedex 03, France
[2] Universidad de Murcia, Departamento de Ecología e Hidrología, Campus de Espinardo, 30100 Murcia, Spain
[3] IRD-UR CoRéUs, Université de Perpignan, 52 avenue Paul Alduy, 66860 Perpignan, France
[4] IRD-US Espace, BP 172, 97492 Ste Clotilde, La Réunion
[5] IFREMER Centre de Brest, Service d'Economie maritime, BP 70, 29280 Plouzané, France
[6] Université de la Méditerranée, Centre d'Océanologie de Marseille, UMR 6540 Dimar, Campus de Luminy, Case 901, 13288 Marseille Cedex 9, France
[7] EPHE UMR 8046 CNRS, 52 avenue Paul Alduy, 66860 Perpignan Cedex, France
[8] IRD Centre de Nouméa, Unité de Recherche CoRéUs, BP A5, 98848 Nouméa Cedex, Nouvelle-Calédonie

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Abstract – The present paper aims at identifying and assessing indicators of the effects of Marine Protected Areas (MPAs) in coral reef regions, based on a bibliography review in ecology, economics and social sciences. First the various effects studied within each of these domains and the variables used to measure them were censused. Potential ecological indicators were assessed through their link with the question used (here termed "relevance") and their "effectiveness" which encompasses the issues of precision, accuracy and statistical power. Relevance and effectiveness were respectively measured by the frequency of use of each indicator and the proportion of significant results in the reviewed articles. For social and economic effects, the approach was not possible due to the low number of references; we thus discussed the issue of finding appropriate indicators for those fields. Results indicate: 1- the unbalance in literature between disciplines; 2- the need for protocols and methodologies which include controls in order to assess MPA effects; 3- an important proportion of ecological indicators with low effectiveness; 4- the large number of ecological effects still not studied or not demonstrated at present.

Key words: Marine Protected Areas / Ecological, economic and social indicators / Pluridisciplinary / Coral reef ecosystems / Coastal management

Résumé – Quels indicateurs pour évaluer les effets des aires marines protégées sur les écosystèmes coralliens ? Un point de vue pluridisciplinaire. Cet article vise à identifier des indicateurs de l'effet des aires marines protégées (AMP) en milieu corallien, sur la base d'une synthèse bibliographique dans les domaines écologiques, économiques et sociaux, et principalement en milieu corallien. Nous recensons d'abord les différents effets attendus des AMP pour chacun des domaines, et les variables retenues pour les étudier. Les indicateurs écologiques potentiels sont évalués au travers de leur lien avec l'effet étudié (ici appelé « pertinence ») et de leur « efficacité » qui regroupe les notions de précision, justesse et puissance statistique. Pertinence et efficacité sont respectivement mesurées par la fréquence d'utilisation et la proportion de résultats significatifs trouvés dans les articles recensés. Pour les aspects économiques et sociaux, le faible nombre de références ne permet pas une approche comparable à celle utilisée pour les indicateurs écologiques, et nous discutons donc de la question de l'identification d'indicateurs, et suggérons quelques pistes de recherche. Les principales conclusions de ce travail sont : i) le décalage entre les nombres de publications entre disciplines ; ii) la nécessité de protocoles et méthodologies incluant des situations de contrôle pour évaluer les effets des MPA ; iii) la faible efficacité de nombreux indicateurs écologiques ; et iv) le nombre élevé d'effets peu ou pas étudiés ou démontrés à l'heure actuelle.

[a] Corresponding author: dpellet@ifremer.fr

1 Introduction

Coral reefs are an outstanding feature of shallow marine areas in tropical regions of the world. They are home to more than one quarter of all known marine fish species (McAllister 1988; Sale 2002; Moberg and Rönnback 2003). Estimates of the seafood productivity of properly managed reefs range from 15 (Bryant et al. 1998) to 35 $t\,km^{-2}\,y^{-1}$ (Russ 1991). Coral reefs host ecosystems that represent a small fraction of the world's commercial fish yield (about 10% of global catches in volume according to FAO figures of 1989), but support subsistence and local economy needs in many developing countries (Medley et al. 1993). Coral reefs have been estimated to provide each year roughly € 30 billion in net benefits in goods and services to world economies, including tourism, fisheries and coastal protection (Cesar et al. 2003). Marine Protected Areas and in particular no-take marine reserves have long been envisaged as a way to protect coral reef ecosystems and associated fisheries, because they were thought more practical than other forms of fishery management (Roberts and Polunin 1991).

The term "Marine Protected Area (MPA)" is defined here in the classical sense of "any area of intertidal or 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 or all of the enclosed environment" (Kelleher and Kenchington 1992), corresponding to resolution 17.38 of the 1988 World Conservation Union (IUCN) General Assembly. In the literature, the terms marine reserve, marine protected area, no-take zone, harvest refugia, sanctuary are often used for areas where fishing is totally prohibited (but see Agardy et al. 2003 for a presentation of the terms in use). In this article, we used the term marine reserve for this kind of area, and the term MPA in the wider sense defined hereabove. However, we do not consider customary marine tenures as described in Ruddle (1989) and Ruddle and Johannes (1990), i.e. Traditional Territorial Use Rights for Fishing (TURF).

MPAs are recent compared to terrestrial protected areas. There were 118 marine protected areas in 1970, 319 by 1980 (Silva et al. 1986; Kelleher and Kenchington 1992), and by 1995, their total number exceeded 1300 (Kelleher et al. 1995). This dynamics was spurred in part by international conventions and organisations such as the World Conservation Union (IUCN), which created specific programs for promoting a worldwide system of MPA, with the main objective "to provide for the protection, restoration, wise use, understanding and enjoyment of the marine heritage of the world in perpetuity through the creation of a global, representative system of MPAs and through the management in accordance with the principles of the world conservation strategy of human activities that use or affect the marine environment" (Kelleher and Kenchington 1992). Most MPAs located in developing countries were created under the impetus of international organisations (like United Nations Educational Scientific and Cultural Organization (UNESCO), United Nations Environmental Program (UNEP), United Nations Development Program (UNDP), IUCN, World Wide Fund for Nature or World Bank), national NGOs or private donors. Out of the 1300 MPA recognised by IUCN[1], 400 have been established in coral reefs (Salvat et al. 2002), mostly in the last two decades. Concomitantly, MPA have been more and more studied as a "new" tool for marine ecosystem conservation and fisheries management, giving rise to many scientific publications, and a number of international conferences, workshops and research projects (Dugan and Davis 1993; Yoklavitch 1998; Conover et al. 2000; Polunin 2000; Kruse et al. 2001; Sumaïla and Alder 2001; National Research Council 2001).

Although there are a number of studies aimed at assessing MPA-related effects, more insight is needed into the question of assessing the ability of MPAs to achieve the management objectives initially stated, taking into account managers' expectations, monitoring needs and constraints. This implies looking at the indicators that are appropriate for assessing the effects of MPAs on ecosystems, resources and human activities. An indicator may be seen as a qualitative or quantitative variable that can be obtained from field surveys or from models, and that can be directly linked to a management objective or a research question (see Ferraris et al. 2005 for references). These authors proposed two main desirable features for a good indicator: i) the relevance to the assessment of interest, i.e. the link with the assessment objective; and ii) the effectiveness, i.e. the reliability in terms of precision, accuracy of the indicator and risk of making a wrong assessment. Selecting appropriate indicators for the assessment of MPA effects thus implies to first identify the objectives that prevail in MPA establishment.

The aim of the article is to identify and characterise the indicators used for assessing the effects of MPAs on coral reef ecosystems, and their associated economic and social consequences, taking the general objectives of MPA creation into account. We focus on quantitative indicators, although we acknowledge the existence of qualitative approaches, that may sometimes be more suitable in data-poor situations or in the case of social studies. Consistently with the definition of indicators proposed above, we make a distinction between the effects of MPAs that need to be estimated, the variables or indices used to measure these effects, and the criteria which can be used to assess the performance of these variables as indicators.

We examined the existing literature to list the ecological, economic and social effects that can be expected from the implementation of an MPA. For each of the effects identified, we listed the variables that were used in published empirical studies. For ecological effects, the relevance and effectiveness of each potential indicator were assessed using scores based on the bibliography analysis. For economic and social effects, we critically discussed the possibility of defining indicators from existing literature.

2 Management objectives

At the 1992 Congress of the World Commission on Protected Areas[2] (WCPA), a total of six categories of protected

[1] United Nations list of National Parks and Equivalent Reserves, 1997 edition.

[2] Includes all protected areas, both terrestrial and marine.

Table 1. Management objectives for marine protected areas (MPA), as listed from the literature. Objectives linked to resolution of conflicts between different users groups were not reported.

Domain	Conservation Heritage preservation	Knowledge	Fishing	Other uses
Objectives	Conservation Habitat protection Protection of emblematic species Heritage preservation	Education Research	Protection of resources Nursery protection Sustainable exploitation Rehabilitation of resources	Promotion of tourism and recreational activities (e.g. diving)

areas reflecting different management regimes and objectives were agreed upon: 1) strict nature reserve/wilderness area; 2) national park; 3) natural monument; 4) habitat/species management area; 5) protected landscape/seascape; 6) management resource protected area. This classification was endorsed at the IUCN general assembly in 1994 (David 1998). Salm et al. (2000) see two main motivations for MPAs: ensuring sustainability of economic resources, and protection of species, biodiversity and landscapes. In a review of 30 articles, Boersma and Parrish (1999) listed more precisely the objectives of establishing marine reserves: protection of local marine resources (93%), promotion or control of tourism (67%), protection of biodiversity (67%), and enhancement of fisheries through protection or management (53%). In the present review, we summarized management objectives from existing literature into four domains: conservation, knowledge, fisheries and other uses (Table 1).

In addition to these objectives, managers also view MPA as a mean to control access to coastal areas for resolving present or anticipated conflicts between coastal area users (Agardy 2000; Claudet and Pelletier 2004). A potential objective of MPAs may be to strengthen property and liability rights to the protected ecosystems, thereby ensuring their more efficient use and protection (Hoagland et al. 1995). This standpoint has however been challenged by Crosby et al. (2002), who pointed out that limiting access to marine resources for some user groups, in particular fishermen, may disrupt the socio-economic stability of coastal communities and result in conflicts among user groups competing for the same limited resources.

3 Effects of MPA establishment: Expectations and observations

In this section, we reviewed the main effects expected from the establishment of an MPA. We examined articles studying the impact of MPAs from ecological, economic and social standpoints. Although the review focused on coral reef ecosystems, we also included a number of studies pertaining to other ecosystems. A distinction was made between effects pertaining to marine populations and ecosystems (referred to as "Ecological effects"), and effects pertaining to economic and social aspects. The literature search focused on primary journals. For ecological effects, the search was restricted to empirical studies concerning existing MPAs, i.e. 94 references. In the case of economic effects, both modelling and empirical studies were considered, which amounted to 32 references. In the case of social effects, we excluded papers that were purely descriptive accounts and too qualitative to allow for subsequent indicator definition. Under these conditions, only 10 accessible references could be found. In each domain, references were classified according to the effects studied, and the variables observed and/or analysed were reported.

3.1 Ecological effects

More than 20 expected effects were listed from articles including a bibliography review (Plan Development Team 1990; Roberts and Polunin 1991, 1993; Jones et al. 1992; Dugan and Davis 1993; Rowley 1994; Bohnsack 1996; Allison et al. 1998; Lauck et al. 1998; García-Charton and Pérez-Ruzafa 1999; Crowder et al. 2000; García-Charton et al. 2000; Pinnegar et al. 2000; Planes et al. 2000; Roberts and Hawkins 2000; Russ 2002; Sànchez-Lizaso et al. 2000; Halpern 2003).These articles generally distinguish effects expected inside and outside the protected areas. Effects of MPA on the environment and ecosystem surrounding the MPA are tied to spillover, i.e. emigration and/or dispersion of recruited stages and exportation of eggs and larvae, the MPA acting as a biomass reservoir, if possible enhancing fisheries yields. Some of the listed effects within MPA may appear redundant since they were formulated in different ways by authors. In the present article, effects were classified as: i) effects at population level (Table 2); ii) effects at community level (Table 3); iii) habitat-related effects (Table 4). Note that expected effects may be desirable or undesirable with respect to management objectives.

Most studies focused on effects at population level, like protection of spawning stock biomass of exploited species (55 references), rehabilitation of demographic structure (35 references) and to a lesser extent exportation of biomass outside the MPA (24 references). At community level, the effects studied are mainly restoration of and changes in assemblage structure (22 references), protection of biodiversity (23 references), and indirect effects on algae and invertebrates (15 references). The other effects are less often addressed in the literature. In particular, habitat-related effects are rarely analysed in the articles reviewed (10 references). Note that the most frequently considered effects are all studied through visual observations of fish abundance and experimental fishing. Commercial catch and effort are seldom used in this kind of studies, except for evaluating the enhancement of fisheries yields around the MPA. To our knowledge, there is no empirical study for several effects mentioned in review articles, namely i) protecting intra-specific genetic diversity; ii) protecting and promoting biodiversity through protection of endangered species; iii) protecting against fishery-related depletion at community level; iv) facilitating recovery from

Table 2. Expected MPA effects at population level, and variables measured to evidence these effects. Expected effects were listed from the references listed from review articles quoted at the beginning of Sect. 2.1. Variables measured were listed from the articles cited. LHT stands for Life History Traits.

Expected effect	Variables measured	Studies
1. Protecting critical spawning stock biomass of species from fishery-related depletion	density, biomass, Catch Per Unit Effort (CPUE) (also termed catch rate), species richness of target species group, frequency of occurrence	Bell (1983); Russ (1985); McClanahan and Muthiga (1988); Buxton and Smale (1989); Russ and Alcala (1989); Cole et al. (1990); García-Rubies and Zabala (1990); Yamasaki and Kuwahara (1990); Bennett and Attwood (1991); Roberts and Polunin (1992); Armstrong et al. (1993); Buxton (1993); Holland et al. (1993); Polunin and Roberts (1993); Francour (1994); McClanahan (1994); Harmelin et al. (1995); Dufour et al. (1995); McClanahan and Kaunda-Arara (1996); Roberts (1995); Jennings et al. (1995, 1996); Letourneur (1996); Russ and Alcala (1996a); Rakitin and Kramer (1996); Stoner and Ray (1996); Watson et al. (1996); Edgar and Barrett (1997); Sluka et al. (1997); Wantiez et al. (1997); Ciriaco et al. (1998); Russ and Alcala (1998)a,b; Babcock et al. (1999); Chapman and Kramer (1999); Johnson et al. (1999); La Mesa and Vacchi (1999); Millar and Willis (1999); Wallace (1999); Chiappone and Sealey (2000); McClanahan et al. (1999); Chiappone et al. (2000); Francour (2000); Kelly et al. (2000); McClanahan (2000); Paddack and Estes (2000); Tuya et al. (2000); Jouvenel and Pollard (2001); McClanahan et al. (2001); Roberts et al. (2001); Macpherson et al. (2002); Rowe (2002); Westera et al. (2003); Denny and Babcock (2004); García-Charton et al. (2004) **(55 references)**
2. Rehabilitating population age structure	Average, modal, size range, size distribution, density or frequency of large / old individuals	Davis (1977); Buxton and Smale (1989); Yamasaki and Kuwahara (1990); Bennett and Attwood (1991); Roberts and Polunin (1992); Armstrong et al. (1993); Buxton (1993); Polunin and Roberts (1993); Francour (1994); Harmelin et al. (1995); Dufour et al. (1995); Ferreira and Russ (1995); Letourneur (1996); McClanahan and Kaunda-Arara (1996); Rakitin and Kramer (1996); Edgar and Barrett (1997); Sluka et al. (1997); Wantiez et al. (1997); Piet and Rijnsdorp (1998); Babcock et al. (1999); Chapman and Kramer (1999); Johnson et al. (1999); La Mesa and Vacchi (1999); Wallace (1999); Chiappone and Sealey (2000); Chiappone et al. (2000); Kelly et al. (2000); McClanahan (2000); Paddack and Estes (2000); Tuya et al. (2000); Jouvenel and Pollard (2001); Béné and Tewfik (2003); Westera et al. (2003); Willis et al. (2003a); Denny and Babcock (2004) **(35 references)**
3. Exportation of biomass	Nb. recaptures, distance travelled, trajectories, density, mean size, biomass and CPUE outside MPA, residence time	Davis (1977); Gitschlag (1986); Buxton and Allen (1989); Davis and Dodrill (1989); Yamasaki and Kuwahara (1990); Holland et al. (1993); Attwood and Bennett (1994); McClanahan and Kaunda-Arara (1996); Rakitin and Kramer (1996); Russ and Alcala (1996b); Zeller and Russ (1998); Chapman and Kramer (1999, 2000); Johnson et al. (1999); Millar and Willis (1999); McClanahan and Mangi (2000); Eristhee and Oxenford (2001); Meyer et al. (2000); Roberts et al. (2001); Willis et al. (2001, 2003)a; Thorrold et al. (2001); Rowe (2002); Zeller et al. (2003) **(24 references)**
4. Enhancing fisheries yield	CPUE, fishing effort (nb. gears, nb. fishers, spatial distribution)	Alcala (1988); Davis and Dodrill (1989); Alcala and Russ (1990); Yamasaki and Kuwahara (1990); Bennett and Attwood (1991); McClanahan and Kaunda-Arara (1996); Frank et al. (2000); Roberts et al. (2001); Rowe (2002) **(9 references)**
5. Increasing fecundity and production of eggs and larvae	Egg production, larvae and nest density	Stoner and Ray (1996); Ciriaco et al. (1998); Edgar and Barrett (1999); Chiappone and Sealey (2000); Kelly et al. (2000); Valles et al. (2001); Rowe (2002); Béné and Tewfik (2003) **(8 references)**
6. Density-dependent changes in LHT and parasitism	Sex ratio, parasite abundance and prevalence, condition index	Buxton (1993); Sasal et al. (1996); Edgar and Barrett (1999) **(3 references)**
7. Protection of recruitment	Recruitment index, Juvenile survival rate	Frank et al. (2000)

catastrophic human and natural disturbances; v) increasing population stability and resilience; vi) recolonisation of shallow habitats by target species; and vii) maintaining areas with undisturbed habitats.

Protection of genetic diversity (i) is probably limited by the relative recentness of most MPA and the scarcity of long term ecological studies in general. Protection of endangered species (ii) should be easier to evaluate, but restoration of long-lived species also requires medium to long term monitoring (see e.g. Bjorndal et al. 1999 for an example on marine turtles).

Protection of community against fishery-related depletion (iii) may be seen as a longer term perspective on the issue of sustainable management, addressing the question: "does the MPA guarantee that the community is going to recover from overexploitation?". Studying recovery from catastrophic events (iv) requires that recovery may be monitored over a

Table 3. Expected MPA effects at the community level, and variables measured to evidence these effects. Expected effects were listed from the references listed from review articles quoted at the beginning of Sect. 2.1. Variables measured were listed from the articles cited. Species groups means families, trophic groups or vulnerable species.

Expected effect	Variables measured	Studies
8. Restoration of / Changes in assemblage structure	Species composition and relative abundance of particular species groups, species richness per group slope of biomass spectrum, stomach content composition	Russ (1985); Russ and Alcala (1989); Polunin and Roberts (1993); McClanahan (1994); Harmelin et al. (1995); Jennings et al. (1995); Letourneur (1996); McClanahan and Kaunda-Arara (1996); Edgar and Barrett (1997, 1999); Wantiez et al. (1997); Arias-Gonzales (1998); Piet and Rijnsdorp (1998); Russ and Alcala (1998a,b); McClanahan et al. (1999); Paddack and Estes (2000); Macpherson et al. (2002); Shears and Babcock (2002); Westera et al. (2003); Denny and Babcock (2004); García-Charton et al. (2004) **(22 references)**
9. Protection of biodiversity	Species richness and diversity indices, species-area relationship	Bell (1983); Russ (1985); Russ and Alcala (1989); Cole et al. (1990); García-Rubies and Zabala (1990); Roberts and Polunin (1992); Dufour et al. (1995); Harmelin et al. (1995); Jennings et al. (1995, 1996); Letourneur (1996); Rakitin and Kramer (1996); Watson et al. (1996); Edgar and Barrett (1997); Wantiez et al. (1997); Arias-Gonzales (1998); Russ and Alcala (1998b); Johnson et al. (1999); La Mesa and Vacchi (1999); McClanahan et al. (1999); Francour (2000); Macpherson et al. (2002); Denny and Babcock (2004) **(23 references)**
10. Indirect effects on algae and invertebrates (cascade effect, food-chain reactions)	Invertebrate density, size and weight, coral cover, spatial distribution of species, predation rate	McClanahan and Muthiga (1988); Castilla and Bustamante (1989); Cole et al. (1990); Engel and Kvitek (1998); Babcock et al. (1999); Edgar and Barrett (1997, 1999); Epstein et al. (1999); McClanahan et al. (1999, 2001); Paddack and Estes (2000); Tuya et al. (2000); Dulvy et al. (2002); Shears and Babcock (2002, 2003); Westera et al. (2003) **(15 references)**
11. Increasing ecosystem stability and resilience	Temporal variability of diversity, biomass and density	Francour (1994, 2000)

Table 4. Expected MPA effects upon habitat, and variables measured to evidence these effects. Expected effects were listed from the references listed from review articles quoted at the beginning of Sect. 2.1. Variables measured were listed from the articles cited.

Expected effect	Variables measured	Studies
Protecting essential habitats for larvae settlement, recruitment, spawning and feeding Maintaining areas with undisturbed habitats	density, biomass and species richness of epibenthos and endobenthos, substrate perturbations, CPUE of exploited fish	Castilla and Bustamante (1989); Edgar and Barrett (1999); Hoffman and Dolmer (2000); Paddack and Estes (2000) (**4 references**)
Detrimental effects due to non-exploitative uses[3]	density, biomass and species richness of epibenthos, substrate perturbations	Engel and Kvitek (1998); Epstein et al. (1999); Rouphael and Inglis (2001); Tratalos and Austin (2001); Milazzo et al. (2002); Zakai and Chadwick-Furman (2002) **(6 references)**

long period of time in both MPA and surrounding areas. Both iii) and iv) require long term studies. In addition, explicit quantitative models of exploited community dynamics may prove necessary to address point iii).

3.2 Economic effects

Contrary to studies of ecological effects and experiences in MPA implementation, the number of applications of economic analysis to assess MPA benefits is small (Talbot 1994; Hoagland et al. 1995; Farrow 1996). As underlined by Rudd et al. (2003), MPAs have rarely been the focus of rigorous policy analyses that consider a full range of economic costs and benefits, including management costs. A limited number of recent publications reviewed the economic effects of marine protected areas, either directly (Dixon 1993; Dixon et al. 1993; Crosby 1994; Hoagland et al. 1995; Pendleton 1995; Farrow 1996; Carter 2003) or via the discussion of the economic value of reef ecosystem goods and services (Hodgson and Dixon 1992; Spurgeon 1992; Lipton and Wellman 1995; Cesar 1996; Turner and Adger 1996; Moberg and Folke 1999; Ledoux 2002; Cesar et al. 2003).

Hoagland et al. (1995) is one of the rare references aiming at establishing a state of the art on assessing MPA net benefits. In their review, only a limited number of references primarily addressed the economic assessment of MPA in coral reef environments: 10 references (out of 61) dealt with the economic valuation of the costs and benefits associated to tropical MPAs, among which 3 references presented empirical estimates of

[3] e.g. trampling, erosion by divers, mooring iMPActs, food-chain reactions.

Table 5. Expected economic effects of implementing a MPA, and variables measured to evidence these effects. References are presented according to type of contribution. In empirical studies, quantitative estimates obtained from data are provided. "Discussed in article" means that the subject is mentioned and discussed from a general and/or theoretical standpoint. Modelling studies present results from mathematical models to illustrate the subject.

Expected priced effect	Variables measured	References	
Financial effects of setting up and managing a MPA			
Costs of designing and implementing a MPA	Direct financial costs of setting up a MPA Costs of compensatory measures for displaced activities	Empirical studies	Dixon (1993); Dixon et al. (1993); Pendleton (1995); Cesar (2002); Bhat (2003)
		Discussed in article	Meganck (1991); Turner and Adger (1996)
Management costs and revenues	Costs of management, monitoring and enforcement Revenues derived from charging users of the MPA (as cost-recovery and/or management instrument)	Empirical studies	Dixon (1993); Dixon et al. (1993); Pendleton (1995); Cesar (2002); Bhat (2003)
		Discussed in article	Turner and Adger (1996)
Opportunity costs of protection			
Opportunity costs of protection	Value of foregone net benefits from the various activity exclusions or limitations resulting from the MPA	Empirical studies	Dixon (1993); Dixon et al. (1993)
		Discussed in article	Cesar (2002)
Effects on commercial fisheries (other than opportunity costs of protection)			
Change in fishing activity and net benefits derived from fishing inside and outside the MPA	Changes in fishing effort, landings in volume and value, catch per unit of effort, operational costs of fishing, income levels derived from fishing, congestion costs (both within and outside the MPA)	Empirical studies	Lipton and Wellman (1995); Cesar (2002)
		Discussed in article	Sumaila and Charles (2002)
		Modelling studies	Holland and Brazee (1996); Hannesson (1998); Conrad (1999); Holland (2000); Sanchirico and Wilen (2001, 2002); Anderson (2002); Boncoeur et al. (2002); Hannesson (2002); Roberts and Sargant (2001); Rodwell et al. (2001)
Effects on recreation-based commercial activities (other than opportunity costs of protection)			
Change in recreation-based activities, and associated net benefits to private businesses	Number of visits and gross expenditure directly related to the MPA, net benefits to local recreation-based businesses, net benefits to international recreation-based businesses	Empirical studies	Dixon (1993); Dixon et al. (1993); Kenchington (1993); Lipton and Wellman (1995); Pendleton (1995); Turner and Adger (1996); Brown et al. (2001); Cesar (2002); Bhat (2003)
		Discussed in article	Kenchington (1991); Badalamenti et al. (2000)
Public costs and benefits associated to the development of recreation-based commercial activities	Changes in public revenue from taxes and user fees on recreational activities, and costs of public support to the recreation-based commercial activities	Empirical studies	Dixon (1993); Dixon et al. (1993)

market values, and another 3 references reported empirical estimates of non-market values (Tables 5 and 6). Remaining references mostly comprised (i) economic valuation studies of tropical reef ecosystems, which can be useful to discuss the costs and benefits of ecosystem protection (8 references); (ii) theoretical approaches to coastal and marine protected areas valuation (17 references); and (iii) general problems of protected areas design and management, and tropical marine ecosystems management issues (15 references).

The present review of the more recent literature confirms this analysis. Although there is a growing interest for bio-economic modelling of area-based fisheries management measures (Holland 2000; Pezzey et al. 2000; Sanchirico and Wilen 2001; Sumaila and Charles 2002) few new empirical

Table 6. Expected economic unpriced effects of implementing a MPA, and variables measured to evidence these effects. References are presented according to type of contribution. All references provide quantitative estimates for studying the effect mentioned, except those in italics that only discuss the subject.

Expected unpriced effect	Variables measured	References
Benefits to recreational users (extractive and non-extractive use values)		
Benefits associated to changes in the number and value of recreational experience	Variation in number of visits directly related to the MPA, variation in consumer surplus associated to a visit	Leeworthy (1991); Dixon et al. (1993); Lipton and Wellman (1995); Pendleton (1995); Brown et al. (2001); Arin and Kramer (2002)
Benefits of the protection of ecosystem services (indirect-use and non-use values)		
Benefits associated to changes in the status of the protected reef ecosystem	Variation in indirect-use and non-use value of ecosystem services	*Farrow (1996)*; Spash et al. (1998); Bhat (2003); Gustavson (2002)
Longer term costs of MPA overuse		
External costs of the development of recreational activities (ecological impacts and loss of amenity)	Variation in number of visits directly related to the MPA, congestion costs, consumer surplus associated to the visit of a degraded ecosystem	*Geen and Lal (1991); Kenchington (1991);* Dixon (1993); Dixon et al. (1993); *Davis and Tisdell (1995, 1996);* Brown et al. (2001)

analyses have been published. Only some of the goods and services provided by reef ecosystems have been included in published valuation exercises, mostly focusing on tourism and recreation, and to a lesser extent on fisheries (Moberg and Folke 1999).

Two kinds of economic effects were distinguished: priced effects (Table 5) that refer to the effects on human activity that can be measured using market prices, and unpriced effects (Table 6) that refer to the effects that require the application of specific valuation methods as they relate to goods and services not traded in markets (see e.g. Turner and Adger 1996). Priced effects described in the literature include financial effects of setting up and managing MPAs, the opportunity costs of protection (i.e. foregone benefits for the users affected by MPA implementation), and the costs and benefits to ecosystem users, in particular commercial fisheries and recreational businesses (Table 5). While MPAs are often assumed to be a preferred option in terms of ease of management, there are few published estimates of the costs of setting up MPAs and/or costs of monitoring and enforcement of effectively applied MPAs (Hoagland et al. 1995). The financial effects of setting up and managing a MPA include design and implementation costs (7 references), management costs and revenues (6 references). In addition to these financial effects, protection usually involves restrictions of access such as limitations or prohibitions on fishing, collecting, mineral exploitation, diving, boating, etc. (Crosby 1994). These were considered in several references as potential significant sources of opportunity costs for MPAs (3 references, Table 5).

Expected economic effects of MPAs on commercial fisheries include changes in fishing activity and in net benefits derived from fishing both inside and outside the MPA. Inside the MPA, they include the costs of new constraints on harvesting and benefits of decreased fishing pressure for the remaining fishing activities. Outside the MPA, they include the costs of displaced effort for fishers and the benefits due to spillover effects. While there has been a growing number of studies discussing these expected impacts from a theoretical perspective (11 references), few empirical applications have been published, particularly in coral reef ecosystems (2 references, Table 5).

More empirical work was carried out on the effects of MPA on recreation-based uses of coral reef ecosystems[4], i.e. associated net benefits to private businesses (13 references), and public costs and benefits associated to these changes (2 references). An important issue here is the allocation of benefits and costs within the local economy, and between the local economy and the rest of the world (Crosby 1994).

Regarding unpriced effects (Table 6), references discuss (and sometimes estimate) the value of changes in the status of protected ecosystems to non-commercial users (7 references), indirect users of ecosystem services and non-users (4 references). Non-commercial users are those who derive value from both extractive and non-extractive uses of the ecosystem, but references mainly consider changes affecting recreational users such as divers. Indirect users benefit from the protection of the ecosystem through the preservation of the services it provides, e.g. the protection from erosion and storm surge afforded by reefs to coastal areas, or the role of seagrass beds in the ecological dynamics of reef species having direct use value (see Holmlund and Hammer 1999 for a discussion of ecosystem services generated by fish populations). Non-users are people granting value to the preservation of coral reef ecosystems independently of any present or future use.

Finally, the existing literature also discusses non-market consequences of the development of recreational activities within MPA, which can lead to overuse if no controls on access are put in place, with negative impacts on the ecosystem and the value of the services it provides (8 references).

3.3 Social effects

While we have focused in the previous point on the economic valuation of MPAs, their other social consequences should also be acknowledged as important components of

[4] With the limitation of some studies to an assessment of the gross expenditure directly associated to the protected areas (see below).

MPA assessment. In particular, the perception of people directly and indirectly affected by the MPA has been stressed as crucial, as it may affect the degree of support or opposition to MPAs, with consequences on the effectiveness of protection (Fiske 1992; Alder 1996; Wolfenden et al. 1998; Sant 1996; Cocklin et al. 1998; Schafer and Benzaken 1998; Suman et al. 1999). In practice, perception is measured via surveys directed at eliciting people's attitudes towards existing (Alder 1996; Shafer and Benzaken 1997; Suman et al. 1999) or projected (Sant 1996) MPAs. Beyond the few references dealing with the perception and attitudes of stakeholders regarding MPAs (Wolfenden et al. 1994; Sant 1996; Cocklin et al. 1998; Schafer and Benzaken 1998; Suman et al. 1999), published assessments of MPA social effects mainly relate to user involvement in co-management strategies (Elliott et al. 2001; Clifton 2003; Scholz et al. 2004), and to the assessment of the general socioeconomic factors influencing MPA success (Pollnac et al. 2001).

Social effects of MPAs are poorly documented compared to ecological and economic effects. There are two main reasons to this. First, social effects *per se* are not easily distinguished from other effects. For instance, local employment in tourism, benefits and costs of the informal sector, costs of local access to the park were listed by Brown et al. (2001) as social criteria for assessing management options in the case of a reef marine park in Tobago. However, such criteria might as well be considered as economic. Secondly, social effects are rather viewed as constraints to the achievement of MPA management objectives, than as real expectations.

In the present article, social effects of MPAs (Table 7) were classified according to three general objectives found in the literature: i) reducing and anticipating conflicts between different user groups; ii) improving visitors' satisfaction; and iii) increasing knowledge about marine ecosystems and biodiversity (for both tourists and local dwellers)[5]. Objective i) is an issue even when ecological and economic objectives are reached, because conflicts may arise if benefits are not shared. Participation and sharing of benefits are then an associated objective of i) (Christie et al. 2004). Effects linked with objective iii) are the most frequently studied (6 references). Target groups are the public or the research community (Davis and Tisdell 1995; Boersma and Parrish 1999). MPAs are seen as tools that facilitate monitoring for the assessment of anthropic consequences on coral ecosystems. Yanez Arancibia et al. (1999) consider MPAs as a suitable place for integrating science and management to the benefit of both. MPAs are also seen as a good laboratory to study Integrated Coastal Zone Management (ICZM) (David 1998).

The improvement of tourists' and local dwellers' satisfaction (objective ii) (5 references) relates to the increase in recreational facilities (Davis and Tisdell 1995), the conservation of beautiful and attractive landscapes (Boersma and Parrish 1999), the improvement of the status of marine life and habitats (Davis and Tisdell 1995), and the protection of archaeological, historical and cultural sites (Davis and Tisdell 1995; Boersma and Parrish 1999). Reducing conflicts between different user groups (objective i)) via the zoning design and management plan is a key objective of MPAs (Suman et al 1999; Day 2002), but studies of related effects are scarce (Table 7). Note that the effects related to objective i) are mostly negative, but that some effects classified under effect ii) may also be seen as positive effects that may contribute to reduce conflicts between user groups.

Among positive effects, community participation in decision making is pointed out as a key for the success of MPA implementation (5 references). This is illustrated by Pollnac et al. (2001) in the case of community-based MPAs in the Philippines. However, community participation is not a sufficient condition as underlined by Christie et al. (2002), and other management measures are needed at a larger scale.

4 Potential indicators for the assessment of MPA impacts

In the previous section, we listed the variables studied in the surveyed literature for assessing a variety of MPA-related effects. To complete the definition of potential quantitative indicators for measuring the impact of MPA, we further need to specify the scale at which the variable was measured. In the literature, a given variable may have been used at several scales, e.g. density per species, density of species group or total density of fish community (Tables 2 and 3). A variable measured at a given level is termed a metric in the rest of the article. A metric constitutes a potential indicator for one or several effects related to the existence of a MPA.

In this section, we considered the metrics used in the surveyed literature, and we assessed their performance as potential indicators of the MPA-related effects identified in Sect. 3. In the case of ecological indicators, we proposed an assessment based on the literature review. In the case of economic and social indicators, the number of references being much lower, we critically discussed the indicators identified in Sects. 3.2 and 3.3. It is not the purpose of this paper to carry out a thorough quantitative analysis of the potential indicators identified from the literature, but rather to highlight their strong and weak points regarding the objective of assessing MPA impact.

4.1 Performance of ecological indicators

The performance criteria used are relevance and effectiveness (see Ferraris et al. 2005) for extensive definitions of indicator properties). The relevance of an indicator illustrates the link between the indicator and the effect it is supposed to indicate. The effectiveness of an indicator gathers the concept of statistical power, precision, variability, sensitiveness and the fact that there are reference values or thresholds against which the indicator can be tested. Such measures pertain to quantitative indicators which are the scope of this paper.

[5] Note that the latter two categories of effects can in principle be included in a total economic value analysis of MPA effects. Indeed, the satisfaction of MPA users has been taken into account in a number of valuation studies. But the effects have also been measured using other approaches such as direct interviews of MPA users, which are accounted for in Table 7.

Table 7. Social effects of implementing MPAs, key factors of success, and variables measured to evidence of these effects. All references provide quantitative estimates for studying the effect mentioned, except those in italics that only discuss the subject.

Objectives	Variables measured	Effect	References
Reducing conflicts between user groups	Complains collected via questionnaires or focus groups	Strong frustration of local fishers concerning decrease in fishing effort	Suman et al. (1999) Scholz et al. (2004)
	Complains collected via questionnaires or focus groups or interviews	Frustration of local stakeholders concerning MPA boundaries and zoning, and the current management system	Sant (1996) Clifton (2003)
	Complains collected via questionnaires or focus groups	Frustration of local fishers concerning the restriction of activities	Sant (1996)
	Perception collected via questionnaires or interviews	Distrust of scientists and MPA managers with respect to stakeholders (mainly fishers), concerning the replenishment concept and the integration of their point of view in decision- making	Suman et al. (1999) Scholz et al. (2004)
	Number of offences noted by the rangers	Poaching	Clifton (2003)
	Frequency of meetings and focus groups between the public and the managers	Community participation in MPA planning and decision making	Wolfenden et al. (1994); Coklin et al. (1998); Suman et al. (1999); Pollnac et al. (2001); Clifton (2003)
	Distance of the MPAside villages from local authorities	Inputs from local authorities	Pollnac et al. (2001)
Improve satisfaction of visitors and local dwellers	Capacity to organise workshops, number of expert visits	Continuing advice from organizations supervising and funding MPA projects	Pollnac et al. (2001)
	Life expectation of projects and amount of income generated	Successful alternative income projects	Pollnac et al. (2001)
	Perception collected via questionnaires or focus groups Willingness of diver tourists to pay to visit marine sanctuaries	Satisfaction of local stakeholders, mainly conservationist group members or tourists concerning the improvement of marine life status	Sant (1996); Suman et al. (1999); Arin and Kramer (2002)
	Perception collected via questionnaires or focus groups	Satisfaction of local stakeholders concerning tourism and job opportunities and the increase in recreational activities	Sant (1996); Suman et al. (1999)
	Size of the population	Homogeneity of MPAside dwelling populations	Pollnac et al. (2001)
	Perceived crisis in terms of reduced fish population before the MPA project started	Awareness of MPAside dwelling populations about ecosystem conservation	Pollnac et al. (2001)
Increasing knowledge about marine ecosystems and biodiversity	Creation of a community-based management system Participative community co-management	Incorporation of local ecological knowledge in policy processes including MPA design and management plan	Scholz et al. (2004) Russ and Alcala (1999); Day (2002)

4.1.1 Relevance

The relevance of a potential indicator was assessed through the number of times it was used for assessing an effect in the reviewed literature. We thus assumed that the more often a metric was used for assessing a given effect, the stronger the link between the metric and the effect. To account for size effects linked to the scale of the metrics (e.g. population level versus community level), we reported in addition the number of articles in which metrics were used. It should be noted that this measure of relevance is subject to publication bias, i.e. the review can only report the content of the article. To reduce this bias, metrics were counted in the reviewed papers from both Method section and Results section, because the latter may not mention all metrics studied.

The proposed estimation of relevance leads us to distinguish metrics widely used in articles (here metrics used in more than five articles) (Table 8) from metrics rarely used (Table 9). A few metrics were very often used but mostly for a single effect: total density and species density to assess the effects on target populations, mean size of species for evaluating the rehabilitation of population age structure, movement patterns for studying the potential for biomass exportation; total species richness for assessing the success of management measures to protect biodiversity, and species richness per family for studying the degree in which assemblage structure

Table 8. Relevance of metrics for each ecological effect, as estimated by the total number of times (over articles) the metrics was used, and between parentheses the number of articles in which a given metrics was used. Only metrics used in more than five articles were reported. Biomass and density are respectively in weight per surface area and in numbers of individuals per surface area. Profiles refer to multivariate relative measures per species or species group (e.g. families). CPUE is either commercial or scientific. Common species are also termed important species, frequently observed species. Total refers to all species, although pelagic species and/or cryptic species are sometimes excluded. According to references, fishable species are termed fished species, commercial species, vulnerable species, target species, exploitable species or exploited species. Size range includes maximum size. Species stage includes age group, size group, maturity group. Total species richness either refers to total fish, or total invertebrates, or total algae depending on effect.

Metrics		Protecting critical spawning stock biomass	Rehabilitating population age structure	Exportation of biomass	Enhancing fisheries yield	Increasing fecundity, eggs, larvae	Density-dependent changes LHT parasitism	Restoration of assemblage structure	Protecting biodiversity	Indirect effects on algae and invertebrates	Protecting essential fish habitats	Detrimental effects on habitat
Variable	Scale											
biomass	total	27 (6)		1 (1)	1 (1)				8 (1)			
biomass	family	36 (7)					9	(1)				
biomass	trophic group	26 (4)										
biomass	species or genus	178 (6)	124 (5)							1 (1)		
density	total	42 (16)						8	(1)			
density	total over fishable species	11 (5)										
density	family	129 (13)						18 (2)	5 (1)	2 (1)		
density	trophic group	20 (6)										
density	size group	4 (3)	1 (1)					3 (1)		4 (1)		
density	species or genus	712 (29)		12 (2)						57 (9)		
density	species stage	21 (5)	17 (4)			4 (2)						
relative density	species stage	8 (4)	9 (4)			2 (1)	4 (1)					
density profile	species	1 (1)						8 (6)		3 (1)		
species richness	total			2 (1)				3 (1)	22 (14)	3 (1)		
species richness	family	58 (1)						136 (7)	2 (1)			
mean size	species or genus	3 (1)	236 (19)		10 (1)		2 (1)			23 (4)		
size distribution	species	14 (1)	30 (6)				4 (1)					
movement patterns	species			31 (10)								
home range	species			15 (8)								
site fidelity	species	2 (1)		9 (6)								
CPUE	total or per gear	7 (3)		8 (3)	10 (3)						1 (1)	
CPUE	species	57 (6)	2 (1)		10 (1)							
benthic cover	macrobenthos type									29 (5)	5 (4)	8 (1)

returned to unexploited levels. Metrics were often used to study more than one effect, in particular biomass- and density-based metrics (Table 8).

Results confirmed that, in addition to effects not studied in the literature (see Sect. 3.1), several effects have rarely been evaluated, namely protecting recruitment; increasing fecundity, egg and larvae production; the occurrence of density-dependent effects; improving ecosystem stability; and protecting essential fish habitats (Table 8).

It is also interesting to take a look at metrics rarely used, which relevance is low given our definition (Table 9). There is a variety of such metrics, and some of them will probably prove useful in future studies, either because of their statistical properties (e.g. robustness), or their complementarity to others.

Table 9. Metrics used in less than five articles, for each ecological effect.

Effect	Metric
1. Protecting critical spawning stock biomass	density of demersal vs pelagic species, overall density of common species, overall density of non fishable species, density ratio per species, presence/absence of species, biomass of demersal/pelagic species, biomass and density per mobility group, CV of biomass and density over common species, mean density per species over fishable species, biomass/density ratio for common species, species richness of fishable species, species richness per trophic group, species richness ratio for abundant species, fraction of occupied lairs, frequency of occurrence per species, frequency of occurrence of fishable species, frequency of occurrence per species and size group, CPUE per species stage, total mortality, nest/lair density per species
2. Rehabilitating population age structure	CPUE per species stage, species sex ratio, biomass of demersal/pelagic species, density ratio per family and size group, mean size over fishable species, mean size per family, mean size per fishable species, mean size per species over fishable species, median and modal size per species, size range per species, mean size per species stage, mean age at stage
3. Exportation of biomass	CPUE per family and fishing gear, species richness of fishable species, overall density of common species, mean size per fishable species, density ratio per trophic group/family, frequency of bites, number of fishers per gear, exploited surface by fishing gear
4. Enhancing fisheries yield	CPUE per family and fishing gear, spatial distribution of CPUE and of fishing effort, number of fishers per gear, exploited surface by fishing gear
5. Protection of recruitment	recruitment index, juvenile survival rate, spatial distributions of CPUE and of recruitment
6. Increasing fecundity, eggs, larvae	mean size per species stage, catch rate of larvae per species and overall, egg production per species
7. Density-dependent changes in LHT and parasitism	growth parameters, length-weight relationship, natural mortality
8. Restoration of assemblage structure	biomass profile per family or trophic group, presence/absence of species, species richness per trophic group
9. Protecting biodiversity	species richness of fishable species, diversity index overall and per family, rarefaction curve
10. Indirect effects on algae and invertebrates	species richness per mobility group, predation rate
11. Improving ecosystem stability and resilience	CV of biomass and density over common species
12. Protecting essential fish habitats	substrate heterogeneity
13. Detrimental effects of non-exploitative uses	number of damages per coral type, richness of benthic species, number of diver contacts with ground, number of dives

But we could not study their effectiveness from the existing literature (see below).

4.1.2 Effectiveness

The effectiveness of a potential indicator was assessed from the proportion of significant effects found in the reviewed studies, whether these effects were positive or negative. The significance of a result is mostly tied to the power of the analysis, which in turn depends on the variability of the system, the sensitivity of the metric to the effect tested, and the experimental design studied (Ferraris et al. 2005). Therefore, effectiveness may thus be seen as a proxy to the statistical power of the analysis. In this definition, we did not account for the existence of reference values or thresholds. All reviewed studies were based on empirical assessments and therefore did not provide reference values. Note however that in such studies, the provision of control sites somehow addresses the issue of reference values. In practice, the effectiveness of a potential indicator was calculated for each effect as the ratio of the number of times it gave a significant result divided by the number of times it was used, across all studies based on inferential statistical analysis. Metrics based on descriptive methods, i.e. non-inferential methods, were considered in the relevance, but excluded from the calculation of effectiveness; therefore numbers may not correspond between Tables 8 and 10. Being based on a ratio, effectiveness was only calculated for effects that were assessed in a sufficient number of studies (metrics from Table 8).

Like relevance, this measure of effectiveness is subject to publication bias, non-significant results being generally less well reported than significant ones. Again, we relied on

Table 10. Effectiveness of metrics used in the literature. Descriptive uses of metrics were excluded from computations. *Eff.* means effectiveness. *n* is the number of articles from which the effectiveness was calculated (each article generally includes several uses of the metric).

Metric		Protecting critical spawning		Rehabilitating population age structure		Restoration of assemblage structure		Protecting biodiversity		Indirect algae and effects on invertebrates		Detrimental effects on habitat	
Variable	Scale	*n*	*Eff.* 1	*n*	*Eff.* 2	*n*	*Eff.* 3	*n*	*Eff.* 4	*n*	*Eff.* 5	*n*	*Eff.* 6
biomass	total	6	85					1	88				
biomass	family	7	72										
biomass	trophic group	4	85										
biomass	species or genus	6	39	5	35					1	100		
density	total	15	56					1	38				
density	total fishable species	5	82										
density	family	12	50					1	60	1	100		
density	trophic group	6	95										
density	size group	3	75	1	100	1	0	2	50				
density	species or genus	29	41							9	39		
density	species stage	5	67	4	71								
relative density	species stage	2	83	2	71								
density profile	species	1	100			2	67						
species richness	total	3	33			1	0	13	59	1	50		
species richness	family	1	34			6	41	2	0				
mean size	species or genus	1	33	18	38					4	39		
size distribution	species	5	95	5	56								
CPUE	total	3	60										
CPUE	species	5	40										
benthic cover	macrobenthos type									4	68	1	100

the Method section. Another drawback of this approach pertains to the lack of coherence in experimental designs across studies. However, few articles contained sufficiently explicit information to account for this. Still, we believe it is useful to carry out this kind of meta-analysis, and we think this measure of effectiveness is suitable for qualitative comparisons across metrics.

The first observation is that few metrics have been widely used, since only 17 out of 41 combinations between metrics and effects were used in more than five reviewed studies (Table 10). For the first effect, the effectiveness of the most often used metrics ranges from ca. 40% (biomass and density per species) to 85% (total biomass). Total density performed relatively poorly (56%), but, interestingly, total density computed over fishable species worked better (82%).

Mean size showed surprisingly poor effectiveness (38%) as an indicator to assess the ability of MPAs to rehabilitate population age structure. Population size distribution was more effective for this effect (56%), this metric being also reasonably well related (95%) to the potential of MPAs to increase population abundance.

The expected restoration of assemblage structure was better assessed by density profiles (67% of effectiveness) than through the species richness of key families (41%), although the latter was more often used than the former. Density profiles were generally analysed through multivariate methods. Total species richness appeared as a relatively effective indicator (59% effectiveness).

The study of indirect effects of protection on algal and invertebrate assemblages (sometimes referred as "cascade effects" of protection) was mostly approached through algae or invertebrate species (or genus) density or cover, but its effectiveness was relatively low (39%); other metrics could prove more effective, but their low utilization rate prevented us from assessing their performance.

If one excludes metrics rarely used for one effect, most efficient metrics were density per trophic group for effect 1 and size distribution for effect 2 (95% effectiveness for each).

4.2 Which indicators for the economic effects of MPA?

The small number of empirical studies of the economic impacts of MPAs made it difficult to carry out the same type of assessment as in Subsection 4.1. Rather, several methodological points should be raised with respect to indicator selection.

In principle, the economic effects of an MPA should be defined as the difference in total net economic benefits derived from the ecosystem with and without MPA (Pendleton 1995). Such differences should be calculated from the measurement of variations in the benefits and costs associated to changes in ecosystem quality and uses that result from reef protection. The metrics used in empirical studies of Tables 5 and 6 may not reflect the true economic effects of MPAs for three reasons.

First, the metrics used often referred to economic *impacts* of MPAs, and not to their economic *value*. We illustrate the difference between these two concepts by the example of accidental pollutions. Resulting cleanup activities may be regarded as having a positive economic impact, but they also have a negative economic value, since cleaning uses resources that would have been otherwise diverted to a more valuable purpose had the pollution not occurred. The key difference between the economic impacts and the economic value of an activity lies in the opportunity costs of the resources used in this activity. Hence, economic impacts relate to the effects of an MPA on levels of economic *activity*, measured e.g. in the case of recreational activities, through gross expenditure by visitors and ensuing revenues to the local and international tourism industry and to the public budget via taxes. In contrast, measuring the economic value of an MPA requires the calculation of variations in total consumer and producer surplus associated to MPA existence. Total producer surplus is calculated as a sum of *net* benefits to producers, taking into account both production and opportunity costs. Total consumer surplus is derived from the demand function for the goods and services considered, e.g. visits to the area in the case of recreation (see Pendleton 1995 for an application to the Bonaire Marine Park).

The use of indicators of the economic impacts of MPAs, rather than indicators of their economic value, is primarily due to the difficulties in estimating producer surplus and demand functions for the goods and services provided by MPAs. In comparison, the information required to assess economic impacts (e.g. number of visitors and average expenditure per visitor in the case of recreational uses) is more accessible. For the same reason, most studies indeed focus on partial rather than total value analysis, e.g. by dealing only with the measurement of a particular economic effect (Tables 5 and 6).

Second, valuation studies often focused on the value of ecosystem goods and services, rather than on changes in their value due to the protection provided by marine parks. For example, they assessed the overall recreational benefits associated to a particular reef area, rather than the variation in these benefits entailed by the implementation of an MPA. Assessing the economic effects of a MPA thus requires the comparison of a scenario with and a scenario without the MPA, taking into account the changes in ecosystem quality and uses resulting from its creation or disappearance. Aside from the recent bio-economic modelling work focusing on the implications for fisheries of creating a closed area (Table 5), there has been little theoretical or empirical work to date along this line.

Third, because the changes that need to be measured are bound to occur over a period of time, economic assessment of MPAs should look at discounted net benefits over such a period (Pendleton 1995). Future costs and benefits occurring only in a distant future may weigh little from a present value perspective.

4.3 Social effects of MPAs: Perceptions, attitudes and conflicts

Given the scope of the paper, the paucity of empirical studies in the literature precluded any attempt to propose (not even evaluate) indicators for social effects of MPAs. The literature that can lead to indicator definition revolves around the issues of perception, attitudes and relationships between and among stakeholders, users and managers. Interviews and questionnaires are the appropriate way of collecting information in this purpose. Metrics to be used should logically be similar to those used in other fields of social sciences, but in the case of MPA, this kind of study is very little developed to date.

According to the literature, the conflicts between the stakeholders living around MPAs, and between these stakeholders and the MPA managers were the only factor which can be classified both as expected social effect and effective social effect of MPAs' implementation. According to our expertise, they are both cause and consequence of MPA failures. Due to its holistic nature, the number of conflicts per year is a potentially interesting indicator to assess the social sustainability of any MPA. It could be measured via interviews of local stakeholders. Pollnac et al. (2001) stress that the involvement of local stakeholders in MPA implementation and compliance to MPA management rules are two key factors of success, and that violation rates are not a good indicator of compliance to the rules, as they may be high where enforcement is strong, and low where it is poor. Therefore, these authors decided to have an expert panel rank the local stakeholders from 0 to 5. Similar approaches could be used to assess the degree of involvement of local stakeholders in MPA implementation.

Unlike ecological and economic studies, social studies about MPA effects are mostly in the grey literature, technical documents, reports or in books and proceedings. In France for instance, social scientists mainly publish in books in French or national symposia proceedings. This literature could not be integrated in the paper, and therefore the perception of social research on MPA may be biased if solely based on primary literature.

In addition, most studies dealing with social considerations of MPA are mainly descriptive, and it is difficult to derive potential indicators, even qualitative ones, from such approaches.

Nevertheless, we believe that social indicators are needed for a better assessment of the social consequences of MPA, and particularly to identify crisis stages through threshold values.

A holistic indicator of MPA success may also be the simple fact that the MPA continues to be effectively managed and funded several years after its establishment.

5 Conclusion

As in many studies of anthropic pressure on marine ecosystems, economic aspects and even more so social aspects are apparently less documented than ecological effects, even though this conclusion might have been mitigated, had grey literature been taken into account. In the light of these differences, distinct approaches were undertaken for each discipline.

Existing literature precludes the identification of indicators for social effects. Economic indicators were also difficult to isolate as the literature does not really address the economic effects of MPAs, but either focus on a partial analysis of MPA effects, or refer to effects on economic activities, rather than on the economic value of MPA which is more informative for management purposes. In the case of ecological effects, a number of indicators could be identified and some assessed. These indicators are not specific to MPAs nor to coral reef ecosystems, and cover ecological assessment in general. Their effectiveness could be assessed for some, showing in particular that the most widely used ones were not necessarily the most efficient (e.g. density at the species or genus level). A number of expected ecological effects have never been really tested (e.g. effects on recruitment, on habitat quality, genetic effects) or too rarely so that the performance of corresponding metrics cannot be assessed. Note that several metrics were not found relevant according to our definition, but may still prove interesting in the future. This analysis should be regarded as a first attempt to score indicators in a meta-analysis approach.

The review of both ecological and economic articles reasserts the need for assessments that take into account the evolution of the ecosystem and its uses in the absence of MPA, referred to as Before/After Control Impacts designs in ecology. Another parallel between ecological and economic studies comes from the need for integrated assessments, referred to as total value analysis in the economic field. Most studies tackle one or two effects of MPA, but never address effects at the system scale, whether the ecosystem, the fishery, or the coastal ecosystem together with its uses. In this domain, perspectives include i) integrated modeling that is in addition needed for constructing indicators of system dynamics; and ii) joint panels of complementary indicators that address different MPA-related effects.

As for ecological effects, the present review shows a striking discrepancy between all the advocated (mostly positive) effects on one hand, and on the other hand, the number of effects that are not studied, or tested through metrics with low effectiveness. This brings us to first conclude that there is an avenue for new empirical studies with rigorous experimental designs. The sources of variability inherent in natural systems make it more difficult to devise and implement efficient designs and to set up indicators that account for these uncertainties. The goal of constructing statistically sound indicators useful for managers might be a good incentive in this respect. Russ (2002) also stressed that "there is a plethora of reviews on what marine reserves could do as a fisheries management tools, and yet there is a distinct paucity of empirical studies demonstrating what they can do"; Willis et al. (2003b) share the same opinion. Our review provides quantifications for these considerations, and shows in addition that they also apply for economic and social effects of MPA. Hence, it would be useful to devote more resources for effective monitoring of ecological, economic and social effects related to established MPAs.

A corollary to this conclusion pertains to the boom in MPA creations, with publicized optimistic views on their positive consequences, even on the short-term. As stressed by Agardy et al. (2003) "…the tendency to decree as many MPAs as possible, an eagerness to do so without a clear understanding of many of the complexities or balanced framework required … may inadvertently impede success". We believe that a closer collaboration with managers would be necessary to anticipate and monitor MPA effects. Investigations of social effects of MPA are particularly needed, because MPAs may be biological successes but social failures (Christie 2004). Therefore, indicators for both ecological, economic and social effects are jointly needed for MPA assessment. Projects aimed at devising ecological, economic and social indicators that are both scientifically grounded and useful for managers seem good opportunities for such collaborations.

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