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Research Article

Zoning of the Mejillones Peninsula marine protected coastal area of multiple uses, northern Chile

Raúl Ulloa[1], Adolfo Vargas[2,3], Cristian Hudson[2] & Marcelo M. Rivadeneira[4]
[1]Centro Regional de Investigación Pesquera, Instituto Nacional de Pesca
Dirección General de Investigación Pesquera Pacifico Norte
Miguel Alemán sur Nº605, C.P. 85400, Guaymas, Sonora, México
[2]Programa Magíster en Ciencias Aplicadas mención Biología Pesquera
Departamento Ciencias del Mar, Universidad Arturo Prat, P.O. Box 121, Iquique, Chile
[3]Centro de Investigación y Desarrollo de Profesionales Marinos Pacífico Ltda.
Vivar 1218, Iquique, Chile
[4]Centro de Estudios Avanzados en Zonas Áridas (CEAZA) & Facultad de Ciencias del Mar
Universidad Católica del Norte, Av. Bernardo Ossandón 877, CP. 1781681, Coquimbo, Chile

ABSTRACT. Marine protected areas of multiple uses (MPA-MU), are an important management tool to protect biodiversity and regulate the use of coastal marine resources. However, robust conservation plans require an explicit consideration of not only biological but also social components, balancing the protection of biodiversity with a sustainable exploitation of marine resources. Here we applied the decision-making algorithm MARXAN to provide a zoning analysis at the Mejillones Peninsula MPA-MU in northern Chile, one of largest MPA's of the Humboldt Current Marine Ecosystem. We set conservation goals for coarse and fine-filter conservation targets that were crossed out against different threats and pressure factors from human activities across the area. We identified a portfolio of sites for conservation, within the Mejillones Peninsula MPA-MU, representing different ecological systems with different levels of human impacts and vulnerability. These results may serve as a foundational guideline for the future administration of the MPA-MU.

Keywords: MPA-MU, MARXAN, conservation plans, marine coastal ecosystems, northern Chile.

Zonificación del área marina costera protegida de múltiples usos de la península de Mejillones, norte de Chile

RESUMEN. Las áreas marinas protegidas de múltiples usos (AMCP-MU), son una importante herramienta de manejo para la protección de la biodiversidad y la regulación del uso de recursos marinos costeros. Sin embargo, planes robustos para la conservación, deben considerar explícitamente no sólo componentes biológicos sino además sociales, equilibrando la protección de la biodiversidad con la explotación sustentable de los recursos marinos. En este trabajo se aplica el algoritmo de toma de decisiones MARXAN, para entregar un análisis de zonificación del AMCP-MU, de la península de Mejillones, en el norte de Chile, una de las AMP más grandes del Ecosistema Marino del sistema de la Corriente de Humboldt. Se fijaron metas de conservación para objetivos de conservación de filtro grueso y fino, que fueron cruzados contra diferentes amenazas y factores de presión, generados por las actividades humanas registradas en la zona. Se identificó un portafolio de sitios prioritarios de conservación, dentro de la AMCP-MU, representativos de diferentes sistemas ecológicos, sometidos a diferentes niveles de impacto humano y vulnerabilidad. Estos resultados pueden proveer las guías fundacionales para el futuro plan de administración de la AMCP-MU de la península de Mejillones.

Palabras clave: AMCP-MU, MARXAN, planes de conservación, ecosistemas marinos costeros, norte de Chile.

Corresponding author: Marcelo M. Rivadeneira (marcelo.rivadeneira@ceaza.cl)

INTRODUCTION

Marine ecosystems are fundamental to the sustainable development of coastal countries, providing a large variety of environmental resources. Currently, these ecosystems face a growing menace of overexploitation of fisheries, pollution, habitat destruction, among other human-driven impacts (Jackson, 2001; Jackson *et al.,* 2001; Jackson & Sala, 2001; Rivadeneira *et al.*, 2010). In this scenario, Marine Protected Areas (MPA) arises as one of most practical strategies for the conservation of the marine biodiversity (Allison *et al.*, 1998). MPA not only seek to protect biodiversity but also allows sustainable exploitation of the ecosystem, providing social, economic, and research benefits (Salm *et al.,* 2000).

In contrast to terrestrial ecosystems, MPA networks are worldwide poorly developed and less than 1% of the global ocean is currently protected (Chape *et al.*, 2005). The situation is no better in Latin America and Caribbean regions, where despite there are over 700 MPA established, only 1.5% of coastal and shelf waters areas are protected (Guarderas *et al.*, 2008). Moreover, vast areas of the Humboldt Current Large Marine Ecosystem, included Chile, are largely unprotected (Guarderas *et al.*, 2008).

The current environmental policy of Chile recognizes eight categories of areas for conservation of biodiversity (Sierralta *et al.,* 2011). Among them, marine protected costal area of multiple uses (MPA-MU) are mixed-used MPA, aimed to conserve biodiversity, protect marine species, reduce conflicts of use, allowing commercial and recreational activities, including fishing and tourism (Sierralta *et al.,* 2011). Currently, there are four MPA-MU established for the Chilean coast (Tognelli *et al.,* 2009). Despite the existing MPA network that seems to protect a large fraction of the marine biodiversity, many species with small geographic ranges are not covered. In addition, the success of a MPA depends on the existence of zoning plans, able to resolve conflicts between local users and the environment, balancing the protection of marine biodiversity with a sustainable exploitation of marine resources and uses of the coastal seascape (Villa *et al.,* 2002; Douvere, 2008). However, to date, such zoning analysis has been implemented only at Isla Grande de Atacama MPA-MU (Gaymer *et al.,* 2008; Rojas-Nazar *et al.,* 2012).

The Mejillones Peninsula (Fig. 1), has been previously identified as a priority site for marine conservation (Tognelli *et al.,* 2005, 2008, 2009; Miethke *et al.,* 2007), and is one of the recently proposed MPA-MU for the Chilean coast (Hudson *et al.,* 2008). The Mejillones Peninsula MPA-MU, is placed in the coastal area of the hyper-arid Atacama Desert, and it is the third largest MPA of the southeastern Pacific, covering more than 400 km² along a stretch of *ca.* 100 km of coast (Wood, 2007). The marine ecosystem is characterized by nearly continuous upwelling events, which introduce cold and nutrient-rich waters to coastal areas (Sobarzo & Figueroa, 2001; Thiel *et al.,* 2007). The high marine productivity and relative isolation from human activities, begets a great diversity and abundance of marine species. The area is a vertebrate hotspot of endemism (Tognelli *et al.,* 2005, 2008), and it is well recognized for the presence of large colonies of sea lions, transit of dolphins, great abundance and diversity of seabirds, and the seasonal arrival of sea turtles and whales (Aguayo & Maturana, 1973; Guerra *et al.,* 1987; Rendell *et al.,* 2004; Vilina *et al.,* 2006; Guerra-Correa *et al.,* 2008).

In spite of the relative isolation of the Mejillones Peninsula, different human activities can be identified, all of which can potentially interfere on marine biodiversity and conservation plans, including both legal and illegal artisanal fisheries, aquaculture centers, and non-regulated tourism from the nearby cities (Hudson *et al.,* 2008). Therefore, conservation plans for the MPA-MU must take into account the integration of human stakeholders in order to find optimal solutions that balance biodiversity protection with socio-cultural and economic realities. In this work, we carried out a spatial zoning analysis to identify specific areas for conservation across the Mejillones Peninsula MPA-MU, using optimization algorithms to reduce human threats and maximize the conservation goals.

MATERIALS AND METHODS

Biological and anthropogenic database

The study area included 435 km², 98.5 km of coastline, encompassing all marine coastal shelf habitats (<200 m depth), from the intertidal to 2.7 km offshore within the coastal shelf. We compiled an exhaustive georeferenced database, documenting different facets of the marine biodiversity and human activities (see below) in the study area. The information data was obtained from four main sources: a) Published scientific literature, including papers, thesis, technical reports from Chile governmental services (*e.g.*, Ministerio del Medio Ambiente de Chile, Instituto de Fomento Pesquero, Fondo de Investigación Pesquera, Comisión Nacional Forestal, and Centro Nacional de Datos Hidrográficos y Oceanográficos), b) Unpublished information, available from Chilean public services (*e.g.*, Servicio Nacional de

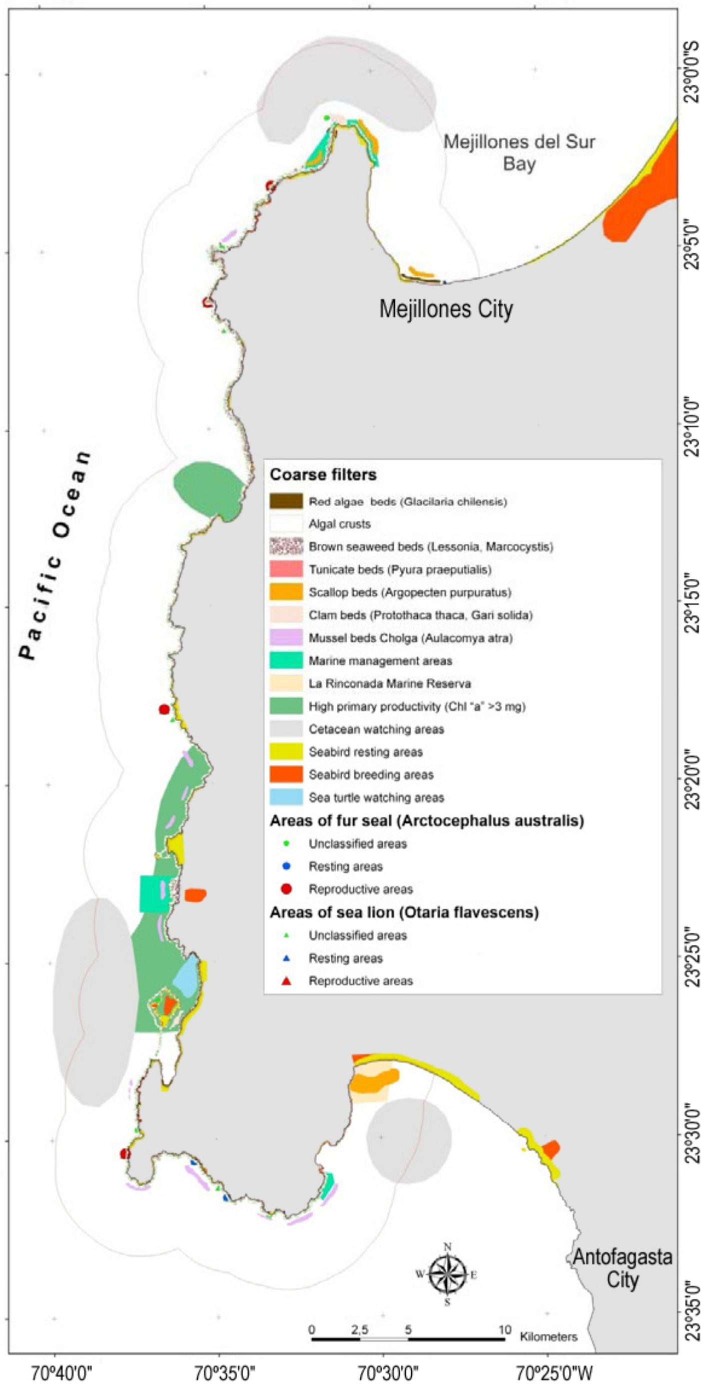

Figure 1. Spatial distribution of the coarse filter for conservation in the study area.

Pesca, Subsecretaría de Pesca, Servicio Hidrográfico y Oceanográfico de la Armada), c) the traditional knowledge of local fishermen regarding fisheries, reproduction and recruitment zone, and sea bottom types, and d) new information from field samplings in intertidal and subtidal benthic habitats, carried out during November 2008. Field surveys allowed a community-level characterization of the biodiversity, and also cross-validate the information provided by the traditional knowledge of fishermen.

The georeferenced information was assigned to 10,873 hexagonal planning units (PU) of 4 ha each (0.04 % of total area of MPA) (Fig. 1). For a geographic homologation we used the zone 19 UTM and Datum WGS-84.

Conservation targets and goals

Conservation targets were defined using two complementary approaches, fine and coarse filters, following previous studies (Day & Roff, 2000; Beck & Odaya, 2001; Roberts *et al*., 2003; Vierros, 2004). Fine filters were selected according two criteria: i) species included in any threatened category according to UICN, CITES, CONAF or MMA, ii) particular traits associated to species; justifying further conservation efforts (*e.g.*, endemic, migratory, keystone, umbrella, and flagship species, Barua, 2011) (Table 1). Because fine filters are typically available only for a very restricted subset of marine biodiversity (*i.e.*, higher vertebrates), we also used coarse filters that may provide a broader picture of ecological processes occurring in the area, including ecosystem engineers, areas of reproduction/resting, areas with existing conservation/management plans, and areas of high primary productivity (Table 2). Ecosystem engineers (Jones *et al.,* 1994), such as kelps, mussels, scallops, and tunicates were included, because they provide a habitat to a vast diversity of other species. Reproductive/resting areas of migratory or flag species imply the existence of a high population abundance were bottom-up/top-down processes may be enhanced. Similarly, the restricted or reduced human perturbations expected in the existing management and exploitation area for benthic resources (MEARB's) and the La Rinconada marine reserve may imply an indirect protection of marine biodiversity (Fernández & Castilla, 2005; Navarrete *et al.,* 2010).

In order to ensure the viability and persistence of each conservation target we assigned a conservation goal to each one (Groves *et al.,* 2000; CONABIO, 2009; Ulloa *et al*., 2006). It should be remarked that these goals were consensual with social actors of the Mejillones Peninsula, including artisanal fishermen, academic researchers and public authorities. We set conservation goals for each target, with values varying between 20% (less relevant) and 100% (irreplaceable).

Pressure factors and threats

Threats to biodiversity were selected based on known impacts of anthropogenic activities on ecological systems. The aim was to use high quality data to characterize pressure factors in order to select sites that could still be valuable to invest in conservation or restoration. The data used by the prioritization algorithm for representing threats is often referred as costs, following the logic that areas suffering from negative impacts are more difficult to protect and require higher conservation investment. Cost information is used to distribute conservation priorities to sites amenable to long-term persistence of conservation features (Chan *et al.,* 2006).

A threat was defined as any human activity affecting negatively marine biodiversity. Threats were identified based on compiled information for five categories: fishing, tourism, human settlements, shipping zones, and aquaculture (Table 4). The spatial extension of each threat was digitalized into a geographic information system. Coasts (arbitrary units) were assigned to each threat, ranging from 500 (lowest) to 10.000 (highest).

Those values were estimated considering the relationship between the spatial extension of the threat and the number of users or elements associated (*e.g.*, number of fishermen, local population, frequency of use of space, volume of production). Thus, despite fishing activities are carried out along all the area, we assigned low to mid costs because of the relatively low levels of fishermen involved in the activity. In contrast, we assigned a large cost to aquaculture, due to the large volume of production involved.

Identifying priority areas for conservation

The identification of priority sites was carried out based on biological variables, and on pressure factors, using the simulated annealing algorithm in the MARXAN software (Ball & Possingham, 2000), a robust and widely used analytic approach (McDonnell *et al*., 2002; Stewart & Possingham 2002). The program was run with 1.000.000 iterations and 10.000 runs, using the adaptive annealing schedule with normal iterative improvement at the end of each run (Cook & Auster, 2005; Chan *et al*., 2006). The type of data and criteria used in the process of assigning conservation goals to biodiversity elements and cost values to represent pressure factors followed the methodology used by different authors (Ball & Possingham, 2000; Groves *et al*., 2000; Ulloa *et al.,* 2006). The selection frequency of a planning unit provides a fundamental measure of conservation value for the unit (Stewart *et al.,* 2007) indicating its relative importance to meet given targets. Planning units included in all the MARXAN solutions are considered irreplaceable, and thus were designated as high priority.

RESULTS

A total of 76 conservation targets, 58 fine filter and 18 coarse filters were identified (Tables 2 and 3). For coarse filters, larger goals (100%) were assigned for reproductive/resting areas of flag or migratory turtles,

Table 1. Criteria used to define fine-filters and conservation goals. Conservation categories according to IUCN and MMA (DD: data deficient, LC: least concern, NT: near threat, VU: vulnerable, EN: endangered).

Taxa	Species	Conservation categories			Species' features relevant for conservation				
		IUCN	CITES	MMA	Endemic	Keystone	Migratory	Flagship	Goal
Ascidiacea	*Pyura chilensis*					X			20%
Bivalvia	*Aulacomya atra*					X			
	Choromytilus chorus					X			
Elasmobranchii	*Catharachta lonnbergi*	LC					X		
	Mustelus mento								
Reptilia	*Microlophus atacamensis*				X				
Aves	*Arenaria interpres*						X		
	Catoptrophorus semipalmatus						X		
	Daption capense	LC							
	Fregata grallaria	LC							
	Fulmarus glacialoides	LC							
	Larus belcheri	LC			X				
	Larus dominicanus	LC							
	Larus pipixcan	LC							
	Oceanites oceanicus	LC							
	Pachyptila belcheri	LC							
	Pelecanus thagus	LC							
	Phalacrocorax brasilianus	LC							
	Stercorarius chilensis	LC					X		
	Sula variegata	EN			X				
Aves	*Diomedea cauta*				X		X		40 %
	Diomedeae pomophora	VU					X		
	Diomedea exulans	VU					X		
	Fregata tropica	LC					X		
	Larus modestus	LC			X				
	Macronectes giganteus	NT							
	Phalacrocorax bougainvillii								
	Phalacrocorax gaimardi	NT							
	Phalaropus fulicaria						X		
	Phoebetria palpebrata	NT							
	Procellaria aequinoctialis	VU					X		
	Pterodroma cookii				X				
	Puffinus griseus	NT							
	Sterna hirundinacea	LC					X		
	Sterna paradisaea						X		
	Sula nebouxii	LC			X		X		
	Thalassarche bulleri						X		
Mammalia	*Globicephala melaena*						X	X	
Aves	*Larosterna inca*	NT							80%
	Procellaria cinerea	NT					X		
	Pterodroma neglecta	LC		EN					
	Sterna elegans	NT					X		
Mammalia	*Arctocephalus australis*	NT					X	X	
	Lagenorhynchus obscurus	DD	X				X	X	
	Lissodelphis peronii	DD	X				X	X	
	Mirounga leonina						X	X	
	Otaria flavescens	NT						X	
	Pseudorca crassidens	DD	X				X	X	
Ascidiacea	*Pyura praeputialis*				X	X			100%
Reptilia	*Chelonia mydas*	EN	X				X	X	
	Lepidochelys olivacea	VU	X				X	X	

(Continuation)

Taxa	Species	Conservation categories			Species' features relevant for conservation				Goal
		IUCN	CITES	MMA	Endemic	Keystone	Migratory	Flagship	
Aves	*Pterodroma externa*	VU		EN					
	Puffinus creatopus	VU		EN					
	Spheniscus humboldti	VU	X	VU	X		X	X	
	Sterna lorata	EN		EN	X				100%
Mammalia	*Delphinus delphis*	EN	X				X	X	
	Lontra felina	EN	X	DD			X	X	
	Tursiops truncatus	EN	X	EN			X	X	

Table 2. Coarse-filters for conservation, indicating the geographic extend (PU's) of each target and the conservation goals set.

Coarse filters	Targets	Shape	Planification Units (PU's)	Goal
Ecosystem-engineer species, subtidal 'type' assemblages	Brown seaweed beds (*Lessonia* spp., *Macrocystis pyrifera*)	Polygon	1055	60%
	Red algae beds (*Gelidium chilensis*)	Polygon	37	60%
	Algal crusts	Polygon	902	60%
	Tunicate beds (*Pyura praeputialis*)	Polygon	78	100%
	Clam beds (*Leukoma thaca, Gari solida*)	Polygon	93	60%
	Mussel beds (*Aulacomya atra*)	Polygon	249	60%
	Scallop beds (*Argopecten purpuratus*)	Polygon	312	60%
Reproductive/resting areas for flag/migratory species	Seabird resting areas	Polygon	1330	60%
	Seabird breeding areas	Polygon	376	100%
	Sea turtle watching areas	Polygon	182	100%
	Resting areas of fur seal (*Arctocephalus australis*)	Point	7	100%
	Reproductive areas of fur seal (*Arctocephalus australis*)	Point	5	100%
	Resting areas of sea lion (*Otaria flavescens*)	Point	10	100%
	Reproductive areas of sea lion (*Otaria flavescens*)	Point	5	100%
	Cetacean watching areas	Polygon	6222	10%
Administrative areas	Management and Exploitation Area for Benthic Resources (MEARB's)	Polygon	707	100%
	La Rinconada Marine Reserve	Polygon	413	100%
Oceanographic	High chlorophyll-*a* concentration (>2 mg L^{-1})	Polygon	4540	10%

Table 3. Different anthropogenic threats identified, and number of planning units (PU's) and costs assigned.

Threat	Threat type	Form	PU's	Degree	Cost
Shipping	Anchoring point	Point	1	Low	500
Fishing	Free-diving fishing	Polygon	130	Low	1130
	Intertidal harvesting	Polygon	74	Low	1604
	Hooka fishing	Polygon	2	Mid	3881
	Pelagic-diving	Polygon	3	Mid	4534
Tourism	Camping areas	Polygon	104	Mid	2500
Fishermen's villages	Juan López cove	Polygon	3	Mid	2500
	Constitución cove	Polygon	1	Mid	1500
Aquaculture	Aquaculture concession	Polygon	238	High	5500
	Aquaculture centers	Polygon	238	High	5500

seabirds and sea mammals (Table 2). However, we also assigned high goals (≥60%) to seaweed and invertebrate beds, MEARB's and the sole genetic reserve in the region. For fine filters, larger goals were assigned to endangered, endemic and flag species. These include the turtles *Chelonia mydas* and *Lepidochelys olivacea;* the dolphins *Delphinus delphis* and *Tursiops truncates,* and also the tunicate *Pyura praeputialis*. In general, the conservation goals were distributed across the entire study region, but particularly in coastal shallower areas (Fig. 1).

We assigned a cost value to each one of the nine types of human threats identified along the Mejillones Peninsula region (Table 3), with larger values indicating a higher potential damage to biodiversity. The largest costs were located in nearshore areas, where intertidal and subtidal benthic areas are subject to human activities, mainly aquaculture, artisanal fisheries, and non-regulated tourism (Table 3, Fig. 2). The spatial integration of the costs of the threats showed that 9% of PU yielded very high costs (*e.g.*, ≥5000).

The zoning analysis yielded a portfolio of 211 PU more frequently selected (5.001-10.000), encompassing 2.4% (844 ha) of the total area evaluated. These areas are spatially clustered in several shallow-water hotspots along the study region (Fig. 3). The two largest hotspots are located at the northern (Caleta Lobería-Punta Angamos) and southern ends (Isla Santa María-La Rinconada) of the Mejillones Peninsula. The analysis also identified several smaller and discontinuous spots highly selected across the MPA-MU.

DISCUSSION

The Mejillones Peninsula has been recognized as a priority the area for the conservation of marine biodiversity in the Chile (Tognelli *et al*., 2005, 2008, 2009; Miethke *et al*., 2007). Therefore, our zonation analysis represents an important step for the establishment of administrative policies of the Mejillones Peninsula MPA-MU.

The definition of conservation goals, in coastal ecosystems, is one the most debated questions in coastal planning, due its complexity and the limited understanding of the ecological processes and its scale-dependency (Roberts *et al*., 2003). Quantitative goals has been introduced only recently, but mainly based on the expert criteria, and the abundance of the conservation targets (Beck & Odaya, 2001; DeBlieu *et al.,* 2005; Ulloa *et al*., 2006). In this vein, our conservation proposed goals, accordingly to four criteria, allowed us to reduce the uncertainty introduced by the approaches based on the expert criteria (Ballantine, 1997), or the abundance of the conservation target. This is particularly relevant because the conservation status is available for a small fraction of species (*i.e.*, mainly vertebrates), leaving out the vast majority of non-vertebrate biodiversity. Indeed, the total number of species used to set fine filters was strongly biased towards seabirds and mammals, representing ca. 11% of total marine richness reported for the study area (Hudson *et al*., 2008). We mitigated this problem by using coarse-filters, which reflect population, community or ecosystem-level properties. Given the high diversity of invertebrates and vertebrates associated to these species, we ensured the secondary protection of many species for which we lack assessments of conservation status

The two areas identified as target for conservation, at the northern and southern ends of the MPA, have been previously recognized as important areas for different ecological processes relevant for conservation plans. For instance, these areas are traditional spots for cetacean watching, such as the common dolphin *Delphinus delphis* (Guerra *et al*., 1987), and resting/reproductive areas of seabirds (Vilina *et al*., 2006). On the other hand, these areas show high abundances of ecosystem engineers (Jones *et al.,* 1994), including kelps, tunicates, scallop and mussel beds, which serve as habitat for a large number of invertebrate and vertebrates (Cerda & Castilla, 2001; Thiel & Ullrich, 2002; Vega *et al.,* 2005; Vasquez *et al.,* 2006). For instance, Cerda & Castilla (2001) reported more than 96 putative species living within the beds of the tunicate *P. praeputialis*, and invasive species but with a very restricted geographic range (*i.e.*, endemic) along the southeastern Pacific coast (Castilla *et al.,* 2004). Hence, setting high conservation goals for these species may ensure the indirect protection of a vast diversity of marine species.

Because of the spatial clustering of the portfolio of priority PU's, connections between areas may be not warranted. Roberts & Hawkins (2000) and Sala *et al*. (2002) have suggested that isolated MPA are of limited use for conservation since they protect a limited fraction of the marine biodiversity, and therefore the distance among MPA's should enable the dispersal among populations. The existence of a permanent off-shore upwelling plume at the region would potentially reduce the larval dispersal alongshore, although larval retention may be enhanced by the existence of eddies (Thiel *et al.,* 2007). However, recent phylogeographic studies have

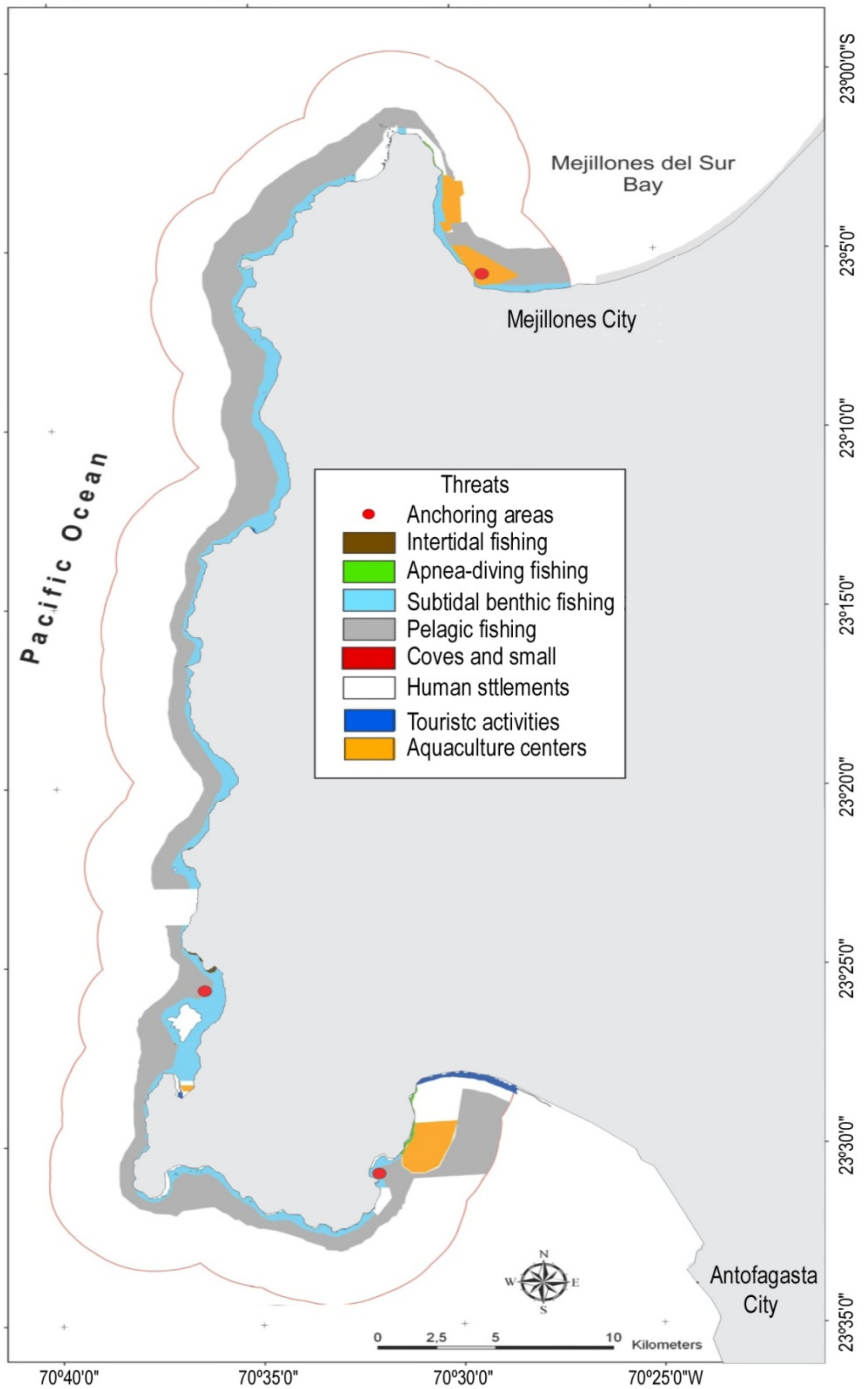

Figure 2. Spatial distribution of the threats for conservation along the study area.

revealed no genetic break within or near the MPA-MU zone in species with very contrasting dispersal capabilities (Cardenas *et al.*, 2009a, 2009b; Tellier *et al.,* 2009), which suggest that populations should be genetically connected across the region. In addition, different oceanographic processes (*i.e.,* Ekman transport, wind velocity, slick occurrence), and the recruitment of intertidal barnacles are structured at spatial scales of *ca*. 50 km (Lagos *et al.,* 2008). Altogether, these pieces of evidence suggest a strong connectedness among high priority PU's, ensuring the conservation potential of the network.

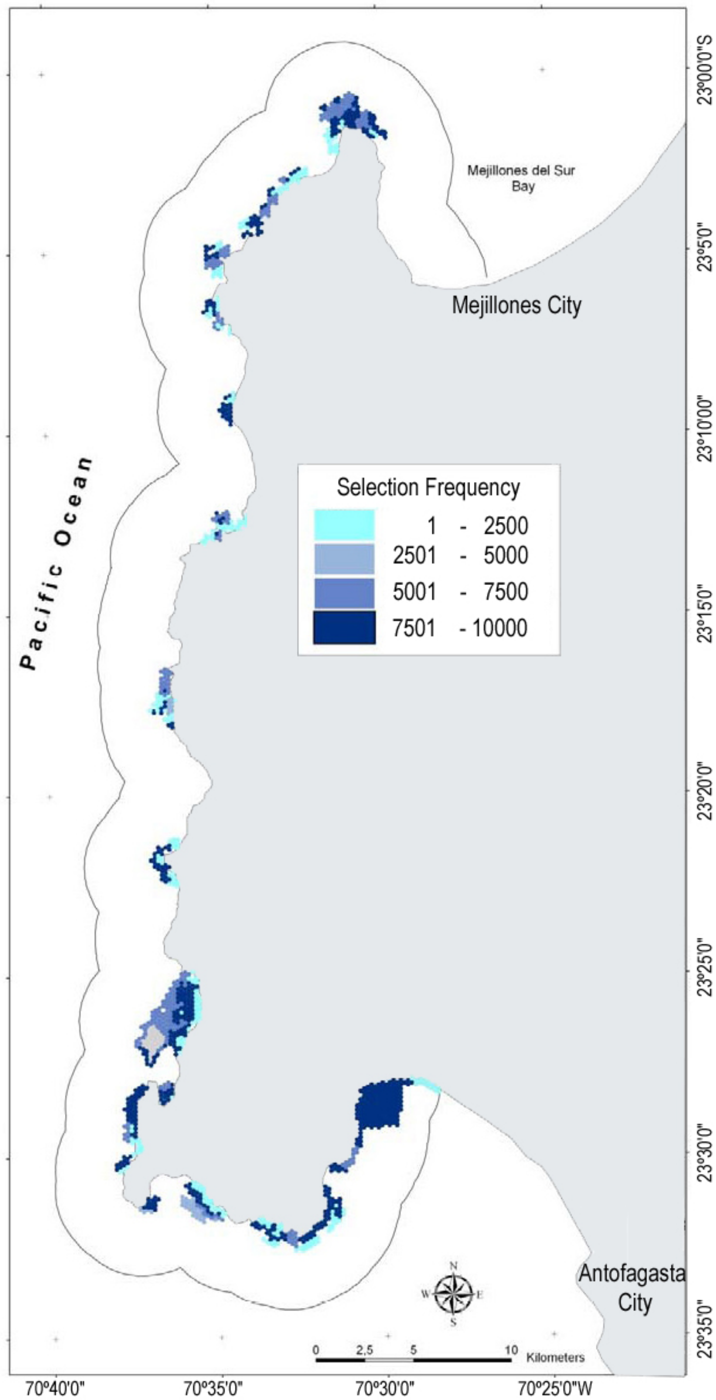

Figure 3. Portfolio of sites identified as conservation priority according MARXAN.

How viable would be our zoning scheme on a long-term basis? This is a question often overlooked by conservation plans (Pressey *et al.,* 2007; Game *et al.,* 2008) partly because of the state-invariant nature of the zoning algorithms such as MARXAN (*i.e.,* conservation targets and threats are temporally invariant). For instance, coarse-scale and fine-scale filters may be deeply altered in occurrence and location during the El Niño events (*e.g.,* Tomicic, 1985) via changes in the structure of local communities (Vásquez *et al.,* 2006; Sielfeld *et al.,* 2010), or inducing shifts in the geographic ranges of the species (Riascos *et al.,* 2008; Carstensen *et al.,* 2010). Moreover, these changes in distribution may not be necessarily transient, but represent the long-term shifts in the geographic distribution of species (Rivadeneira & Fernández, 2005), and hence potentially altering the diversity and composition of species at the MP. While the MP area is far away from the biogeographic breaking zones, described for different marine taxa across the Pacific coast of South America (Lancellotti & Vásquez, 1999, 2000; Camus, 2001), which may reduce the potential impacts of the shifts of the geographic ranges of species, a real evaluation of this threat remains untested. Future studies may improve our model by considering uncertainties introduced by increasing threats (*e.g.*, increasing fishing effort, and aquaculture center and touristic activities).

The Mejillones Peninsula, encompassing an extension of 435 km^2, is the third largest marine protected area of the Humboldt Current Large Marine Ecosystem (Wood, 2007), harboring more than 500 species, from diatoms to whales (Hudson *et al.*, 2008). Our analysis could set the foundational basis for robust conservation plans of the Mejillones Peninsula Marine Protected Area. A similar zoning approach may be undertaken, at a much larger spatial scales, in order to design a regional/nationwide network of MPA's able to balance the growing needs for robust plans of conservation of marine biodiversity, and the sustainable use of coastal spaces and the management of marine resources.

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