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Review

Using very high resolution remote sensing for the management of coral reef fisheries: Review and perspectives

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ABSTRACT

Coral reef fisheries are critical for food security and as a source of income in developing and developed countries, but they are collapsing in many areas. Following the emergence and routine availability of commercial very high spatial resolution (0.6–10 m) multispectral satellite images, we reviewed the use of these new high-quality remote sensing data and products for coral reef fisheries management. The availability of habitats maps improves management by guiding sampling strategies, mapping resources, involving local communities, identifying conservation areas, and facilitating Ecosystem Based Fishery Management (EBFM) approaches. However, despite their potential, very little use of products designed specifically for fishery management can be reported, likely due to high costs, inherent technology limitations and lack of awareness on the possibilities. Given the theoretical benefits brought by relevant habitat maps in EBFM frameworks, we advocate the use of adequate remote sensing products that integrate fishery technical services demands and local requirements.

1. Introduction

Fisheries are an important source of food and livelihood worldwide (FAO, 2009) but they increasingly appear under threat of collapse (Worm et al., 2006). Overexploitation of many stocks, both for commercial and subsistence purposes, have largely depleted the populations of species of interest (Grainger and Garcia, 1996; Mullon et al., 2005). Fisheries have been widely studied for many decades but failure or non-application of management plans, resource crash, fishing down marine food webs and overexploitation did occur (Botsford et al., 1997; Pauly et al., 2002). In a global context of increasing population and protein-demand, there is an urgent need to promote sustainable management solutions that could mitigate fishery collapse more successfully. This includes Ecosystem Based Fishery Management (EBFM) and Ecosystem Approach to Fisheries (EAF) (Garcia et al., 2003; Hall and Mainprize, 2004; Pikitch et al., 2004). After a slow start in the years 1970s, the creation of networks of no-take marine reserves and protected areas (MPAs) became common practice as part of such frameworks (Roberts, 1995). MPA networks are increasingly designed to ensure that all habitats and functional processes are included to represent and protect ecosystems services and functions, including fishery stocks integrity (Bohnsack, 1998). EBM frameworks emphasize the links between fishery stock sustainability and habitat quality (Pikitch et al., 2004). As such; management actions must assess and conserve habitats with their physical and biological connections, and, in a fishery context, their valuable resource stocks.

Habitat is a key level of biological descriptions, and can be a convenient criterion for management decisions. Indeed, among the different levels of biological descriptions (from genes to ecosystems) on which reef management decisions focus, the habitat-level is the only one that can be synoptically observed and mapped with current remote sensing technology (Andréfouët et al., 2004). Remote sensing (RS) technology is an emerging tool which should contribute to help coral reef fisheries management, especially when management use habitat-level guidelines and recommendations (UNEP/CBD/COP/8/31, 2006). In favorable shallow depth and water clarity conditions, remote sensing may provide information on the reef itself (direct reef sensing, sensu Andrefouet and Riegl, 2004; Dalleau et al., 2010; Wabnitz et al., 2010), such as benthic cover, habitat locations, habitat diversity and patchiness, geomorphologic structures, bathymetry, and water circulation. Satellites also sense the reef environment (indirect reef sensing), including the ocean (temperature, wave height, sea level, turbidity, chlorophyll and colored dissolved organic matter concentrations), the atmosphere (wind, aerosols, rain, solar insolation, cloud cover) and the nearby lands (vegetation cover, watershed structure, urban growth) (Andréfouët, in press).

The objective of this paper is to draw an updated picture of the current and potential applications of direct remote sensing for coral reef fishery science and management, particularly in the light of the capacities and limits of the very high spatial resolution multispectral data available since the early years 2000. These sensors

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provide commercial panchromatic and multispectral images anywhere on the planet. As a consequence of there enhanced spatial resolution, they also provide in many cases a better thematic resolution, i.e. the capacity to map accurately a greater number of habitats. In a fishery context, this means that they should be useful in mapping more precisely the specific shallow habitats of selected fishery resource of interest, and thus should open new perspectives for fishery science and management.

2. Methods

In this study, the term "very high resolution" refers to sensors and techniques at spatial resolution (i.e. size on the ground of a pixel of a digital image) between 0.6 and 10 m. This is in contrast with "medium resolution" sensors at few hundreds of meters (e.g. MODIS sensor on board Terra and Aqua satellites, or MERIS sensor on Envisat), and "high resolution" sensors at few tens of meters (e.g. sensors on board the SPOT 1–4, Landsat 4–7 satellites). Thus, our focus is to review the use of the recent very high spatial resolution multispectral (VHRM) spaceborne digital images from the IKONOS, Quickbird, SPOT 5, FORMOSAT, GEOYE 1, Orbview-4 and World-View 2 satellites and sensors. We focus on these commercial tools because they have quickly transformed the field of remote sensing in terms of potential and applications (Goward et al., 2003). By choosing those sensors, the considered time frame for this review is the last decade (2000–2010). As such, this study updates for reef fisheries a previous review compiled by Green et al. (1996) devoted to coastal management in general. Since very high spatial resolution is also achieved with aerial digital photography frequently available at less than 1 m resolution, we have considered recent applications based on digital aerial photographs and videos as part of the VHRM data set.

We searched and analyzed exhaustively all referenced papers on coral reef sessile invertebrate fisheries (e.g. trochus, giant clams, queen conch, etc.) and fisheries of mobile organisms (lobsters and finfish) that used VHRM sensors. We searched the ISI Web of Knowledge℠, Sciencedirect® and Google™ Scholar databases, online conference proceedings (e.g. International Coral Reef Symposium) and selected on-line libraries (www.reefbase.org) that could point to relevant grey literature reports difficult to locate otherwise.

Before summarizing hereafter the results in the form of key main points, we first systematically organized and synthesized the various studies according to: objectives of the study, sensor types, locations, type of targeted resources, and achieved management objectives. To discuss the results, we also included in this review a number of representative studies on subjects closely related to fisheries, such as habitat mapping, design of marine protected areas, mapping of indigenous local knowledge, species–habitat relationships, and biodiversity survey designs. Finally, to draw a parallel with VHRM new sensors, we also considered a number of new and past representative fishery studies based on high resolution sensors (e.g. Landsat at 30 m resolution).

3. Results and discussion

The compilation of the various studies suggests a number of lessons that we discuss below by order of decreasing importance. Obviously, this is subjective ranking. The discussion could be organized differently, for instance to emphasize differences in finfish fisheries vs invertebrates fisheries, or local-scale fishery management vs large-scale management, or simple use of VHRM vs sophisticated use. We preferred to discuss around more general noteworthy conclusions relevant for managers, and when suitable, we include technical comparative aspects under the main discussion points.

3.1. The use of very high resolution remote sensing products designed specifically for reef fisheries is very limited

Surprisingly, and despite a large number of *in situ* traditional studies focussing on tropical high commercial-value populations and stocks (e.g. queen conchs, lobsters, clams, sea cucumbers, fishes), we recorded only one study using satellite VHRM products made specifically to assist in the management of coral reef fisheries, and two recent studies based on aerial photographs and video data and derived habitat maps (Table 1).

Gilbert et al. (2006) estimated stocks of giant clams in Polynesian islands using habitat maps derived from Quickbird images. These stocks estimates and maps were used afterward by the French Polynesia Fishery Service to estimate the sustainability of the current rates of harvests and exports and to select the location of no-takes reserves (Gilbert et al., 2005). On the same vein, but with aerial photographs, Andréfouët et al. (2005) conducted a stock assessment of giant clams in Fangatau atoll (French Polynesia) using field census data and a habitat map designed to reflect the gradient of clam densities. Bello-Pineda et al. (2006) used a multi-sensor (aerial video, aerial photographs, and Landsat image) habitat map combined with other attributes to model a variety of uses of fish and spiny lobster populations in Alacranes Reef (Mexico).

A key point here is that Bello-Pineda et al. (2006) used remote sensing products established *before* the design of the fishery application. In other words, map products were not specifically designed and optimised for the particular fishery application. They were generic habitat maps. This is the difference, conceptually; with Andréfouët et al. (2005) and Gilbert et al. (2006), where remote sensing products were conceived according to the French Polynesia clam fishery management requirements. Maps were created to capture in the most accurate way the range of habitats that reveal the most finely the spatial distribution of the targeted resource. In these studies, the goal was not to assess how to empirically use an existing map for a fishery application, typically by "forcing" a pre-existing generic habitat typology to represent the resource distribution (Harborne et al., 2006). Instead, the entire design of the clam stock assessment study was made considering the potential of VHRM remote sensing in capturing specific habitats present on the studied sites and relevant to characterise the resource distribution (Gilbert et al., 2006). To our surprise, we did not identify any other recent work conceived in a similar optimized way.

The interest of specifically designed optimal products is to estimate as precisely as possible the available resource stock and biomass for the total area under management, which means, ideally, a precise estimate for each habitat of interest present on the focal area. This requires estimating accurately the variance of the variable of interest (density, biomass, population size class structure) for each habitat (Gilbert et al., 2006). With an estimate per habitat, it becomes possible to scale-up effectively the relevant fishery information (biomass, number of individuals per surface area, catch per unit effort) for the entire system, assuming the properties are spatially additive, by using a GIS or image-processing package.

In truth, the vast majority of coral reef and remote sensing scientific literature is on the creation of generic habitat maps not specifically designed to represent a suite of benthic or pelagic resources. For recent very high resolution generic habitat mapping studies, see for instance Maeder et al. (2002), Andréfouët et al. (2003), Isoun et al. (2003), Garza-Perez et al. (2004), Purkis (2005), Benfield et al. (2007), Bertels et al. (2008), Houk and van Woesik (2008) and Scopelitis et al. (2009). Despite the fact that new habitat mapping case studies keep being published using a variety of sensors and approaches (Andréfouët, 2008), not many are constrained by fishery applications. Maeder et al. (2002) and

Table 1
Main characteristics of very high resolution remote sensing studies for coral reef fisheries.

Source	Location	Objective (VHRRS uses)	Target (exploited resources)	Platform/sensor	Data	Spatial resolution
Andréfouët et al. (2005)	Fangatau atoll (Tuamotu Archipelago, French Polynesia, South Pacific Ocean)	Stock assessment of the resource (field surveys planning, habitats mapping, resource assessment/ management, MPA planning)	Giant clam (*Tridacna maxima*)	Aircraft	Digitalized aerial photographs	1.5 m
				ISS (International Space Station)	Digital high resolution astronaut photographs	5.6 m
Bello-Pineda et al. (2005)[a]	Alacranes Reef (Gulf of Mexico)	Coral reefs habitat mapping (field surveys planning, habitats mapping, resource assessment/management, MPA management)	Reef habitat	Aircraft	Digitalized aerial photographs	3.8 m
					Digital aerial video	0.5 m
Bello-Pineda et al. (2006)	Alacranes Reef (Gulf of Mexico)	Suitability assessment models for coral reef resources (habitats mapping, resource assessment/ management)	Reef resources	Aircraft	Digitalized aerial photographs	3.8 m
					Digital aerial video	0.5 m
Bertels et al. (2008)[a]	Pulau Nukaha reef system (Tanimbar Archipelago, Southeast Moluccas, Indonesia)	Coral reef monitoring (bathymetry/ topography/habitats mapping, MPA planning/management, routine monitoring)	Reef habitat	Aircraft	CASI (Compact Airborne Spectrographic Imager)	2.5 m
Friedlander et al. (2007)	Hawaii (North Pacific Ocean)	Evaluation of existing MPAs (habitats mapping, MPA planning/ management)	Marine resources	Aircraft	Digital aerial photographs	?
				IKONOS	Multispectral IKONOS satellite imagery	4 m
					Hyperspectral imagery	?
Gilbert et al. (2006)	Fangatau atoll, Tatakoto atoll, Tubuai atoll (Tuamotu and Australes Archipelago, French Polynesia, South Pacific Ocean)	Comparison between stocks and management (field surveys planning, habitats mapping, resource assessment/management, comparison between sites)	Giant clam (*Tridacna. maxima*)	Aircraft	Digital aerial photographs	1.5 m
				Quickbird	Multispectral Quickbird satellite imagery	2.5 m
Maeder et al. (2002)[a]	Roatan Island (Bay of Honduras, West Caribbean Sea)	Coral reef habitat classification (habitats mapping, resource assessment/management)	Reef habitat	IKONOS	IKONOS	4 m

[a] Not focused on the resource itself.

Bertels et al. (2008) specifically state that their habitat products should help fishery management (Table 1) but it is in fact unknown if the products have been really used afterwards for fishery management.

One local-scale study discusses the benefits of using optimal habitat maps (derived from Quickbird) in assessing commercial benthic invertebrates and especially clam resource status in Raivavae Island (French Polynesia) (Andréfouët et al., 2009a). A survey conducted without image-support provided general management recommendations consistent with the survey conducted with image-support, but the former could not provide a precise estimate of the stocks, nor their location according to finely mapped habitats distribution. In other islands, this information was critical to identify conservation areas and set up new no-take MPAs specifically aimed at preserving local fishery resource (Gilbert et al., 2005). Optimal habitat maps reflecting accurately the distribution of the resource appear critical for local optimal management and conservation.

3.2. Historical pilot remote sensing studies have not blossomed towards routine integrated management approaches taking advantage of very high resolution sensors

Several pilot products designed specifically for fisheries have been published more than 20 years ago. Bour et al. (1986) identified relevant habitat boundaries in an exploited New Caledonian reef to estimate trochus (*Trochus niloticus*) stocks with SPOT images and aerial photography. Long et al. (1993) conducted a large-scale study on trochus stocks in northern Australia using Landsat images and coarse habitat/geomorphology descriptions. Kulbicki (1995) used SPOT images and black and white aerial photographs on Ouvea Atoll (New Caledonia) to map habitats and estimate fish stocks. As a more recent study based on high resolution Landsat products, Bello et al. (2005) surveyed *Panulirus argus* lobster populations on Alacranes Reef (Mexico).

Despite the poor spatial resolution and accuracy of these pioneer studies, all stressed the convenience and efficiency of using RS tools for synoptic evaluation in shallow environments. However, except in the aforementioned giant clam studies, we did not identify a fishery survey designed only with VHRM data, while Landsat 7 images for instance were still used in 2000 for the survey of the conch *Strombus galeatus* in Pacific Panama (Cipriani et al., 2008). Interestingly, Benfield et al. (2007) report a IKONOS habitat mapping exercise for the same area (Las Perlas Archipelago), but the two studies, habitat mapping and conch assessment seemed unlinked to date. Similarly, the queen conch *Strombus gigas* population was assessed in Los Roques (Venezuela) in 1999 by Schweizer and Posada (2006), but the Landsat-based habitat map developed by Schweizer et al. (2005) was apparently not used afterwards to generalize the assessment. Finally, a study on queen conch larvae in Alacranes Reef (Mexico) was not stratified according to existing habitat maps (Aranda and Perez, 2007; Bello-Pineda et al., 2005; Bello et al., 2005).

As shown for the Panama (Cipriani et al., 2008), Venezuela and Mexico studies, remote sensing researches potentially helpful to fisheries do not seem coordinated towards a common management goal. The interface between remote sensing researchers, biology researchers and technical fishery services remains too limited. These examples show that the linkages between image patterns and resources often remain not fully exploited, or not exploited at all. Generalizing the *in situ* results in the form of spatially-explicit resource products, such as biomass maps for instance, remain rare practice in coral reef environment. The French Polynesia giant clams suite of studies (Andréfouët et al., 2009a, 2005; Gilbert et al., 2006, 2005), and the US (Caribbean and Hawaiian coastal waters) ecological studies linked to fisheries and MPAs (Friedlander et al., 2007; Monaco et al., 2007; Pittman et al., 2009; Wedding et al., 2008) seem to provide the only coral reef examples of efficient coordinated effort taking advantage of remote sensing capabilities to move toward better management.

3.3. Do inherent technical limitations and costs limit the use of very high resolution remote sensing products in fishery management?

The key remote sensing layer for reef fishery application is an adequate habitat map, as an indirect link to resource maps, and as a source of information for EBM. There are currently a number of limitations to the routine automatic production of habitat maps. Tables 2 and 3 show, respectively, the potential benefits and limits inherent to the use of high resolution remote sensing tools. It is important to stress that despite their potentials, remote sensing products provide limited information, or no information at all, in areas deeper then 30 m in clear waters, and much shallower in turbid waters. Is it the reason why VHRM data are under used? Probably not, as the benefit for management can be high for many favorable locations despite these inherent limitations.

A number of other factors can be listed to explain the poor spreading of remote sensing products. First, Green et al. (1996) stated that "*with present technology, satellite remote sensing is unlikely to attract the interest of ecologists because it does not provide information at a fine enough scale*" and that "*the relationship between image data and ecological systems is poorly understood*" for coastal management. This remains a difficulty, but this should be now partly overcome when using optimized VHRM-derived habitat maps. Habitat mapping benefits from well developed and understood concepts that allow the building of a thematically rich, qualitative (through a habitat typology) and quantitative (through habitat metrics) link between an image and the spatial organization and properties of ecosystems and landscapes (Harborne et al., 2006; Purkis et al., 2007).

Second, limitations on habitat maps availability are partly due to limited spreading of techniques apparently too sophisticated for local managers to apply themselves. But user-oriented solutions are available to overcome the technical challenges (Andréfouët, 2008; Dahdouh-Guebas et al., 2006). With proper training, non-specialists have shown quick understanding and excellent practicing of the GIS tools necessary to make use of VHRM data after only a few days of training (Andréfouët, personal observations). This would obviously facilitate local management by local stakeholders, especially by using first-hand local knowledge.

Third, cost of VHRM images is a likely explanation. However, at prices starting (as in 2010) at 13US$ km^{-2} for archived images, costs is an issue only for large areas. For many small MPAs of few hundreds of km^2, the cost of one image and its processing

Table 2
Potential benefits to the practical use of very high resolution remote sensing for application on coral reefs fisheries. To facilitate interpretation of the table, benefits have been separated into four general categories discussed in most of the papers (field data collection, digital data acquisition, data analyses, tool performance).

Potential benefits to the practical use of very high resolution remote sensing for application on coral reefs fisheries		Andréfouët et al. (2005)	Bello-Pineda et al. (2005)	Bello-Pineda et al. (2006)	Bertels et al. (2008)	Friedlander et al. (2007)	Gilbert et al. (2006)	Maeder et al. (2002)
Field data collection	Not intrusive		✓					✓
	Does not need a large set of data to calibrate model				✓			
Digital data acquisitionData analyses	Spaceborne: large areas can be mapped at once				✓			
	Spaceborne: available commercially for any site worldwide	✓						
	Digital tools (easy to georeference and manipulate, no data size and format problems)		✓					
	Shallow habitats easy to identify		✓					✓
	Spaceborne: calibrations are accurate	✓						
	Spaceborne: 11-bit dynamic range helps avoid saturation in bright areas	✓						
	Spaceborne: efficient and easy image-processing	✓						
Tool performance	Cost effectiveness (time, people, resources reduced)		✓		✓			
	Accuracy (the higher the spatial resolution, the more accurate the product)	✓	✓	✓				✓
	Ideal for quantitative analysis					✓		✓
	Quick and useful for preliminary results		✓					✓
	Performs in turbid waters				✓			
	Airborne: highly accurate for discrimination of ecological properties in coral reefs		✓					
	Airborne hyperspectral: powerful tool for application or algorithm development (versatile)		✓		✓			

Table 3
Potential limits to the practical use of very high resolution remote sensing for application on coral reefs fisheries. To facilitate interpretation of the table, limits have been separated into four general categories discussed in most of the papers (field data collection, digital data acquisition, data analyses, tool performance).

Potential limits to the practical use of very high resolution remote sensing for application on coral reefs fisheries		Andréfouët et al. (2005)	Bello-Pineda et al. (2005)	Bello-Pineda et al. (2006)	Bertels et al. (2008)	Friedlander et al. (2007)	Gilbert et al. (2006)	Maeder et al. (2002)
Field data collection	Difficulty in obtaining ground control points sometimes (time, cost of survey, remoteness)	✓	✓				✓	
Digital data acquisition	Airborne: high costs	✓	✓		✓			
	Airborne: limited coverage (time, remoteness)	✓			✓			
	Airborne: flight operator not reliable (lack of experience of collecting RS data, sensor not calibrated, data not delivered in a reasonable timeframe…)				✓			
Data analyses	Data pre-processing (corrections for sun glint, wind, waves, haze, clouds, time of the year, time of the day…)	✓			✓			✓
	Estimation of water column optical properties (seabed reflectance, depth effects)				✓			
	Spectral sensitivity to habitat composition, depth and proximity (leads to confusion among spectral classes)		✓		✓			✓
	Benthic cover heterogeneity (classification accuracy decreases because spectral separability between cover classes is poor)				✓		✓	✓
	Depth (below 15 m depth: overestimation of the bathymetry, decreasing accuracy of benthic composition)		✓		✓			
	Airborne: segmentation of land areas hard to precise	✓						
Tool performance	Approaches are site-specific (different habitats typologies and projects)		✓				✓	
	Inaccuracy/uncertainty of product increases when spatial resolution decreases	✓	✓					✓
	Identification of deeper habitats is difficult	✓						

(assuming simple methods are applied) is negligible compared to other costs like field surveys, gas, salaries, consulting, etc.

Based on the above considerations, we suggest that managers do not promote, even for small areas, the use of VHRM data by lack of awareness on the potential or by lack of competent staff immediately able to valorise VHRM data (Andréfouët, 2008).

3.4. A trade-off is needed between the use of very high resolution products and the spatial scale of the management

Both local and regional scales are important to consider in the context of top-down (actions taken by governments) and bottom-up (actions taken by fishermen and villages) management and governance. Ideally, assuming that the whole is the sum of the parts, all national and regional conservation policies should be based on the integration of detailed local results, such as detailed biomass scaling combined with relevant estimates of catch per unit efforts and socio-economic data. However, technically, this will remain likely unachievable, especially in countries with several thousands of kilometers of coastline, like Indonesia or Philippines. Mapping in detail and accurately these areas with VHRM data would be a daunting and costly task. In addition to costs and the technical problem of mapping in details the different habitats relevant to fisheries management, scaling and integration of data is also highly dependant on the level of governance fragmentation. If, like in Philippines and Fiji, a management unit is under the control of a small human community, each community may have different management options. This complicates the feasibility and implementation of top-down, national and regional management strategies. Specifically, EBM approaches requiring transboundary data (e.g. for protection of connectivity of essential habitats and protection from watersheds pollution) would be difficult to organize (Christie et al., 2009).

Most sophisticated and precise scaling of fishery data based on habitat data was achieved by Gilbert et al. (2006) at island scale using Quickbird images. They used habitat maps designed to show precisely the distribution of the biomass variability. Conversely, (Rhodes et al., 2008) for Pohnpei (Federate States of Micronesia) and (Bell et al., 2009) at regional scale for all Pacific Island Countries and Territories used Landsat-derived coral reef maps from the Millennium Coral Reef Mapping project (Andréfouët et al., 2006). They combined precise estimates of coral reef areas, but all habitats being lumped together, with one generic estimate of fish biomass per km^2. Finally, for their global-scale analysis, Newton et al. (2007),without any remote sensing data, combined very coarse estimate of reef extent with one standard yield of fish tons per km^2, leading to estimates and inter-country comparisons that do not really hold when better fishery and habitat data are used. This set of studies clearly shows the trade-off between the size of the targeted area, the thematic resolution of the available habitat maps that can be used, and the precision of the available fishery data across the entire domain. Managers need to keep in mind this trade-off according to the size of their focal areas (Fig. 1).

For all the reasons aforementioned, we predict that VHRM data will remain preferentially used by reef fishery management agencies for small-scale, local projects, unless very significant efforts are made to streamline the production of high thematic resolution habitat maps (Fig. 1). This would be very satisfactory in itself. Sound local work taking advantage of VHRM images is more likely to lead to more efficient recommendations than regional ones, for instance for overfishing regulations (restrictions on locations, habitats, targeted species and quotas, fishing gears). Local-scale work allows involving local population, technical services, and scientists to collect habitat and socio-economic data with optimized sampling schemes and protocols resource, frequently if needed (Andréfouët et al., 2009a; Bell et al., 2009; Christie et al., 2009; Guillemot et al., 2009). Local optimization of fishing regulations and involvement of local communities is a ticket to ensure compliance, and management effectiveness with legal support, improved understanding of benefits from MPAs, improved habitat conditions and increased fishery yields associated with MPAs (Cudney-Bueno and Basurto, 2009; Lowry et al., 2009).

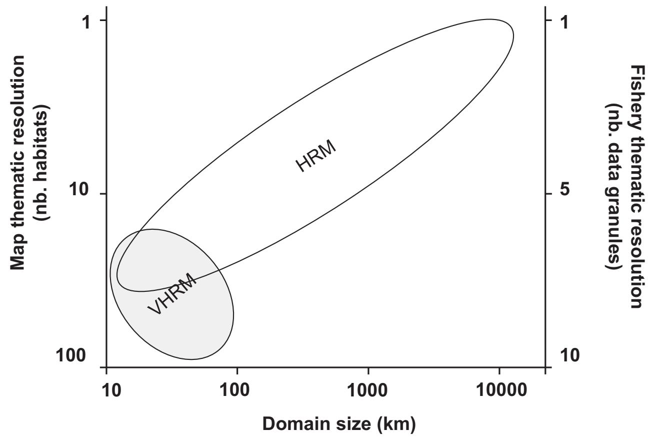

Fig. 1. Diagram illustrating the relationships between domain size, map thematic resolution and fishery data. The trend is that very high resolution multispectral (VHRM) images can provide thematic maps with several tens of classes (high thematic resolution), but only for small domains of few hundred of square kilometer. For such small domain, it is possible to acquire numerous habitat and resource-specific fishery data (e.g. for a series of given commercial species: biomass per habitat, life trait data, catch per unit effort, etc.). With larger domain, available data decrease. High resolution images can be used to map from small to large domain, but with a limited thematic resolution. For very large domain (e.g. global-scale), habitat classes of interest mapped consistently can be very limited, as well as the fishery data (per habitat or per species of interest) that exist consistently across the entire domain.

3.5. New valuable remote sensing products based on habitat maps are in development for fishery management applications…but this remains exploratory

Three types of fishery-related applications needs to be mentioned here: the characterisation of fish–habitat relationship at different scales, detection of fish spawning aggregation sites, and designing MPA networks. They have in common to use habitat maps as input of spatially-explicit modelling work.

First, an area of active research in reef ecology and fishery science is to enhance the representation of reef fish communities and variables with mapped habitat and environmental variables (review in Mellin et al. (2009, 2010)). Thus far, the work of many researches has shown that this requires taking into account a large suite of scales and processes (Mellin et al., 2009). The variety of these scales, methods applied, sites, and considered fish variables (biomass, diversity, richness, trophic levels, sizes, ontogenic stages) tend to call for a considerable amount of work ahead, before any output can be used with confidence and routinely by fishery managers (see "tool performance" limitations in Table 3). Pioneer works have shown that there are no single answer to the problem of scaling and mapping fish variables in coral reefs (Mellin et al., 2009). However, it is possible to use local field data and VHRM habitat maps to constrain local spatial models with good accuracy but generalization from one site to another is not granted. Eventually, validated local models and products should be helpful in a local management context (Knudby et al., 2010; Mellin et al., 2007; Purkis et al., 2008).

Second, other relevant study for fishery consists in identifying critical and essential locations and habitats for key species or for a guild of species (Stoner, 2003). One of those locations are spawning aggregations sites (SPAG), traditionally targeted by fishermen due to the high density of resources aggregating at one time in one spot. Resource depletions have promoted the protection and temporary closure of these sites, but it requires first their identification (Heyman et al., 2005). To the best of our knowledge, no VHRM data have been used to identify and map SPAG, but Palmer et al. (2004) have modelled the Caribbean basin coastline geometry using Landsat-derived Millennium geomorphological reef maps in order to identify promontories and other topographically suitable sites for snapper and groupers spawning sites.

Third, MPA network design is now a phenomenal topic of interest for conservationist and fishery managers. Spawning sites are key habitats to be included in MPAs (see above), but other habitats are also focal conservation targets for fishery management and biodiversity conservation (Green et al., 2009). MPA networks are increasingly designed to represent a substantial fraction of the extent of ecosystems and habitats, used as surrogates of other biological organization levels (genes, species) (Dalleau et al., 2010; Wabnitz et al., 2010). Reliable optimization algorithms and decision-support tools can be used to identify networks of management units selected to obey habitat representativeness conservation criteria (e.g. include 20% of the surface of all inventoried habitats as part of the MPA network) (Beech et al., 2008; Leslie et al., 2003). To the best of our knowledge, no VHRM habitat maps combined with fishery data have yet been used to design an actual MPA network in coral reefs, but this is likely to occur very soon. Simulations based on VHRM habitat map have been proposed in Andréfouët et al. (2009b) for Wallis Island, but they have not been used yet by managers.

3.6. Before accessing optimised and innovative spatial products, remember that simple and generic products are also very useful for fishery management

Despite the limited use of remote sensing as an analytical tool, remote sensing images and products are not absent from fishery offices. We identified the report of georeferenced fishery data on a background image or map as the most common applications, using a GIS software package or a visualization tool like Google Earth® (see Table 1 for VHRM related work). This applies even if *in situ* data were collected without the help of any images or maps. This application is not reflected necessarily in a peer-review literature search, but it is apparent in every governmental fishery office we had the opportunity to visit. The practical value for managers is to visualize the sampling efforts, the locations of study sites and statistical data on a background of spatial information they can understand and manipulate easily. The possibility to spatially visualize the distribution of data provides the most common decision-support tool found in fishery management offices. For instance, a recent survey of sea cucumber resources in New Caledonia (Purcell et al., 2009) shows the locations of transects data on Google Earth® very high resolution background images, where geomorphology and habitat criteria used for the sampling are visible.

Close and Hall (2006) and Hall and Close (2007) have created in Turk and Caicos maps of reef fished zones on a background of simple maps to guide the implementation of a management plan based on fisherman knowledge and selected scientific data on spiny lobster, queen conch and species of fish. The use of unprocessed, true-color images in print or digital format, to assist field surveys is likely much more common than what scientific publications suggest (e.g. Aswani and Lauer, 2006; Guillemot et al., 2009). Using map products and raw true-color images to design resource sampling strategies was not an uncommon exercise since the availability of Landsat and SPOT images (Long et al., 1993), but this remains limited using VHRM.

One VHRM study took advantage of existing maps to help evaluating the efficacy of MPAs through the differences in fish biomass present in the different MPAs (Friedlander et al., 2007). In Hawaii, Friedlander et al. (2007) used IKONOS-derived habitat maps to stratify the fish sampling. As in Bello-Pineda et al. (2006), the maps were designed and created well before the MPA application was conducted. The authors estimated that the pre-existing products were suitable for their applications, but it is possible that better products could have been made to represent better the commercial fish distribution patterns. Nevertheless, this example shows that available generic habitat maps can be beneficially used by managers, even if not optimized for a particular resource. The risk is to miss specific areas of interest, or to consider habitats that may be irrelevant for a specific resource but are present on the map. This is less a problem for mobile species, like some type of fish, than for species more closely associated to specific substrate, like invertebrates.

3.7. Perspectives: towards Ecosystem Based Management approaches?

There is a widespread agreement to move to holistic approaches for reef fishery management, like EBFM. However, following Pitcher et al. (2009) it is safe to state that not a single reef fishery is currently managed following EBM concepts, even if there is a strong will to apply EBM concepts worldwide (e.g. McClanahan and Cinner, 2008; Tissot et al., 2009). Even the fisheries closest to this Holy Grail (see the Philippines case study in Armada et al. (2009)) are not strongly advanced on all the criteria and steps listed by Pitcher et al. in their Table 1. At least, a growing number of reef fisheries is obviously managed with an Ecosystem Consideration (EC) approach, where ecosystem information is considered part of the basis for management (Christie et al., 2009). This is a reasonable pragmatic first step given the sum of knowledge gaps in trophic interactions, fish and invertebrate life traits, habitat distribution and connectivity (to name a few of the information ideally required for EBM) to attain "*an understanding of spatial context, connections, and scales of processes…needed to set conservation priorities that ensure the representation and continued persistence of species and habitats within functioning ecosystems*" (Lourie and Vincent, 2004).

To achieve EBM of fisheries, the list of steps provided by Pitcher et al. (2009) identifies a number of habitat-driven indicators, criteria and actions to consider for a successful approach. These can all be potentially realized with VHRM, especially if local scale if the scale of interest. Specifically, this allows:

- inclusion of ecological values,
- a comprehensive and inclusive management system, structured using ecological classification (such as ecoregions, bioregions and habitat classes).

The steps to achieve these broad indicators and/or that benefit from relevant habitat layers are to:

- prepare map of ecoregions and habitats,
- establish ecosystem values and determine the factors influencing ecosystem values (e.g. extent of loss/damage of habitats),
- conduct ecological risk assessment,
- design information system, including monitoring,
- establish research and information needs and priorities,
- prepare education and training package for fishers.

In truth, the different steps of this wish-list are far from being routine. Significant research work and data collection remain necessary in most places to simply initiate these activities for which useful and pragmatic methodological guidelines are often unavailable. Keeping in mind this caveat, within this canvas and while respecting the match between the spatial range of the reef systems and the governance system (Armada et al., 2009), remote sensing tools and products should offer a fair basis to allow initiating EBM projects in reef fisheries. This is particularly adapted to current questioning in a society where the policy makers ask for rapid development of scientific and management tools to support practical implementation (Smith et al., 2007).

4. Conclusion

Management of coral reef resources is a challenging task because of the spatial and ecological complexity of this ecosystem and the common lack of local accurate relevant information and maps. The key remote sensing layer for reef fishery application is an adequate habitat map, as an indirect link to resource maps, and as a source of information for EBM. The previous sections highlighted their use to:

- visualize fishery data on a georeferenced background,
- elaborate sampling design for fishery and habitat mapping data collection,
- provide habitat maps, optimized for a specific resource, or generic,
- elaborate fish data collection to test MPA efficacy,
- analyze spatially multi-scale resource–habitat relationships,
- scale-up biomass and achieve stock assessment, especially for invertebrate resources, while more efforts are required to validate in different locations generic reef fish–habitat models,
- propose new policies to insure food security in the long term,
- design new MPA networks to protect fishery resources.

Thus, it can be said that considerable progress has been made in the use of remote sensing tools for the assessment and management of coral reef resources since Green et al.'s review in 1996, but the number of case studies remains extremely narrow. This is partly due to the inherent limitations of optical remote sensing tools and its costs, but one of the major gaps identified by this study seem to be the need for additional awareness and coordination by project managers to integrate remote sensing capabilities early in the design of the fishery assessment. With the current trend to move towards ecosystem approaches, we expect to see in the future a growing number of very high resolution remote sensing-based applications for coral reef fishery science and management, first at local scales, and on the long run at regional scales.

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