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Review

Quantitative mapping of fish habitat: A useful tool to design spatialised management measures and marine protected area with fishery objectives

O. Le Pape [a,*], J. Delavenne [b], S. Vaz [c]

[a] Agrocampus Ouest, UMR985 ESE Ecologie et santé des écosystèmes, F-35042 Rennes, France
[b] Ifremer, Laboratoire Ressources halieutiques, 150 Quai Gambetta, B.P. 699, 62321 Boulogne sur Mer, France
[c] Ifremer, UMR EME 212, Av. Jean Monnet, BP171, 34200 Sète, France

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A B S T R A C T

The delineation of essential fish habitats is necessary to identify, design and prioritize efficient marine protected area (MPA) networks with fishery objectives, capable, in addition to other possible objectives and functions of MPAs, of sustaining the renewal of marine living resources. Both the methods available to map essential fish habitats and the usefulness of these maps are discussed in this paper.

Generally, the first step to obtain maps of essential fish habitats consists in choosing one of the numerous existing statistical approaches to build robust habitat suitability models linking relevant descriptors of the marine environment to the spatial distribution of fish presence or density. When these descriptors are exhaustively known, i.e. maps are available for each of them, geo-referenced predictions from these models and their related uncertainty may be imported into Geographic Information Systems for the quantitative identification and characterization of key sites for the marine living resources.

The second part of this paper deals with the usefulness of such quantitative maps for management purposes. These maps allow for the quantitative identification of the different habitats that are required for these marine resources to complete their life cycles and enable to measure their respective importance for population renewal and conservation. The consequences of anthropogenic pressures – not only fishing but also land reclamation, aggregate extractions or degradation of habitat quality (e.g. nutrient excess or xenobiotics loadings, invasive species or global change) – on living resources, may also be simulated from such habitat models. These quantitative maps may serve as input in specific conservation planning software based on the systematic conservation approach. Fish habitat maps thus may help decision makers to select relevant protection areas and design coherent MPA networks which objectives are to sustain fishing resources and fisheries.

1. Introduction

Many populations, particularly of fishes, are only remnants of their original numbers due to direct or indirect human pressure and, as such, need to be protected. Following the establishment of the Convention on Biological Diversity, the 2002 World Summit on Sustainable Development (Johannesburg) recommended to adopt an Ecosystem Approach to Fishery management to both achieve conservation of marine ecosystems and maximise economic profitability of fisheries (Brownman et al., 2004). If measures of regulation at stock scale remain necessary (e.g. limiting fishing pressure to maintain the size of the spawning stock; Hilborn and Walters, 1992), it has been agreed to develop complementary methods to manage ecosystems, in particular to establish a worldwide system of marine protected areas (MPAs) (Mora et al., 2006). MPAs are considered efficient instruments for the protection of critical habitats, biodiversity, and ecosystem functions (Leathwick et al., 2008) and there is growing evidence of their usefulness in the management of fisheries (Halpern and Warner, 2002; Gell and Roberts, 2003; Vandeperre et al., 2011; Mesnildrey et al., 2013).

Although marine reserve objectives increasingly include the protection of marine living resources to maintain fish populations and fisheries, uncertainties remain about their optimal design to that aim (Claudet et al., 2008; Mesnildrey et al., 2013). Marine reserves are considered for their ability to improve species conservation within their limits and fishery yields outside, through the export of fish and larvae to fished areas (Gell and Roberts, 2003;

* Corresponding author.
E-mail address: olivier.le.pape@agrocampus-ouest.fr (O. Le Pape).

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Grüss et al., 2011b). Their positive influence on densities, biomass, size structure and life history traits of living resources inside their limits is well established (Lester et al., 2009). However, there is still a high level of uncertainty regarding their impact on surrounding exploited areas (Sale et al., 2005; Grüss et al., 2011b; Mesnildrey et al., 2013).

Marine fish populations are not randomly distributed, but exhibit distributions that are structured both in space and time (Mello and Rose, 2005). A species distribution results from the combined action of several forces (Planque et al., 2011a), some of which are external (such as environmental conditions or food availability), whereas others are internal to the considered species, population or community (such as total population size; Aarts et al., 2013). The set of conditions required for individual survival and reproduction constitute the "ecological niche" within which a species may indefinitely sustain itself. The geographical projection of this fundamental niche corresponds to the habitat of the considered species (Chase and Leibold, 2003). The analysis of relationships between species and their habitats has always been a central issue in ecology and is used to investigate the role of the different factors that may affect a population and to characterize the mechanisms determining habitat suitability.

For numerous marine organisms, habitat requirements change over the course of their development (Harden, 1968), resulting in distinct distributions along the life cycle; the displacement between these zones being ensured by passive or active migration (Grüss et al., 2011a,b). Ontogenic habitat switching structures the spatial distribution of organisms from each phase throughout the entirety of their life cycles (van de Wolfshaar et al., 2011). Indeed, the life strategy of most marine fishes is characterized by high fecundity and high mortality in young life stages (Juanes, 2007). The low survival of eggs, larvae (Houde, 2008) and juveniles (Le Pape and Bonhommeau, in press) strongly depends on abiotic and biotic environmental factors. This high mortality at early life stages has been identified as a main determinant of the abundance of marine populations (Houde, 2008) that reduces the correlation between the spawning biomass and the subsequent year class (Hilborn and Walters, 1992). As a consequence, the functionality of essential fish habitats, such as spawning or nursery grounds (Le Pape et al., 2003; Van de Wolfshaar et al., 2011) but also migration routes along ontogenic migrations, is essential to sustain the renewal of marine fish populations (Iles and Beverton, 2000). Interactions between fisheries and species habitats must be included in management plans (Peterson, 2003) and there is a need to protect the ecological function of essential fish habitats, not only for sustaining marine fish population and associated fisheries (Hall, 1998) but also for conservation purposes (e.g. the protection of endangered species; Martin et al., 2012).

Planque et al. (2007) distinguished three types of habitats for given functions: potential, realized and effective. The potential habitat represents the suitable areas for the function studied. The realized habitat corresponds to the portion of the potential habitat that is effectively occupied at a given time. The effective habitat corresponds to that portion of realized habitat that will be proved to contribute the most to the survival of the species by allowing the completion of its life cycle (Dahlgren et al., 2006). Taking into account effective fish habitats in marine reserve design, thus protecting successive fish habitats along their life cycle (i.e. spawning, nurseries, feeding grounds, migration routes), for exploited and endangered species is of major importance. Larval, juvenile and adult habitat selection, and also mobility and ontogenic migrations along the life cycle, have a considerable influence on the efficiency of MPAs in reaching fisheries goals (Kaplan, 2009; Moffitt et al., 2009). For mobile populations, MPAs should cover a large fraction of the total distribution area to offer effective protection (Grüss et al., 2011a,b). Protecting targeted zones where animals are associated with particular developmental stages could be as effective, or even more effective (Grüss et al., 2011a) than closing off large parts of the population distribution area to fishing and other anthropogenic activities. For instance, protecting restricted but highly productive areas where juvenile fitness is enhanced through optimal feeding conditions (Pelletier and Magal, 1996; Van de Wolfshaar et al., 2011), establishing spawning area closures to preserve fecund individuals, to provide sufficient spawning habitat for optimal stock abundance and improve fish reproductive capacity, or temporarily closing migration routes should increase recruitment success and be especially effective (Mesnildrey et al., 2013).

Among suitable tools matching the ecosystem approach to fisheries (de Jonge et al., 2012), there is a need to identify and map essential fish habitats in order to improve design, and furthermore, to prioritize fishery oriented MPA networks, to ensure that they are efficient in maintaining the renewal potential of marine living resources. To that aim, it is possible to predict the geographic distributions of species through life stages from habitat mapping approaches (Rubec et al., 1999; Martin et al., 2009; Lauria et al., 2011); then to combine these life stages and/or species specific maps in multiscale Habitat Suitability (HS) maps (Brown et al., 2000; Store and Jokimäki, 2003); or to integrate these maps on portfolios for measuring integrated conservation value (Delavenne et al., 2012). HS maps are essential elements in the identification and prioritization of suitable areas for conducting spatial ecosystem assessments and conservation actions (Brown et al., 2000; Cogan et al., 2009). Especially, HS maps may answer questions about what exactly constitutes high value or even critical fish habitat for exploited (Fodrie and Mendoza, 2006) or endangered (Martin et al., 2012) species, and may provide information needed to conserve essential fish habitats (Stoner, 2003). The successive steps of the general and most widespread approach to build quantitative maps of essential fish habitats are described here first (defining goals and choosing species and habitats descriptors, modelling then mapping; Fig. 1). Then we focus on the usefulness of these maps to investigate and delineate fish habitat, to compare the respective importance of different habitats on population renewal and to estimate and/or to simulate the consequences of anthropogenic pressures on living resources. The use of these maps and quantitative information to prioritize protection areas and improve fisheries management systems is finally discussed.

2. Building quantitative maps of essential fish habitats

Identifying factors that condition the spatial distribution of a given species represents the core of predictive geographical modelling in ecology. Habitat modelling (modelling species distribution) and Geographic Information Systems (GIS) are key tools that lead to a better understanding of species–environment relationships. Developing quantitative maps of fish distribution, based on environmental descriptors, requires successive steps (Fig. 1): (i) selecting the species accounted for, (ii) fitting and evaluating HS models that relate species or stage specific distribution to environmental factors, (iii) using HS indices from model outputs to create predicted distribution maps within a Geographic Information System (GIS) and (iv) combining these maps to help decision making.

2.1. Developing HS models for marine fish communities, populations or life stages

2.1.1. Selecting study areas, species and life stages

Designing efficient MPA networks to maintain sustainable living resources and fisheries requires the identification of priority areas