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Review

Spillover from marine protected areas to adjacent fisheries has an ecological and a fishery component

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ABSTRACT

Marine Protected Areas (MPAs), if well designed and managed, can produce conservation benefits to fish assemblages within no-take zones and fishery benefits in neighboring areas through 'spillover'. However, although plenty of studies have provided evidence of the benefits produced within MPA boundaries, overall benefits to local fisheries, especially via spillover, seem to be still unclear. Because of the lost fishing grounds following an MPA establishment, local fishermen usually oppose MPAs. There is, therefore, the urgent need for a better understanding of the mechanism(s) through which MPAs can export fishable fish biomass towards adjacent fished areas, a process that could counterbalance the loss of fishing grounds. Here we review the literature on spillover for refining the terminology, detailing the underlying mechanisms and identifying both the existing and needed methodological approaches to measure spillover. Operationally, two types of spillover should be considered: *ecological spillover* (i.e. the net export of juvenile, subadult and adult biomass from MPAs outwards driven by density-dependent processes) and the *fishery spillover* (i.e. the proportion of this biomass that can be fished, taking into account regulations and accessibility). Underwater visual census and tagging/tracking may allow getting evidence of ecological spillover, while experimental catch data are essential to assess and monitor fishery spillover, which is the main component of MPAs that can provide direct benefit to local fisheries.

Contents

1. Introduction

Marine Protected Areas (MPAs) are generally defined as portions of oceans where fishing and other potentially impacting human activities are regulated. Inside well enforced MPAs commercial species recover in density, size and biomass (Claudet & Guidetti, 2010a, 2010b; Guidetti et al., 2008, 2014; Guidetti & Sala, 2007;

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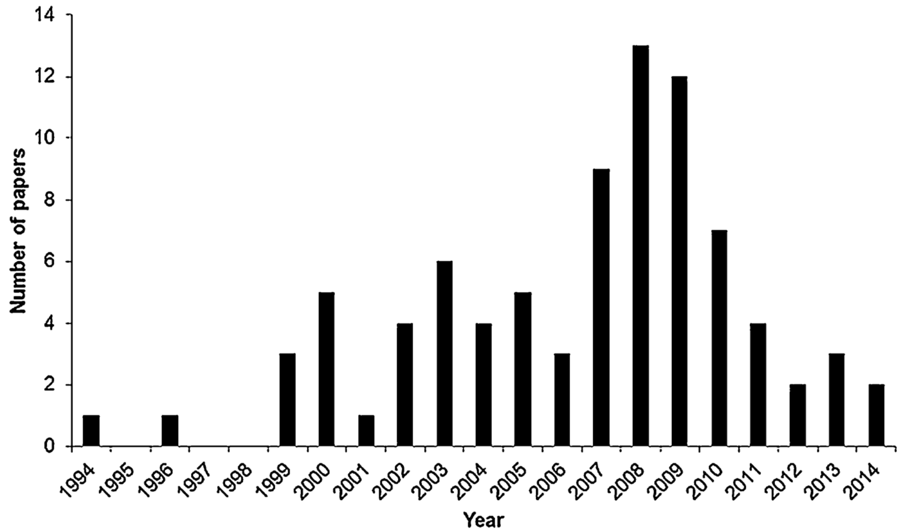

Fig. 1. Number of articles on '*spillover*' published within the period 1994–2012.

Lester et al., 2009; Roberts & Polunin, 1991; Rakitin & Kramer, 1996; Sala et al., 2012).

The creation of MPAs may involve negative impacts on local fisheries (at least in the short term) as a consequence of the fishing regulations (e.g. catch quotas, regulated mesh size; Guidetti and Claudet, 2010) or the subtraction of fishing grounds (McClanahan, 1999). These are the main reasons why local fishermen usually negatively perceive and oppose MPAs before or shortly after they are established.

MPAs, in addition to their conservation goals, are however recognized as effective fishery management tools (Di Franco et al., 2014; Gell & Roberts, 2003; Goñi, Hilborn, Díaz, Mallol, & Adlerstein, 2010; Halpern et al., 2009; Kerwath, Winker, Gotz, & Attwood, 2013; Russ & Alcala, 2011). To provide fisheries benefits part of the biomass produced inside the MPA as a response to protection has to be exported outside the MPA boundaries in the surrounding fishing grounds. Export of individuals can happen either through the active movement of juveniles, subadult and adults (spillover *sensu stricto*) or the passive export of eggs and larvae outwards from the MPA (better defined as recruitment subsidy; Grüss, Kaplan, Guenette, Roberts, & Botsford, 2011). The two types of export have either short-term/short-distance or longer-term/longer-distance fisheries effects, respectively (Halpern & Warner, 2002; Guidetti et al., 2014). The net active movement of commercially exploitable individuals from MPAs to fished areas (usually defined as spillover; Rowley, 1994) is the process leading to the most direct and palpable local fisheries effects: increase in yields close to the MPA boundaries.

The term spillover, however, is not used coherently throughout the literature and many authors name spillover processes that are indeed different. There is clearly the need to tease apart confounding processes to extract what spillover is to further successfully promote MPAs as a local fishery management tool. Here, we assess how spillover can be generalized by critically reviewing the literature on the subject, better defining the terminology, identifying its two components, characterizing the underlying mechanisms necessary for spillover to occur and promoting the adequate methodological approaches to measure both spillover components.

2. Materials and methods

We reviewed articles on spillover from the published peer-reviewed literature back to 1994 through Web of Science. We used the following search string: (spillover OR spill-over OR "spill over") AND ("marine protected area*" OR "marine reserve*" OR "no-take zone*" OR "fisher* closure*)". We searched the reference lists of the retrieved articles, personal archives and we contacted authors of older articles on movement of individuals from MPAs to fished areas. We identified 85 articles published from 1981 to 2014 (Supplementary Appendix I): 63 field studies, 11 reviews and 11 modeling articles. The number of articles published annually on spillover from MPAs increased 10-fold from 1994 to 2008–2009, before decreasing up to now (Fig. 1). Empirical studies (n = 63) analyzed spillover from 57 MPAs worldwide with most articles (n = 43) focusing on one MPA; the remaining articles (n = 20) focused on two to 13 MPAs. In our review, experimental studies were analyzed in more depth than theoretical studies.

3. Spillover: definition, mechanisms, occurrence and magnitude

The term and concept of spillover from MPAs is widely accepted but its use is not univocal. To our knowledge, Davis (1981) was the first author who referred to the process of biomass export from MPAs. About one decade later, Rowley (1994) explicitly introduced the term spillover to refer to the net movement of individuals from marine reserves towards fished areas. This term, however, has then been largely used to define any movement/displacement of biomass or individuals from MPAs towards fished areas disregarding the life stages (i.e. adults, juveniles, larvae) or the underlying mechanisms (i.e. density-dependent or density-independent) involved.

Before spillover takes place, populations of fish within an MPA must recover to make it possible for fish to actually spill across or overflow the MPA boundaries. This implies that MPAs should be properly enforced and rules complied with to then expect protection responses like recovery inside and spillover outside to happen (Edgar et al., 2014; Guidetti et al., 2008). Therefore, spillover in MPA

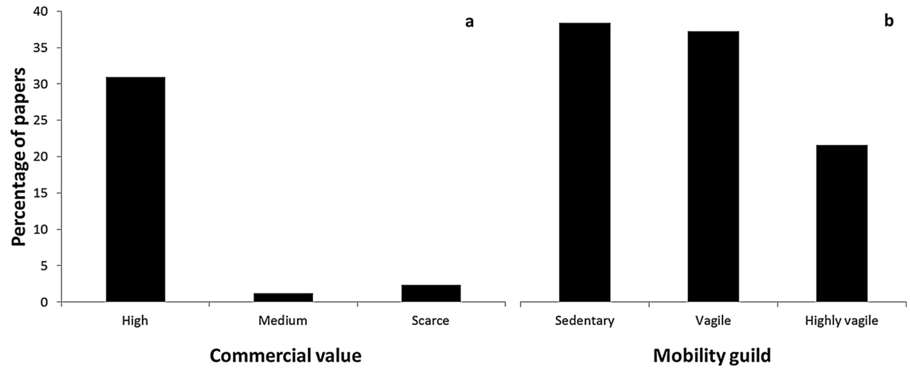

Fig. 2. Commercial value (a) and mobility (b) of the species studied to assess spillover.

science is a density-dependent mechanism where an increased competition within the MPA triggers a movement/transfer of individuals/biomass towards adjacent areas outside MPAs (see also Kramer & Chapman, 1999; Roberts & Polunin, 1991). In just two of the 85 articles spillover is potentially driven by density-independent processes (e.g. home range movement, ontogenetic movement, seasonal reproductive migrations; Goñi et al., 2010; Garcià-Rubies, Hereu, & Zabala, 2013). Such processes are independent of the presence and effectiveness of an MPA. In 32 articles the underlying mechanism was not specifically mentioned but, while defining spillover, the authors referred to other articles where the increased intraspecific competition after recovery from protection was identified as the main driving force of spillover. In the remaining 50 articles, spillover is explicitly referred to density-dependent processes.

Spillover was observed in 80% of the empirical studies we have analyzed. However, because of publication bias in ecology, and specifically in the MPA science (Edgar, Bustamante et al., 2004; Edgar, Barrett, & Morton, 2004; Sale et al., 2005), the 20% of remaining studies that failed to provide any avidence of spillover is likely to be underestimated. Within MPAs, except for MPA of Balicasag (Alcala & Russ, 2006), a recovery inside the boundaries compared with adjacent fished areas was always reported.

About the articles where spillover has not been observed, there is a point to take into account: spillover is a phenomenon that may require several years to take place after a significant recovery occurs inside the MPA borders (Russ & Alcala, 1996).

Habitat continuity across MPA boundaries has been suggested to potentially facilitate spillover (Chapman & Kramer, 1999; Rowley, 1994; Sanchez Lizaso et al., 2000). Overall, information on habitat continuity/discontinuity across MPA boundaries was found in 54 out of the 63 field studies selected: in 36 cases, habitats were continuous across MPAs boundaries, while in 18 cases there was not any habitat continuity across MPA borders. Overall, evidence of spillover was reported from 75% (n = 27) of studies dealing with MPAs where habitats were continuous, and from 67% (n = 12) of studies where there was a discontinuity of habitat across the MPA boundaries (Fig. 2).

Another crucial issue is to get evidence about the spatial relevance of spillover (i.e. how far from the MPA borders it can be detected). Only one third (n = 28) of the articles analyzed reported an estimation of the distance from the MPA boundaries at which spillover occurs (Supplementary Appendix I). Such estimates were affected by the techniques used. Most of these studies, carried out by means of visual census techniques, reported that, spillover can be detected up to a few hundreds of meters from the MPA boundaries (Supplementary Appendix I). Differently, individuals tagged/marked in MPAs have been recaptured at larger distances (up to 5 km for lobsters; Follesa et al., 2011; up to 150 km for fish; Tremain, Harnden, & Adams, 2004). Halpern et al. (2010), generalized the distance at which spillover might occur, highlighting that spillover is generally detectable between 600 and 1500 m beyond MPAs boundaries.

4. Experimental/methodological approaches used to assess spillover

Three main approaches were used to assess spillover. The most frequent approach was underwater visual census data (UVC) (41%; n = 26; Supplementary Appendix I), which allows evaluating distribution patterns of density and/or biomass of target species at increasing distance from the center of MPAs towards fished areas. In the literature the strip transect technique (Harmelin-Vivien et al., 2008) has been employed with varying dimension of transects according to authors, regions, habitats (e.g. rocky or coral reefs), and other environmental features (e.g. water clarity). Sampling designs always involved replicated UVCs inside and outside the MPA. More than 75% of the UVC studies (n = 19) also included temporal replication throughout multiple years, while the remaining 25% (n = 6) were carried out within the temporal window of just one year. In 6 articles, a BACI (before-after-control-impact; Underwood, 1996) design was used (Abesamis & Russ, 2005; Alcala, Russ, Maypa, & Calumpong, 2005; Francini-Filho & Moura, 2008; Russ & Alcala, 2011; Russ & Alcala, 1996; Russ, Alcala, & Maypa, 2003; Russ, Alcala, Maypa, Calumpong, & White, 2004; Samoilys et al., 2007).

The second most frequent approach we found in the literature stems from the possibility of assessing individual movement patterns inside-outside MPAs by means of external tags or internal transmitters (34%, n = 21; Supplementary Appendix I). In about 63% of these studies, individuals were marked both inside and outside the MPAs, while in 37% of studies individual fish movements were monitored only inside MPAs. External tagging studies were carried out at a temporal scale between 1 and 10 years, while most tracking studies were carried out up to 1 year, chiefly due to technological limitations (e.g. battery life).

Fisheries catch data were used to assess biomass gradients at increasing distance from the MPA boundaries in about 20% of articles (n = 14; Supplementary Appendix I). Almost all of these studies evaluated spillover only by carrying out fishery surveys outside of the MPA (n = 13) at increasing distance from boundaries, while in a single study fishery yields have been monitored both inside and outside the MPA (Stobart et al., 2009). In all 13 studies, fishery data have been collected for more than one year.

Spillover was investigated using questionnaires administered to fishermen in n = 3 articles (5%).

5. Species and organisms selected to assess spillover

Spillover was assessed on a total of 203 marine species. The bulk of species were represented by fish, while just seven species were invertebrates (Mediterranean lobster *Palinurus elephas*, Atlantic spiny lobster *P. argus*, California spiny lobsters *P. interruptus*, red rocky lobster *Jasus edwardsii*, and European lobster *Homarus gammarus*; queen conch, *Strombus gigas*; mud crab, *Scylla serrata*; Supplementary Appendix II). The species analyzed were subdivided into three categories on the basis of the commercial value (high, medium, scarce) and mobility (highly mobile, vagile, sedentary) (Supplementary Appendix II).

Most articles (59%; n = 37) investigated a range between 2 and whole fish assemblages species characterized by different commercial value and mobility. The remaining articles (41%; n = 26) evaluated spillover on a single species.

Literature assessing spillover mainly focused on high commercial value species (Fig. 5). Specifically, 26 articles concerned single species belonging to this category, and 18 articles dealt with species falling within other commercial categories. Spillover of medium commercial value species was studied in just one article (Fig. 2). In 17 articles, medium commercial values species were investigated in combination with other commercial categories. Two articles investigated just species of low commercial value (Fig. 2).

As regards the mobility (Fig. 2), most articles (n = 32) focused on sedentary species; vagile species were investigated in 31 articles; fewer articles (n = 18) assessed spillover of highly mobile species.

6. Improving spillover assessments

Results of this review allow to suggest some clues to improve spillover assessment. First of all, since spillover is a process through which MPAs can benefit local fisheries, we think it would be useful distinguishing, from an operational point of view, two types of spillover. *Ecological spillover* encompasses all forms of net emigration of juveniles, subadults and/or adults from the MPA outwards. It has been the subject of most studies published until now. The *fishery spillover*, encompassing only a subset of ecological spillover, is the fraction of spillover that can more directly impact fishery yields and revenues.

The distinction proposed here is chiefly operational and is proposed for the purpose of making spillover comprehensible to a wider audience than the scientific community. MPA science needs to better clarify spillover that clearly produces direct and immediate effects on fisheries in order to foster better dialogue involving stakeholders and policy makers. Obviously, this operational distinction does not imply that the complex processes in nature that support fisheries are not interrelated. Larval/egg production and export from MPAs (recruitment subsidy *sensu* Grüss et al., 2011) and juvenile/subadult/adult fish export (spillover *sensu stricto*), together contribute to sustain fisheries. But their effects occur at different temporal and spatial scales, and are affected by different processes (e.g. larval mortality or post-settlement mortality).

This distinction between the two types of spillover can also further help targeting appropriate monitoring tools to assess spillover and, especially, to understand when spillover can be expected. The choice and effectiveness of the sampling method is indeed crucial to evaluate spillover as monitoring methods have their own selectivity and biases. Spillover has mainly been assessed using three techniques (UVC, tagging and catch data). UVC is an important tool to evaluate the population recovery inside an MPA and such information must be viewed as the first step to later study spillover (*ecological spillover*). Because of an increased competition for resources (e.g. space and/or food) UVC may allow for indirect estimation of the biomass of fish moving beyond MPA borders. Tagging methods can provide evidence of the movement of fish from inside to surrounding/fished areas (spill-over) compared to movements from outside to inside MPA (spill-in). This method also allows understanding of whether the individuals move to fished areas to relocate their home ranges due to density-dependence or for reasons not related to the MPA ecological effectiveness (e.g. spawning migrations, Di Lorenzo et al., 2014). The above mentioned methods provide evidence on ecological spillover, which is the necessary step for fishery spillover to occur. The fishery spillover should be assessed and monitored with the same gear(s) that are commonly used by fishermen in the fishery grounds surrounding the MPA(s) of interest. Too few studies exist that actually assessed fishery spillover (Kerwarth et al., 2013). Obtaining such evidences is crucial to convince stakeholders (e.g. fishermen, policy makers) about the importance of MPAs and to involve them in the management process (Claudet & Guidetti, 2010a, 2010b).

We showed that habitat continuity does not affect spillover effectiveness. Although habitat continuity across MPA boundaries could facilitate spillover (Bartholomew et al., 2008), fish can also cross unsuitable habitats (e.g. often represented by sandy bottoms deprived of shelters) when competition pressure is strong. The likeliness of fish crossing different habitats rather than staying in the preferred one may depend on how fish integrate the patched habitats to minimize overall costs and risks (Belisle, 2005; Wiens, 2002). This evidence could suggest that individuals subject to strong competition inside MPAs can get the risk to cross unsuitable habitats to try to get other less crowded portions of preferred habitat elsewhere (Wiens, Stenseth, Van Horne, & Ims, 1993). Therefore, habitat continuity (*sensu stricto*) could not be an absolute discriminating factor for the occurrence of spillover (Tupper, 2007), and a different habitat outside MPAs can be a barrier to fish movement (landscape connectivity, *sensu* Taylor, Fahrig, Henein, & Merriam, 1993) only if a threshold level of population density is not exceeded. If the threshold is exceeded, fish could cross MPA boundaries, whatever the habitat type or continuity, searching for other places where to re-locate the home range.

7. Conclusions

Spillover is a common phenomenon occurring worldwide in MPAs where fish populations first recover inside the MPA boundaries. To properly evaluate spillover, we suggest to operatively distinguish between the ecological and fishery components of spillover. Spillover assessments should include: 1) a first evaluation ensuring that density and/or biomass recovery within the MPA takes place; 2) an analysis of the home range of individuals to assess whether the MPA covers individual home ranges entirely or partially; 3) a monitoring of net individual movements across MPA boundaries; and 4) a monitoring of catch data at increasing distances from the MPA.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jnc.2016.04.004.

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