A seascape approach to investigating fish spillover across a marine protected area boundary in Hawai'i

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ABSTRACT

Marine protected areas (MPAs) can benefit fisheries through export of pelagic eggs and larvae and the net emigration of adults and juveniles (spillover). Spillover was investigated for a marine protected area on the north shore of Oahu, Hawai'i utilizing a seascape approach. This study incorporated habitat variables and underwater visual surveys of fishes and benthos measured at two distinct scales (125 m^2 and 1000 m^2) inside and outside the protected area at varying distance from the boundary. The relationship between fish biomass from fine-scale surveys and key habitat variables was found to account for a large portion of the variability for both resource (targeted) fish species (15%) and non-resource fish (28%). The remaining variation in resource fish biomass was significantly correlated with distance from the MPA boundary showing a decreasing gradient from inside to outside ($r^2 = 0.46$, $p = 0.001$), indicating fish spillover at a local scale (<1 km). In contrast, non-resource fish biomass demonstrated no such relationship ($p = 0.45$). The evidence of spillover based on the fine-scale surveys was corroborated by results from broad-scale surveys, which also showed a significant relationship ($r^2 = 0.19$, $p < 0.01$) between resource fish biomass and distance from the MPA boundary. In addition, observed spatial distribution of fishing effort was consistent with predictions that fishers respond to biomass gradients across protected area boundaries. Fish spillover can help mitigate costs associated with the establishment of marine protected areas in terms of lost fishing area and therefore have a positive effect on the attitudes of fishers toward marine reserves and marine protected areas.

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1. Introduction

Marine protected areas (MPAs) are widely utilized as a management tool to conserve biodiversity and to protect or restore fish populations within their borders (Lester et al., 2009). Numerous field studies have documented how population numbers and biomass, species richness, size of organisms, reproductive potential, and/or community structure are positively affected by protection from fishing (Halpern and Warner, 2002; Gell and Roberts, 2003; Micheli et al., 2004). Another potential benefit of MPAs is that they supplement adjacent fisheries through two primary mechanisms: increased production and export of pelagic eggs and larvae, and net emigration of adults and juveniles ("spillover," Rowley, 1994). While density dependent emigration (hereafter spillover) can supplement fishery yields (McClanahan and Mangi,

2000), it is generally believed that the export of eggs and larvae provides greater overall fishery benefits (Palumbi, 2004; Sladek Nowlis and Friedlander, 2005). One effect of spillover of mature fishes could be to reduce potential for reproductive output from within the MPA with possible negative implications for stock enhancement (Sladek Nowlis and Roberts, 1999). From a fishers perspective; however, spillover of adult fish from MPAs may provide a more tangible benefit than larval export and serve to improve perceptions of marine protected areas (Russ and Alcala, 1996). Fisher attitudes toward MPAs and marine reserves have important implications for maintenance, enforcement, and designation of new protected areas (Suman et al., 1999).

Therefore, for a number of reasons, an understanding of the rate and extent of adult spillover from MPAs is essential for the evaluation of their effects on connected fisheries.

With higher densities and larger sizes of fished species inside of marine protected areas, considerations of spatial habitat use and behavior of fish (Lizaso et al., 2000; Abesamis and Russ, 2005) lead to predictions that population density and mean fish size will form gradients across protected area boundaries (Rakitin and Kramer, 1996). For this reason, gradients of fish abundance and

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biomass have been utilized as indicators of fish spillover across MPA boundaries and to assess the scale of influence of protection (McClanahan and Mangi, 2000; Ashworth and Ormond, 2005; Abesamis et al., 2006). The significance of gradients is further supported by Kellner et al. (2007) whose model shows that considering the effect of harvesting and the diffusion rate of species, the distribution of abundance or biomass with increasing distance from an MPA should produce a gradient with a steeper negative slope as diffusion process becomes more important or as fishing pressure increases. The existence of such a negative gradient could therefore be interpreted as evidence of spillover of adult fish. However, habitat variability is a primary factor driving the distribution of fish assemblages (Friedlander and Parrish, 1998; Friedlander et al., 2007a; Forcada et al., 2008) and can confound reserve effects. Therefore, the influence of habitat must first be resolved in order to show the effects of protection (Chapman and Kramer, 1999; Harmelin-Vivien et al., 2008). Additionally, information on fishing effort by gear type can provide important perspective for interpreting abundance and biomass gradients across the boundary and reveal linkages between fish spillover and fisher behavior (Russ et al., 2004; Russ and Alcala, 2004; Kellner et al., 2007).

Over the past four decades a series of MPAs known locally as Marine Life Conservation Districts (MLCDs) have been established in Hawai'i. Originally intended to provide areas for the public to interact with marine life, the MLCDs vary in size, habitat quality, and management regimes. Five of the eleven MLCDs (or portions of them) are true no-take marine reserves. All of the MLCDs have been shown to conserve fish populations within their boundaries to varying degrees (Friedlander et al., 2007a, 2007b, 2010). Friedlander et al. (2007b) showed that MLCD size is positively correlated with a number of fish assemblage characteristics, including species richness, density, and biomass and concluded that all of the MLCDs are likely too small to have any measurable influence on adjacent fished areas. Williams et al. (2009) investigated the effects of a marine protected area network in West Hawai'i on the distribution of yellow tang (*Zebrasoma flavescens*) a species important to the aquarium fishery (Walsh et al., 2003). After controlling for structural complexity, results indicated export of adults from protected areas, as shown by significantly higher densities at sites near protected area boundaries than at distant sites.

Given that MPAs in Hawai'i have higher levels of fish richness, abundance and biomass than adjacent fished areas (Friedlander et al., 2007a, 2007b, 2010) gradients of fish biomass across MPA boundaries should be detectable (Rakitin and Kramer, 1996). If these gradients exist as a result of protection, one would expect to see this pattern only for resource (targeted) species (Rakitin and Kramer, 1996; Williams et al., 2008). Furthermore, spatial patterns of fishing effort should correspond to resource fish biomass gradients (McClanahan and Mangi, 2000; Kellner et al., 2007). The goal of this study was to evaluate the spatial pattern of total biomass of resource fish species across an MPA boundary in order to determine if a negative gradient exists, and to determine if is a function of fishing protection (i.e. spillover) by comparing it to the total biomass of non-resource fish species and spatial patterns of fishing effort. In order to accomplish this, several assumptions needed to be tested. First, that biomass (as well as species richness and abundance) of fishes was higher inside the MPA than outside (Friedlander et al., 2010). Second, that habitat variability is the primary driver of fish distributions and must be controlled for in order to test for protection effects (Friedlander and Parrish, 1998; Chapman and Kramer, 1999; Forcada et al., 2008). And finally, that fishing pressure is lower inside the MPA than outside. This study examined a marine protected area on the north shore of Oahu, Hawai'i using a seascape approach; controlling for habitat parameters, sampling at two distinct spatial scales, and measuring fishing effort in order to address

three main questions: (1) Does resource fish biomass form a negative gradient ("spillover") across the boundary of the MPA into the fished area? (2) If so, does non-resource fish biomass follow a similar pattern which contraindicates a response to fishing? and (3) How does this gradient of resource fish biomass (if detected) relate to fisher behavior in terms of spatial patterns of fishing effort?

2. Methods

2.1. Study area

To address our research questions we evaluated the Pupukea MLCD on the north shore of Oahu (Fig. 1). This MPA was established in 1983 (0.11 km^2) and expanded in 2003 (0.71 km^2) through a community-driven process (Friedlander et al., in review). The area is completely no-take except for collection of two species of seaweed throughout the MPA and in the Waimea Bay portion only; limited pole fishing from shore and seasonal net harvest of two coastal pelagic species (Fig. 2). Throughout the protected area, and extending out into the fished area to the north is a continuous stretch of hard bottom reef habitat (based on NOAA benthic habitat maps – Battista et al., 2007) (Fig. 2), which was the focus of the biological surveys.

2.2. Experimental design

Surveys stations were randomly located on hard-bottom habitats, with stations stratified by distance into 200 m long blocks in two study zones: 'MPA' and 'open'. To avoid overlap, stations were separated by a minimum distance of 30 m. Zones consisted of adjacent areas approximately 1000 m in length and a depth range corresponding to the Pupukea MLCD (0–15 m). The MPA zone was located inside the MLCD with the north boundary at one end and the open zone located adjacent to this boundary (Fig. 2). Therefore, survey stations were located a maximum of 1000 m from the boundary. A total of 80 independent fine-scale fish and benthic surveys and 40 broad-scale fish surveys in a variety of hard-bottom habitats were conducted between June and September 2010. Timing was in large part dictated by winter surf patterns on the north shore of Oahu where diving is nearly impossible between October and May. Fishing effort surveys took place the following summer during June–September 2011. To address habitat effects and biomass gradients, resource fishes and non-resource fishes were analyzed separately (Abesamis et al., 2006; Williams et al., 2008). These classifications were formed based on commercial catch data from the Hawai'i Division of Aquatic Resources (2009) where resource fishes were defined as those species with at least 1000 lbs/year landed.

2.3. Data collection

2.3.1. Fish surveys

Fine-scale (125 m^2) fish surveys used belt transects oriented at 200° – roughly parallel to shore. A diver swam along a 25 m × 5 m transect at a constant speed and identified to the lowest possible taxon all fishes visible within 2.5 m to either side of the centerline. Survey duration varied from 10 to 15 min, depending on habitat complexity and fish abundance. Total length (TL) of fishes was estimated to the nearest centimeter (Bell et al., 1985; Friedlander and Parrish, 1998). The same diver surveyed fish on all transects.

Broad-scale (1000 m^2) fish surveys were focused on resource fishes >15 cm only and used timed swims with a pair of divers each counting, sizing, and identifying fishes within adjacent 5 m wide belt transects. Survey duration was 5 min with one diver towing a surface float equipped with GPS to enable measurement of transect