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Exploring the effect of the spatial scale of fishery management

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HIGHLIGHTS

- We explore the effect of spatial scale of fishery management in a bioeconomic model.
- Finer spatial scales of management can significantly improve optimal fishery profit.
- Profit increases nearly linearly with management scale for uncorrelated landscapes.
- Profit has diminishing returns with management scale for autocorrelated landscapes.
- An intermediate optimal management scale is more likely for autocorrelated landscapes.

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ABSTRACT

For any spatially explicit management, determining the appropriate spatial scale of management decisions is critical to success at achieving a given management goal. Specifically, managers must decide how much to subdivide a given managed region: from implementing a uniform approach across the region to considering a unique approach in each of one hundred patches and everything in between. Spatially explicit approaches, such as the implementation of marine spatial planning and marine reserves, are increasingly used in fishery management. Using a spatially explicit bioeconomic model, we quantify how the management scale affects optimal fishery profit, biomass, fishery effort, and the fraction of habitat in marine reserves. We find that, if habitats are randomly distributed, the fishery profit increases almost linearly with the number of segments. However, if habitats are positively autocorrelated, then the fishery profit increases with diminishing returns. Therefore, the true optimum in management scale given cost to subdivision depends on the habitat distribution pattern.

1. Introduction

The importance of spatial scale has been well recognized in many fields of ecology (Levin 1992), such as species-area relationships, maps of species richness, and conservation planning (Palmer and White, 1994; Schwartz, 1999; Margules and Pressey, 2000; Turner and Tjørve, 2005; Hurlbert and Jetz, 2007). Spatially explicit approaches to ecosystem management introduce a management scale overlaid on the natural spatial scale of ecological processes. Specifically, managers must decide how much to subdivide the area under concern: from implementing a uniform approach across the region to considering a unique approach in each of hundreds of patches and everything in between. This scale of management assessment and implementation affects the ability to achieve management goals. For example, analysis of range-map data at inappropriately fine resolutions might lead to the identification of erroneous "biodiversity hotspots" with overly optimistic estimates of species representation in reserves and potentially invalid complementarity sets for identifying conservation priorities (Hurlbert and Jetz, 2007).

Ecosystem-based fisheries management (EBFM) is an inherently spatially explicit approach to fisheries management, including the implementation of marine reserves, or no-take zones (Pikitch et al., 2004). Marine reserves goals range from conserving species to support sustainable fisheries management (Leslie, 2005; Lester et al., 2009). Even without reserves, EBFM typically involves a spatially explicit approach to harvest decision in terms of zonal allocations of fishing effort (Francis et al., 2007), which can increase fishery profit over spatially uniform management if appropriately based on habitat distribution and connectivity (Rassweiler et al., 2012). However, few studies explicitly considered the effect of the choice of spatial scale in spatial fishery management on achieving management goals.

Under spatial fisheries management, managers must choose a management scale to define a management unit (i.e., zoning unit), and fishing regulations such as entry limitation and establishment of reserves occur within these zoning units (Cancino et al., 2007; White

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and Costello, 2011). For example, the concept of setting variable harvest rates over space was implemented for co-occurring fisheries of less productive and productive species in the US west coast, such as yellowtail and canary rockfish (Francis, 1986) and yelloweye rockfish and lingcod (Dougherty et al., 2013). Spatial management through a fine filter enables managers to allocate fishing efforts and reserves more flexibly compared to management through a coarse filter, but a finer filter imposes greater complexity on the decision-making process and enforcement. For territorial user rights fisheries (TURFs), coarser management scales increase achievement of optimal harvest due to the greater degree of ownership and lower competition (White and Costello, 2011). However, for fisheries under top-down control such as the case where federal level government decisions determine individual fishing effort, the appropriate management scale might change because competition between management units does not occur.

To investigate how the choice of spatial management scale affects fishery and ecological outcomes such as optimal fishery profit, biomass, fishery effort, and the fraction of habitat in marine reserves, we construct a spatially explicit bioeconomic model that follows an age-structured harvested population. Using two California species, cabezon (*Scorpaenichthys marmorata*) and red abalone (*Haliotis rufescens*), we compare two spatial management strategies: allocating reserve or non-reserve patches with a uniform fishing rate versus allocating fishing rate in each patch, where allocation within the management scale maximizes fishery profit. We then investigate the relationship between the spatial scale of management and the above-mentioned fishery and ecological outcomes under varying degrees of autocorrelation in the habitat, which determines the spatial scale of habitat.

2. Methods

We aim to construct the simplest possible model that allows us to quantify the relationship between the choice of spatial management scale and our metrics for fishery and ecological outcomes. As detailed below, the managed population occurs in a naturally patchy habitat, where the choice of management scale relative to the natural habitat patch size determines its effect on population dynamics. We explore different values of spatial autocorrelation in habitat patches to model different levels of natural patchiness. Larval dispersal connects the patches, where populations then experience density-dependent recruitment. Post-settlement individuals remain within habitat patches (i.e., a relatively sedentary species) according to an age-structured model with density-independent natural and harvest mortality; the structured population dynamics allow us to determine the effect of management decisions on population biomass and biomass yield. To model top-down control given a particular management scale, the fishery optimizes profit across the entire habitat based on management-patch-specific effort allocation, with two approaches. First, management patches have either zero effort (reserves) or harvest, with the same effort in all harvested patches and both this effort level and which patches are harvested are chosen to maximize yield (uniform effort, or UE, strategy); this approach models the optimal use of reserves in fishery management, with no further spatially explicit management beyond reserve designation. Second, the amount of effort in each management patch (including the possibility of zero effort) is chosen to maximize yield (fine-tuned effort, or FE, strategy); this approach models a fully spatially explicit management approach. We then determine the effect of management scale on effort and profit as our fishery outcomes as well as population biomass and fraction of the habitat in marine reserves as our ecological outcomes.

3. Environmental and management scale

The target species population occurs along a coastline where we approximate the geographic landscape by a one-dimensional patchy environment with different patterns of autocorrelation in habitat quality. The minimum size of habitat defines the environmental scale that determines the population dynamics. Whether or not fishing occurs in a given location depends on a separate management scale (Fig. 1). We define the management scale as the size of a minimum management unit where fishing effort is uniform within the region. We assume that the minimum management scale is the environmental scale. The environmental scale inherently depends on ecological and physiological characteristics of a species and geomorphological patterns (Levin, 1992). The management scale depends on managers or fishermen based on, for example, assessment data or range maps (Hopkinson et al., 2000, Hurlbert and Jetz, 2007), and it characterizes the spatial fishery management. Here we set the environmental scale (minimum habitat patch size) to 1 km to match the minimum environmental scale of the target species in their post-larval home

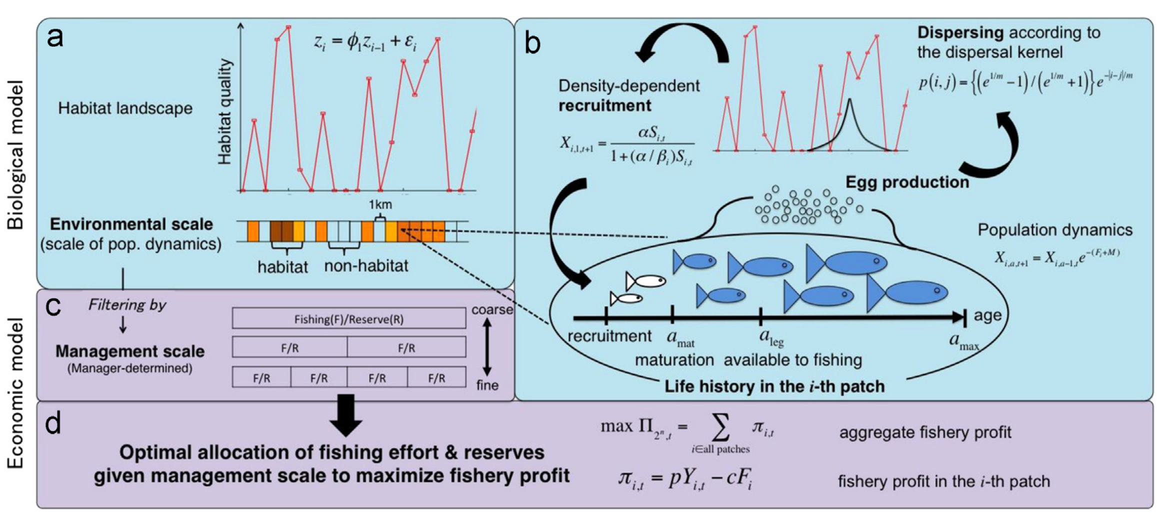

Fig. 1. Schematic description of the model. (a) The degree of autocorrelation determines the environmental scale. (b) Population dynamics occur at the environmental scale. Planktonic larval dispersal connects individual patches. Larvae successfully arriving at a patch experience density-dependent recruitment and subsequently follow age-structured dynamics. (c) Managers chose a management scale for a given region. (d) Managers allocate fishing efforts and reserves to each management patch so as to maximize fishery profit for each given management scale.