# SPATIAL BIOECONOMIC DYNAMICS OF MARINE FISHERIES

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## Contents



## Summary

Spatial management of fisheries requires understanding the spatial behaviour of species with the corresponding abundance heterogeneity in space and time and the ecological interdependencies within an ecosystem framework. It also involves proper understanding of fisher behaviour driving the spatial allocation of fishing intensity. The recognition of the implications of dynamic pool assumptions in over estimating stock abundance, is discussed together with spatial modelling efforts aimed at relaxing this unrealistic assumption for sedentary species and many low mobility demersal resources. Progress aimed at considering management implications of metapopulations and source-sink configurations present in many marines populations, is also discussed. The establishment of marine reserves as a strategy for enhancing the conservation of marine resources is examined with respect to the implications of their size and location when considering metapopulations and source-sink configurations. Recent reports of the benefits and costs of Marine Protected Areas are also summarised.

## 1. Introduction

Understanding the spatial dynamics of marine fisheries allows proper management of fish resources that distribute heterogeneously in space and time. This consideration is relevant for most marine species, but critical for sedentary marine resources. Dynamic pool fishery models developed in the 1950's, have been criticized as unrepresentative of events in a fishery in that spatial realism is sacrificed. Authors of these models, nonetheless laid the foundations for incorporating spatial considerations into population dynamics, but in the 1950's were unable to follow up their ideas due to the inadequacy of computational facilities. In general, these models are based on dynamic pool assumptions, which establish that: (*i*) the resource is homogeneously distributed in space; (*ii*) ages are perfectly mixed; and either (*iii*) fishing effort is applied uniformly over the range of resource distribution, or (*iv*) after fishing effort has been applied, the resource is able to redistribute itself according to (*i*) and (*ii*). Studies typically confirm that local habitats are unequal in quality and holding capacity throughout the stock range. Not surprisingly, for sedentary resources, models based on dynamic pool assumptions are inadequate and result in serious model error. The spatial distribution of these resources is patchy, in terms of size, density and age structure. As a result, the allocation of fishing effort is spatially heterogeneous. The principal consequence of this spatial heterogeneity is that under dynamic pool assumptions, the productive potential of the stock is overestimated, increasing the risk of over-exploitation and collapse of the fishery.

Spatial components have subsequently been introduced into population models for a variety of motives: to explore sequential fisheries, to examine spatial allocation strategies, and to consider the implications of optimal foraging theory. Spatial modelling exercises introducing elements of spatial realism, both in the distribution pattern of the resource and the fishing strategy, usually result in the management implications for age-structured models less optimistic.

## 2. Models of exploited populations incorporating spatial structure

Dynamic pool models suppose that each individual has an equal probability of mating and spawning, and this has been referred to as panmixia**.** However, more recent studies of marine fish populations using trace elements, parasites and genetypes have begun to discover genetic differentiation within demersal marine resources of continental shelves, suggesting that metapopulations are fairly common, especially for sedentary or territorial species. Hence, the effective reproductive size of a population may be much smaller than its total population size and reproductive age groups and spawning sites may not be equally successful in their reproductive activities throughout the species range. One common variant is where a progressive isolation of source areas occurs with distance, leading eventually to the separation of local genotypes.

To deal with this complexity an early spatial model, YAREA, explored harvest strategies for spatially-differentiated resources and fishing strategies, and was developed further under a variety of assumptions to address both resource and bioeconomic considerations. The authors developed a suite of models for exploring the implication of port location and distance from fishing grounds and a bioeconomic simulation of age-structured spatial populations, and an explicit consideration of spatial considerations was later extended to optimizing rotating harvest management strategies. General models of how spatial considerations affect stock and fleet dynamics were also developed. Some studies have reviewed how geographical considerations affect exploitation of marine populations. More recently, scientists modelled the heterogeneity in resource and effort distribution using the negative binomial distribution in an environment of risk and uncertainty.

## 3. Heterogeneous recruitment density in space and time

The heterogeneous distribution of recruits over space can be modelled by multiplying the estimated number of recruits produced by the spawning stock ($SS_t$) over time $R_t = f(SS_t)$ (e.g. estimated using Ricker, Beverton-Holt or stochastic recruitment functions) by a probability density function that distribute them over space.

For instance, a general Beverton-Holt stock-recruitment function can be multiplied by an appropriate probability distribution (i.e. negative binomial distribution, that allows for patches of zero recruitment) to generate a heterogeneous recruitment density over time, as expressed by Equation (1) as follows:

$$R_t = \frac{B_t \cdot \alpha}{\beta + B_t} \cdot P(d) \qquad (1)$$

Where $B_t$ is the total spawning biomass over time, $\alpha$ is maximum annual recruitment, and $\beta$ is total spawning biomass for $\alpha/2$. *P(d)* is the negative binomial probability density function. An important assumption of Equation (1) is that recruitment depends on the total spawning biomass rather than the locus-specific spawning biomass. This assumption is likely to be valid when the life cycle of species involves indirect development, that is, when juveniles do not emerge directly from the egg but rather as a result of metamorphosis of larvae that can recruit in a different locus from the one inhabited by the parental stock.

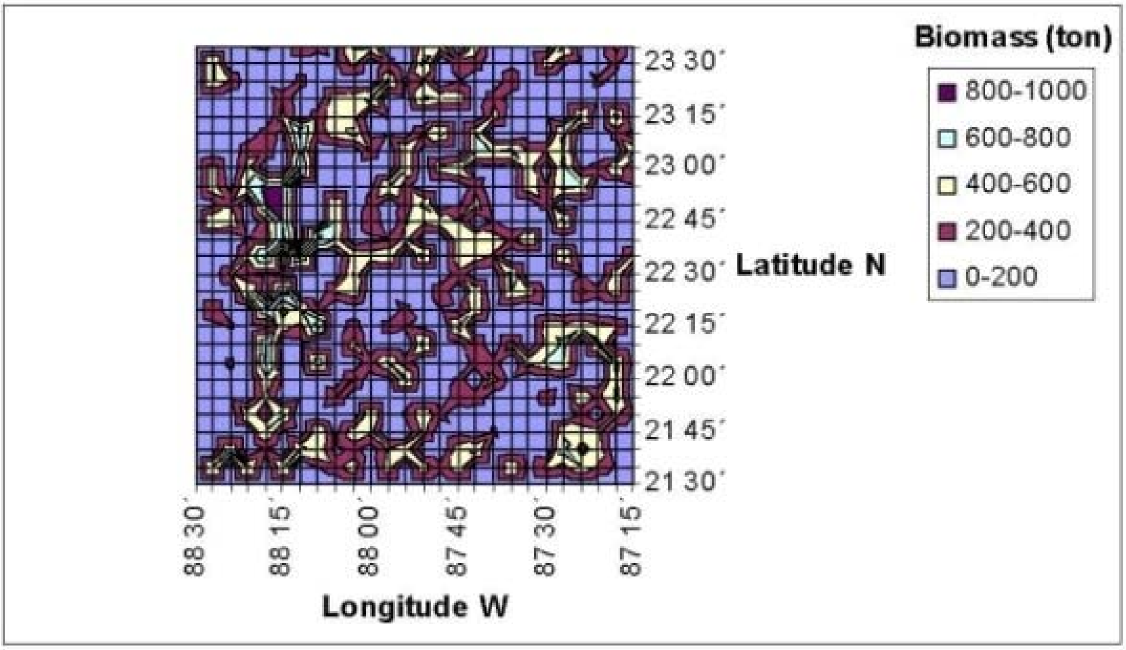


Figure 1. Spatial distribution of biomass using a negative binomial function for recruits settlement over space.

The negative binomial distribution used to represent spatial heterogeneity in recruitment densities is estimated as follows:

$$P(d) = (1+\frac{\mu}{\varepsilon})^{-\gamma} \cdot \frac{(\varepsilon + d - 1)!}{d!(\varepsilon - 1)!} \cdot (\frac{\mu}{\mu+\varepsilon})^{d} \qquad (2)$$

Where $d$ represents recruitment density, $\varepsilon$ is the family member of the negative binomial, and $\mu$ is the mean recruitment density. The basic assumption is that the stock can be subdivided into 'loci', each assuming different resource densities. A 'locus' here is effectively the smallest geographical unit considered. Each locus would contain several age classes, all of which would have different densities. 'Locus' can be considered synonymous with 'cell', 'quadrat' or 'pixel' in common usage, and can be assigned a specific geographical position or latitude/longitude (Figure 1).

## 4. Spatial allocation of effort

Modelling the short-run spatial dynamics of marine fisheries allows for better understanding the inter-temporal allocation behaviour of fishing effort and thus to develop adequate management strategies.

Some spatial allocation strategies documented in the literature include the following:

- Proportional allocation according to the spatial abundance of the resource.
- Sequential allocation to those patches of greatest abundance
- Random search
- Free distribution of allocation of fishing intensity
- Proportional allocation to:
    a. The quasi-rent of the variable costs (including transfer costs resulting travelling from port to alternative fishing grounds).
    b. The friction of distance, i.e. non-monetary costs associated to vessel distance travelled to fishing grounds
    c. The probability of finding the target species in profitable levels.

This last spatial allocation strategy, involving a short-run effort allocation decision, is expressed in equation (3) as follows,:

$$SAE_{kht+1} = \frac{P_k \cdot quasi\pi_{kht} / D_{hk}{}^{\phi}}{\sum_k P_k \cdot quasi\pi_{kht} / D_{hk}{}^{\phi}}$$

Where, $P_k$ is the probability of finding the target species in profitable levels in alternative fishing grounds k. The *quasi* rent of the variable costs (rent obtained after paying for the variable costs of fishing) received by the average vessel leaving port $h$ by fishing in site $k$ in time t is expressed as $quasi\pi_{hkt}$. Finally, $D_{hk}$ represents the distance from port h to fishing site $k$, and $\phi$ the friction of distance parameter that accounts for the non-monetary costs associated to distance travelled to fishing site.

The properties of this simple spatial allocation model (SAE) are summarized in Table 1 for alternative fishery cases.

| **Fishery Case** | **Monetary costs associated to distance D** | **Friction of distance[1] ($\phi$)** | **Probability of finding the resource *(P)*** | **Expected spatial distribution of effort** |
|---|---|---|---|---|
| Case 1 | $D_1 = D_2 = \ldots = D_k$<br>$\theta = 0$ | $\phi=0$ | $P_1 = P_2 = \ldots = P_k$ | Proportional to resource abundance |
| Case 2 | $D_1 \neq D_2 \neq \ldots \neq D_k$<br>$\theta > 0$ | $\phi=0$ | $P_1 = P_2 = \ldots = P_k$ | Proportional to the quasi-rent of the variable costs |
| Case 3 | $D_1 \neq D_2 \neq \ldots \neq D_k$<br>$\theta > 0$ | $\phi>0$ | $P_1 = P_2 = \ldots = P_k$ | Proportional to the quasi-rent of the variable costs and $1/D^{\phi}$ |
| Case 4 | $D_1 \neq D_2 \neq \ldots \neq D_k$<br>$\theta > 0$ | $\phi>0$ | $P_1 \neq P_2 \neq \ldots \neq P_k$ | Proportional to the quasi-rent of the variable costs, $1/D^{\phi}$ and $P_k$ |

[1] Non-monetary cost associated to distance.

Table 1. Alternative strategies of spatial allocation of effort.

Considering the $SAE_{kht}$ function at least four types of distributions that account for spatial variations in fishing intensity can be described:

### 4.1 Case 1: Small-scale littoral fisheries.

For intertidal and sandy beaches bivalve fisheries where distance from port to alternative fishing areas becomes irrelevant in terms of transfer costs from ports to alternative fishing areas ($\theta = 0$), the corresponding friction of distance is also zero ($\phi = 0$), and the probability of find the target species at profitable levels in alternative sites ($P_k$) is not significantly different, then the resulting $SAE_{kht}$ distribution is *proportional to the spatial variations in stock abundance*.

### 4.2 Case 2: Small scale fisheries in bays, coastal lagoons and estuaries.

Where transfer distances from port to alternative fishing grounds are relevant ($\theta > 0$), but non-monetary costs are negligible (friction of distance, $\phi = 0$) because of easy fishing operation and navigability in naturally protected (from wind and wave action) fishing grounds, and again the probability of find the target species at profitable levels in alternative fishing sites is again not significantly different, then the resulting $SAE_{kht}$ distribution is *proportional to spatial variations of the quasi-rent of the variable costs.*

### 4.3 Case 3: Fisheries in exposed coastal zones.

When ($\theta > 0$), the friction of distance is substantial ($\phi > 0$) and $P_1 = P_2 = \ldots = P_k$ , the $SAE_{kht}$ distribution is proportional to the quasi-rent of the variable costs, and inversely related to the friction of distance from port alternative fishing grounds.

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962. [A bioeconomic model is developed to determine optimal harvest allocation between "offshore" and "inshore" fleets exploiting a single fish stock in sequential fisheries. The socially optimal policy for maximizing total discounted rent is determined in terms of optimal escapement levels in each fishery. Whether exclusion or coexistence of the two fleets occurs under open access and under optimal management is found to depend primarily on inshore/offshore price and cost ratios, together with biological parameters related to the age structure of the fish stock. The authors discuss how fishery regulations, such as separate landings taxes imposed on each fleet, can be used to jointly optimize open-access exploitation in sequential fisheries.]

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**Biographical Sketch**

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Resource Economics from Michigan State University. He has taught for 20 years graduate and undergraduate courses in Fisheries and Aquaculture Bioeconomics. His academic work has been published in scientific journals that include Marine Resource Economics, Journal of Aquaculture Economics and Management, Fisheries Research, Philosophical Transactions of the Royal Society, among others. He is author of two books in his field of specialization. He has taught specialized courses in bioeconomics organized by FAO and UNESCO in Chile, Uruguay, Peru, Colombia, Venezuela, Panama, Guatemala, Cuba, and Trinidad, and has participated in Expert Consultations invited by FAO in Lysekil, Sweden (1995), Australia (1998), Rome (2000), Mauricio (2003), and Cambodia (2004). He has been guest and visiting professor in the Ocean University of Taiwan (Keelung), Center for Marine Studies of the University of Delaware, and the Institute of Aquaculture of the University of Stirling. He is currently Chairman of the Scientific Advisory Group of WECAFC (West Central Atlantic Fisheries Commission), and Board member of the North American Association of Fisheries Economists (NAAFE).