ICES Journal of Marine Science, 57: 858–865. 2000
doi:10.1006/jmsc.2000.0816, available online at http://www.idealibrary.com on IDEAL®

Incorporating the spatial component of fisheries data into stock assessment models

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Booth, A. J. 2000. Incorporating the spatial component of fisheries data into stock assessment models. – ICES Journal of Marine Science, 57: 858–865.

Fisheries-dependent and independent data have a strong spatial component. These data are also multi-dimensional, making them difficult to visualize and analyze, prompting the use of spatial analysis to facilitate an understanding of their relationships. One aspect of fisheries data that is often ignored is the distribution and abundance of a particular resource and the fishing patterns of its harvesting fisheries. In order to improve management advice, stock assessors need to incorporate the spatial component of these data into an existing assessment framework. This paper presents a three-dimensional visualization of the age-structure and fishery dependent and independent data associated with the sparid fish *Pterogymnus laniarius* on the Agulhas Bank, South Africa. A spatially-referenced spawner biomass per-recruit model is developed to illustrate the applicability of incorporating spatially referenced information in providing management advice. The model provided evidence that, even on a spatial scale, fishing mortality is significantly correlated to fishing effort. Areas of high levels of spawner biomass are noted, all of which corresponded to those geographic areas with a combination of low fishing effort and high adult biomass.

Key words: visualization, spatial analysis, age-structured stock assessment model, spawner biomass-per-recruit, fishing effort, *Pterogymnus laniarius*.

Received 21 December 1998; accepted 11 January 2000

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Introduction

It has long been realized that almost all fisheries data, collected from both commercial and research sources, has a spatial component. This component is mainly ignored, with the exception of the determination of absolute abundance indices using geostatistical analyses such as kriging in conjunction with variographic analysis (Sullivan, 1991). Ignoring these spatial trends can often provide inaccurate relative abundance estimates (Swartzman *et al.*, 1992) and lead to misleading interpretations of the various aspects of a species' biology, such as its distribution, growth, reproductive and feeding patterns. As a result, an investigation into spatial trends relating to key population parameters needs serious consideration as it could elucidate migratory patterns, nursery areas and feeding grounds.

To date, there has been little attempt to incorporate the inherent spatial variability of a stock's age-structure, maturity, selection or growth patterns and commercial catch data into a stock assessment framework. This is of concern, as commercial catches are geo-referenced. By neglecting this spatial component existing stock assessment models assess the status and productivity of the stock based on lumped or pooled catch-at-age data, fishery-independent survey indices and key population parameters. If a stock is relatively resident and only specific areas are fished, then it would be reasonable to assume that only a portion of the stock would be subjected to fishing mortality. This could result in a non-spatial assessment, which might suggest that the entire stock is moderately overfished when in fact from a spatial perspective, only that portion of the stock subject to fishing pressure is overfished. The remaining portion of the stock would be in a relatively pristine state.

This paper presents the spatial component of research survey and commercial fishery data collected on the commercial sparid fish *Pterogymnus laniarius*, on the Agulhas Bank, South Africa. An age-structured, spawner biomass-per-recruit model was developed and tuned, using observed spatially disaggregated age-frequency data, to provide spatially referenced management advice on the status of the resource.

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The gear selectivity and maturity patterns were considered to be temporally and spatially invariant over the study period and are represented by a logistic ogive of the form:

$$S_a = \frac{1}{1+e^{-(a-a_{50})/\delta}},$$

where S_a is the maturity/selectivity of the gear on a fish of age a, a_{50} is the age-at-50%-maturity/age-at-50%-selectivity, and δ is the parameter which determines the width of the age-specific maturity/selectivity function.

The observed fishing mortality rate (F_{ij}) was estimated by calculating the negative slope of log-transformed fully selected number of fish-at-age at geographic location, ij.

Results

From both the age-structured and disaggregated life-history stage data, distinct patterns of distribution were evident when all trawl surveys were pooled between years 1988 and 1995 (Figs 1 and 2). Juvenile fish (<13 cm TL or 2 yr of age) were distributed in a narrow area over the central Agulhas Bank within the 60–90 m isobath between 20–21°E, forming a nursery area. Sub-adult fish (14–23 cm TL or 3–4 yr of age) exhibited an intermediary distribution pattern between juvenile and adult fish, becoming more widely distributed than juvenile fish, yet more restricted than adult fish. Sub-adult fish were also distributed predominantly over the central Agulhas Bank (20–22°E), up to Plettenberg Bay, although at depths greater than juvenile fish. Adult fish (>24 cm TL or >4 yr of age) were widely distributed, inhabiting deeper waters. Three distinct areas of high adult density were noticed: off the Central Agulhas Bank, west of Plettenberg Bay and east of Port Elizabeth. This confirms anecdotal evidence from fishermen who report high adult biomass in these areas.

The spatial distribution of total *P. laniarius* biomass followed a pattern similar to the adult density data due to the domination of the biomass estimates at each geographic location by the larger and heavier fish (Fig. 3). During the 1995 surveys in spring and autumn, all three dominant areas of abundance were highlighted. Biomass indices represented two-dimensionally for four-depth strata between 1986 and 1995 are illustrated in Figure 4. The indices reveal that there is an increasing trend in abundance for *P. laniarius* over the Agulhas Bank with fish more abundant between 100 and 200 m.

The spatial distribution of Cape hake directed fishing effort is illustrated in Figure 5. Three areas of high effort were evident. These were areas inshore at approximately 21°E 34°30′S and offshore at approximately 20°E, 35°30′S and 25°E 34°S. The inshore areas (<140 m) are utilized by the sole and hake directed inshore trawl

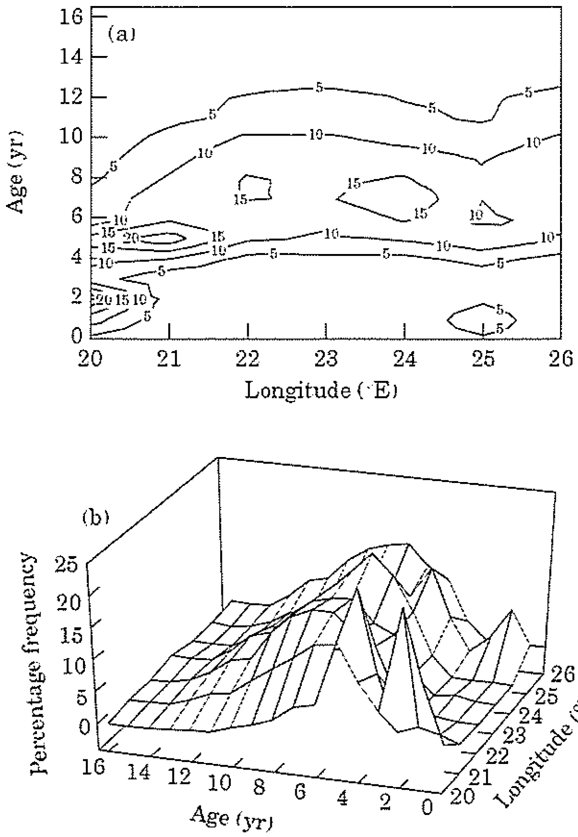

Figure 1. Spatial age structure of the *Pterogymnus laniarius* stock on the Agulhas Bank, South Africa. The age-frequency distributions have been normalized to the total catch in each degree longitude. The data are represented in three-dimensions either in the form of contour (upper panel) or surface response plots (lower panel).

vessels, whilst the offshore fleet directs effort on the Cape hakes in water deeper than 160 m.

The results of the model fits to the data were reasonable. In those cases where fish were well represented in all age classes the model produced meaningful results with little evidence of model misspecification. The model fared poorly, however, in those areas where there was a predominance of either old or young fish. The spatial distribution of fishing mortality obtained from the catch-curve analysis was interpolated and illustrated in Figures 6 and 7. These results show a similar distribution as the fishing effort data illustrating that the fishing mortality was highest where the fishing pressure was the most intense. The relationship between all the latitude–longitude observed fishing effort and fishing mortality using least-squares regression was statistically insignificant ($R^2=0.20$; p value=0.14) (Fig. 8). When two highly influential outliers were omitted from the analysis, the results were significant correlated ($R^2=0.65$; p value <0.001). Using the pooled longitude data, fishing mortality was significantly correlated to fishing effort ($R^2=0.59$; p value=0.04).

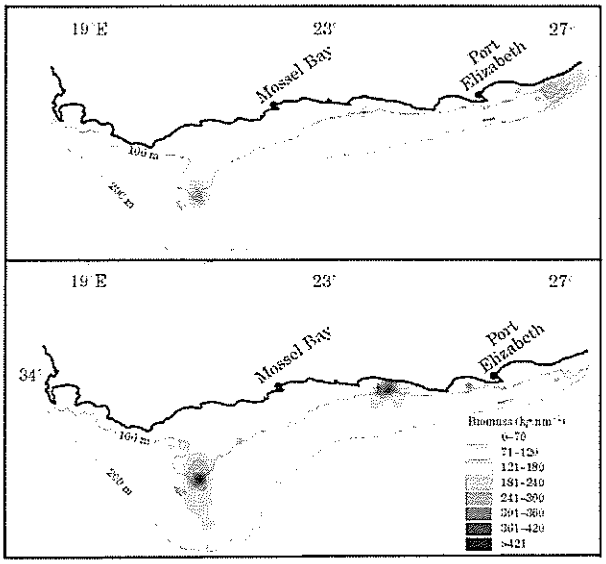

Figure 3. Spatial distribution of *Pterogymnus laniarius* biomass on the Agulhas Bank, South Africa during spring (upper panel) and autumn (lower panel) during research cruises in 1995.

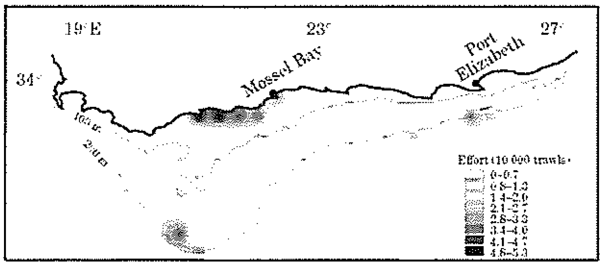

Figure 5. Spatial distribution of commercial Cape hake (*Merluccius* sp.) directed trawl fishing effort (10 000 trawls) on the Agulhas Bank, South Africa during 1996.

Discussion

Fisheries data, be it fishery-dependent or independent, can be represented easily in two-dimensions, such as abundance over time, abundance over a specific area or catch over time. This approach unfortunately often loses the spatial information associated with the survey and frequently becomes tedious to visualize and interpret when the datasets are large. The underlying reason for this problem is that survey data can only be represented accurately in at least three-dimensions, such as latitude, longitude and abundance or effort. If a temporal component, or physical and environmental variables sampled at each survey location are also considered, the dimensionality will increase and visualization will be impossible. As a consequence, if fisheries data are to be fully understood, the data must be reduced to at most three-dimensions, with the response variable as a function of its geographical co-ordinates.

If fisheries data that are commonly available are to be correctly interpreted new methods need to be developed

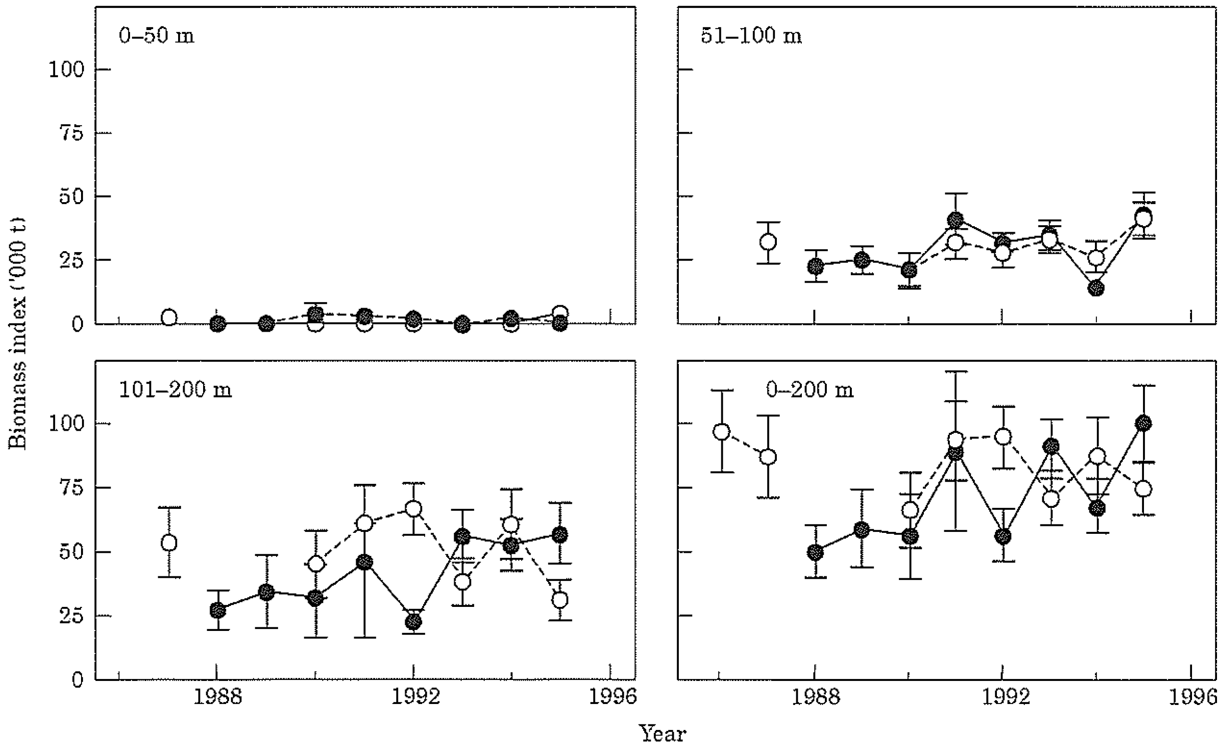

Figure 4. Biomass indices for *Pterogymnus laniarius* collected from four depth strata on the Agulhas Bank, South Africa. Data were collected either in autumn (April/May – ○) or in spring (September/October – ●) between 1988 and 1996.

embarking down the road of hypothesis testing. The development of real-time graphical visualization tools such as virtual reality and animation show definite potential as the temporal component of the data can be easily incorporated into the analysis.

From the age-structured data presented spatially it appears that the panga has a distinct ontological shift in distribution with respect to size and age. This was noticeable in the distinct nursery area for immature fish over the central Agulhas Bank. It was noted that after sexual maturation, at approximately four years of age (>23 cm TL) (Booth and Buxton, 1997b; Booth and Hecht, 1997; Booth, 1998), corresponding to the stage when fish feed predominantly on harder shelled, soft-stratum prey, a large proportion of the adult population migrated eastwards.

The effort data used within this study have been obtained from fishing vessels that principally target Cape hake (and Agulhas sole in the inshore sector). Of all the bycatch species caught incidentally, *P. laniarius*, is considered to be one of the most important, principally due to the large quantities caught and landed. The effort data, therefore, are merely a proxy for the fishing effort imposed on the *P. laniarius* stock on the Agulhas Bank. Low fishing mortality estimates were noticeable for the *P. laniarius* stock on the south coast, just west of Mossel Bay despite the high fishing effort in this area. This discrepancy points to the unsuitability of using directed effort from a fishery whilst assessing the status of one of its bycatch components. The inshore area is heavily fished by the sole directed trawl fleet where the substratum is generally soft, comprising of mud the preferred habitat for this species (Japp *et al.*, 1994). In contrast it appears that *P. laniarius* prefers the harder ground of low and high-profile reef, some of which is accessible to conventional trawl gear and hook-and-line fishers (Japp *et al.*, 1994). *P. laniarius* is, however, caught in considerable amounts by the hake-directed trawlfleet as they appear to be sympatrically distributed with the shallow water Cape hake *M. capensis* (Booth *et al.*, 1999). It is suggested that if a similar analysis were to be conducted on species such as the Cape hakes or on the Agulhas sole, a similarly and possibly clearer trend between fishing mortality and fishing effort would be evident. Despite the problems inherent in the effort data there are clear trends from the modelled output. There was a positive correlation between fishing mortality and fishing effort. Whilst these results could be construed as stating an obvious fact, there is no published evidence available to support this trend from a spatial perspective.

The simple per-recruit model provides further evidence to support the suggestion that fishing grounds that are heavily fished impact the stock to a greater extent than those areas that are lightly fished. Hence overall estimates of fishing mortality derived from commercial data would be biased towards the more heavily fished areas or, if the data were pooled, it would give only an overall perspective on the relative status of the stock. In this situation it would seem appropriate to incorporate spatially referenced data with more complicated and computationally intensive stock assessment methodologies. Examples are VPA (Pope and Shepherd, 1985; Butterworth and Andrew, 1984; Butterworth *et al.*, 1990), age-structured production modelling (Booth and Punt, 1998), adaptive frameworks (Gavaris, 1988) and integrated analysis (Deriso *et al.*, 1985). Overall the results of the per-recruit analysis support those obtained using non-spatially disaggregated per-recruit (Booth and Buxton, 1997a) and age-structured production modelling (Booth and Punt, 1998), and suggest the spawner biomass-per-recruit of the stock is currently at least >60% of pristine levels.

Optimal management areas can be obtained by selecting those areas that are the most suitable for fishing. Using a spatial approach the biomass of the stock can be easily disaggregated by region or life history stage, thereby facilitating and improving age-structured modelling. The most suitable areas would therefore include those in which fishing effort, and hence fishing mortality, is reduced on vulnerable life history stages and to those areas where fishing effort is unsustainably high. These would include nursery areas or annual migrations of spawner biomass to specific spawning areas. In the case of *P. laniarius*, only the former constraint applies as adult fish spawn throughout the year throughout their distributional range (Booth and Buxton, 1997b). As *P. laniarius* is also caught predominantly as bycatch in the demersal trawl fishery (Booth and Buxton, 1997a; Booth and Punt, 1998), optimal areas for harvesting should also include most of the areas fished by the existing demersal trawl fleet. This includes most of the Agulhas Bank. In both optimum-fishing scenarios presented by Booth (1988) in Figure 10, the fleet should be restricted only from fishing on the mid-central Agulhas Bank area. If these results are incorporated with the results from this study then *Pterogymnus laniarius* directed effort should be restricted to the eastern Agulhas Bank, east of 23°. This would protect effectively the nursery area for this species despite there being evidence for a relatively high level of adult biomass in the region.

The value of spatial analysis in identifying trends in fish distribution and abundance and to incorporate trends in assessment models and fisheries management is easily appreciated. For the reasons given above the results from this study are being used in the development of a larger Fisheries Information System including the spatial analysis of all other sympatric species and the fishing patterns on the Agulhas Bank. Each spatially referenced dataset will be used in the development of a new modelling approach to manage simultaneously the resources in question and the fisher communities that exploit them.