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Is catchability density-dependent for schooling prawns?

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Abstract

Banana prawns, *Penaeus merguiensis*, in the Gulf of Carpentaria, Australia typically form dense aggregations during a fishing season. It has been speculated that catchability decreases significantly as the fishing season progresses and stock size decreases. We used commercial catch effort data from 1987 to 2004 for three stocks in the Gulf to investigate whether density-dependent catchability exists in this species of aggregating penaeid. We developed two stochastic models based on an improved depletion method, one assuming a linear relationship between catchability and abundance and the other assuming a nonlinear power function between catchability and abundance. A stock-specific annual catchability coefficient, initial biomass, and a shape parameter of the power function were estimated using maximum likelihood or hierarchical Bayesian approach (for density-independent catchability models). For the majority of the datasets, the two models result in similar estimates. Although a weak but statistically significant density-dependent catchability, either positive or negative, was detected in about one fifth of the datasets, there is no clear pattern that points to positive density-dependence as suggested by previous studies. With all years and stocks combined, the density-dependent parameter in the second model has an overall mean of −0.03 and a standard deviation of 0.57 from all datasets, and its distribution looks approximately normal. However, a between year negative power function relationship between catchability and abundance appears to exist in this prawn species.
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1. Introduction

The catchability coefficient is one of the key parameters for fish stock assessment. This quantity, commonly denoted as q, can be interpreted as the probability of capturing one particular individual from the population by one unit of effort, or the proportion of fish in the population being caught per unit of effort. Catchability has been widely considered as a constant for a particular fishery, although it has been recognized that catchability is determined by availability and vulnerability of fish (Francis et al., 2003), which in turn are affected by many factors such as distribution of fish, abundance, fish behaviour, population biology, environmental conditions, fishing gear efficiency, distribution of fishing fleet, and fishing strategy, etc. (Swain and Sinclair, 1994; Arreguin-Sanchez, 1996; Addison et al., 2003; Salthaug and Aanes, 2003). Debate on whether q depends on abundance has continued since Paloheimo and Dickie (1964) suggested that catchability would change with abundance. It is conceivable that catchability may not be constant due to such factors as random variation, gear competition or cooperation, and spatial and temporal effects (Quinn and Deriso, 1999). Among the publications that assert that q varies with abundance, the majority of them claim that catchability is a negative power function of abundance, i.e., q increases as abundance declines (Bannerot and Austin, 1983; Shardlow and Hilborn, 1985; Angelsen and Olsen, 1987; Crecco and Overholtz, 1990; Rose and Leggett, 1991; Arreguin-Sanchez, 1996). Because of the importance of this parameter, there has been extensive research on the effect of abundance on catchability. However, the majority of work comes from fish species. There are few studies on the relationship between catchability and abundance of *Penaeus* species (but see Griffin et al., 1997 on the standardization of fishing effort of a shrimp fleet; Perez and Defeo, 2003 on the catchability and CPUE of shrimps; Die and Ellis, 1999 on the depletion of aggregated prawns).

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The Northern Prawn Fishery (NPF) is one of the most valuable fisheries in Australia. The NPF has produced 2157–7245 tonnes of banana prawns (*Penaeus merguiensis*) annually since 1987 (Perdrau and Garvey, 2004). Banana prawns in the Gulf of Carpentaria form dense aggregations that are targeted by trawl vessels. Using logbook data from 1991 and 1992, Die and Ellis (1999) estimated that in the first 3 weeks of the fishing season the number of aggregations decreased by 83% and the average biomass of an aggregation decreased by 93%. Together, they estimated that a decline of 99% of the total biomass occurred in the first 3 weeks. This was considerably greater than the 66% decrease that can be estimated from catch per unit effort data. They suggested that catchability is positively related to stock abundance: catchability decreases significantly as the stock size decreases.

Vance et al. (2003) conducted the first stock assessment analysis for banana prawns in the NPF. Based on Die and Ellis's suggestion of a positive power function between q and biomass, they estimated a positive power function for three of the seven stocks in the NPF. Since the model they used was considered as preliminary, they strongly recommended that further research was needed and identified that the relationship between catchability and abundance is of particular importance.

This paper is motivated by Die and Ellis's research and the quantitative modelling by Vance et al. (2003). Our main objective is to investigate whether catchability changes as abundance declines over the fishing season.

The primary source for our study is commercial logbook data. We use a binomial model to capture the dynamics of the fishable population over time during each fishing season. The model is based on the concept of Leslie and DeLury removal or depletion methods which have been widely applied in fishery research (Mahon, 1980; Farman et al., 1982; Cowx, 1983; Akamine, 1990; Akamine et al., 1992; Hilborn and Walters, 1992; Riley and Fausch, 1992; Maceina et al., 1993, 1995; Rider et al., 1994; Volstad et al., 2000; Burridge et al., 2003; McAllister et al., 2004; Young et al., 2004; Wright et al., 2006). The traditional depletion methods assume that: the population is closed, i.e., there is relatively little emigration and immigration during the fishing period; the catchability and natural mortality are constant throughout the fishing period; a linear relationship holds between catch rate and abundance. In our study, we also assume that recruitment into the fishable population and migration in and out of the fishing grounds are insignificant during the relatively short fishing season. However, because our main interest is to test whether catchability is dependent on population density, in one of our models we assume that the catchability coefficient varies over time as abundance decreases in the season. We did not use the traditional regression approach, rather used more robust maximum likelihood estimation (MLE) (Schnute, 1983; Loneragan et al., 1995) for each stock-year, and used hierarchical Bayesian model (HBM) for meta-analysis of combined data (Liermann and Hilborn, 1997; Adkison and Su, 2001; Harley and Myers, 2001; Su et al., 2001; Rivot and Prevost, 2002; McAllister et al., 2004). Also, instead of modelling catch per unit effort data, we directly modelled the catch as a binomial process, an approach similar to Schnute (1983), Bedrick (1994), Warren (1994), Loneragan et al. (1995), Wang and Loneragan (1996), and Wang (1999). Further, we expanded the technique by incorporating stochastic fishing processes (Dupont, 1983; Sampson, 1988), natural mortality, overdispersion, and a nonlinear relationship between catchability and abundance into our modelling. However, HBM had difficulties dealing with models that include a density-dependent catchability function. As a result HBM was applied only to density-independent catchability models. Hence, we focused on the MLE results for the density-dependent and density-independent catchability models to examine the relationship between catchability and abundance within each fishing season. We reported the HBM results for the density-independent models only to examine the across-year relationship between catchability and abundance. The detailed comparisons between MLE and HBM for density-independent catchability models will be reported elsewhere (Zhou et al., in review).

2. Methods

2.1. Data

The primary data come from augmented commercial logbook records (personal observations). There are 11 banana prawn stock regions in the NPF. Among these, three major stocks are found in the southeast Gulf of Carpentaria (SE GoC, Stock 9), east Gulf of Carpentaria (E GoC, Stock 10) and Albatross Bay (Stock 11). The E GoC stock includes statistical areas of Keerweer, Edward, and Mitchell as defined by the Australian Fisheries Management Authority (Perdrau and Garvey, 2004). Other stocks typically have too low catches in many years to allow a complete analysis using the model described below. The NPF started in the late 1960s. It was a year-round fishery in the early years. Since 1987, the fishing season for banana prawns has been largely constrained to less than 2 months each year. Such a management practice provides ideal data for depletion analysis. We have a total of 54 datasets from 1987 to 2004 from these three stock regions. However, there were too few fishing days and too little catch on two occasions: the SE Gulf in 1990 and Albatross Bay in 2003 to allow for any analysis. Therefore, we excluded these two datasets.

2.2. Density-independent catchability model

Catch in a fishery can be expressed in a classical form as (Quinn and Deriso, 1999):

$$C = \frac{qE}{z} N_0 (1 - \mathrm{e}^{-z}), \tag{1}$$

where C denotes catch, q the catchability coefficient, E the fishing effort, z the total instantaneous mortality, and N_0 is the initial population size of target species. The total mortality $z = F + m$, where instantaneous fishing mortality $F = qE$, and m is the instantaneous natural mortality. From this relationship q is derived as

$$q = \frac{C}{E\bar{N}}, \tag{2}$$

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