Fisheries Research 158 (2014) 5–14

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Fishery selection and its relevance to stock assessment and fishery management

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ARTICLE INFO

Article history:
Received 9 June 2013
Received in revised form 8 October 2013
Accepted 10 October 2013
Available online 7 November 2013

Keywords:
Fishery selection curves
Selectivity
Spatial population dynamics

ABSTRACT

Fishery selection (selectivity for short) is the term often used to describe the phenomenon whereby a fish stock experiences mortality due to fishing that is age- or size-specific. Selectivity operates both at a local scale, as in the direct interactions of individual fish with the fishing gear (contact selection), and at a stock-wide scale (population selection), as evidenced by the differential rates of fishing mortality-at-age that are generally observed in stock assessment results. All age-structured stock assessment models have some form of fishery selection to modulate the impact of fishing mortality on differing age-classes, but selection coefficients, from a stock assessment viewpoint, generally are nuisance parameters rather than a focus of attention. This paper provides an overview of the three main processes that contribute to and influence population selection: (1) physical sorting by the fishing gear or differential behavioral responses of the fish to the gear produce the phenomenon of contact selection; (2) differing selection properties of different types of fishing gear (e.g., trawl versus longline) in turn generate a composite selection curve that is a weighted average of the different kinds of contact selection; and (3) when the fish are not well mixed spatially, then the spatial distribution of fishing relative to the spatial distribution of the fish also affects population selectivity. Fishing mortality-at-age estimates derived from a published Virtual Population Analysis of Scotian Shelf haddock are used to illustrate the diversity of shapes that can be seen in population selection curves and their considerable temporal variability. A spatial model for fishery age-selectivity is then used to demonstrate that the maximum relative yield harvested from a stock can be a function of both contact selection and the spatial distribution of fishing.

1. Introduction

Because fishing operations capture collections of fish whose composition differs from the mix of species, sizes, and ages that are actually present in the water, the process of fishing is fundamentally selective. A variety of mechanisms can cause this phenomenon. Fishers deliberately deploy gear that increases their chances of catching those fish that are highly valued and avoiding those that are not. In addition to the selective nature of the gear, because fish are not uniformly distributed, fishers may also be able to deliberately operate their gear in areas with disproportionately high concentrations of the more desirable species or sizes of fish. Also, because fish distributions often vary diurnally or seasonally, the timing of fishing operations is yet another potential factor influencing selectivity. Most modern approaches to modeling fish stock dynamics employ an explicit age- or length-structure that directly incorporates selection coefficients to account for fishing mortality that varies by age or length (Quinn and Deriso, 1999). The term “selective fishing” is also used in the fisheries science literature in reference to fishing techniques that attempt to avoid the bycatch of certain species that are considered vulnerable to overfishing (e.g., the mandatory release of wild salmon, Lawson and Sampson, 1996) or that have special legal status (e.g., the use of turtle excluder devices; Sala et al., 2011). This paper will use the terms selection and selectivity in a single species context, in reference to the age- or length-specific effects of fishing on a single fish stock.

The processes that can produce selectivity operate at different spatial scales (Millar and Fryer, 1999). Not all fish that directly encounter fishing gear are caught and retained by the gear. This first form of selection, contact selection, has been the focus of numerous published studies that have measured how fish are able to escape from gear they encounter, either because of their behavioral traits (e.g., Ryer, 2008) or because of physical sorting by size, as in larger fish being more likely than smaller fish to be retained in the meshes of gillnets (e.g., Millar, 2000) or trawls (e.g., Somerton et al., 2011). A second form of selectivity, sometimes described as availability, is due the possible differential availability of fish to the gear. For

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http://dx.doi.org/10.1016/j.fishres.2013.10.004

example, fish that associate with extremely rough substrates may be available to hook-and-line gear but unavailable to trawls. The third form of selectivity, population selectivity, reflects the combination of the other two forms of selectivity, integrated across the entire spatial region occupied by the fish stock. Population selectivity is the selection process relevant to assessing and understanding a stock's dynamics (Scott and Sampson, 2011). Population selectivity, which can also be described as fishery selectivity because it measures differential mortality due to fishing, is the focus of this paper.

The paper begins with definitions of terminology and a review of some of the fundamental processes that result in fishery selectivity, including contact selection by a single type of gear and by mixtures of different gear-types. Then the simple spatial model of Sampson and Scott (2011) is reviewed to illustrate the effects of fish availability on selectivity at the population level. Subsequently, selection curves derived from a Virtual Population Analysis, following the approach of Sampson and Scott (2012), are presented to demonstrate the shapes and temporal variability that apparently can occur. Lastly, in an extension of previous work, the spatial model of Sampson and Scott (2011) is combined with the standard equations for growth and reproduction to form an equilibrium model for spawning biomass and yield, which is used to explore how maximum equilibrium yield is influenced by the spatial distribution of fishing.

2. Some selectivity fundamentals

The processes leading to size- and species-selection by fishing gears have been studied in detail by fishing gear technologists (Fridman, 1986; Walsh et al., 2002) and by fishery scientists concerned with the design of research surveys (Gunderson, 1993; Walsh, 1996). There are well established procedures for measuring the escapement of fish, standard terminology for describing technical details of the gear and rigging, and a large body of literature documenting previous experiments and research. In contrast there has been very little research focused on how contact selection by the fishing gear interplays with fish availability to generate selectivity at the broad level of a population. This section will attempt to lay out a cohesive framework for describing and exploring the elements and properties of population selectivity.

2.1. Selection coefficients and selection curves

Many of the equations commonly used in fisheries to model population dynamics treat age and time as discontinuous phenomena, with the fish discretized into a set of distinct age-classes. When the instantaneous rates of fishing mortality differ by age-class, then the selection coefficients measure the relative fishing mortality experienced by each age-class. How one expresses a relative rate of fishing mortality is arbitrary. In this paper, as is common practice on the Pacific side of North America, selection coefficients are standardized so that the age-class experiencing the maximum rate of fishing mortality has a selection coefficient value of one, and in any given year the selection coefficients (S) are related to the fishing mortality rates (F) by age (a) as follows:

$$F_a = \max(F_a)S_a = FS_a \quad (1)$$

where F, with no subscript, is the full instantaneous rate of fishing mortality. Because of the term $\max(F_a)$, most age-classes suffer fishing mortality at rates less than F, but at least one age-class experiences the full F. The S_a are the selection coefficients, and they define population selectivity. It is common to describe the S_a values for a given year as a selection curve, even though they are a set of discrete numbers (at least one of which has the value 1).

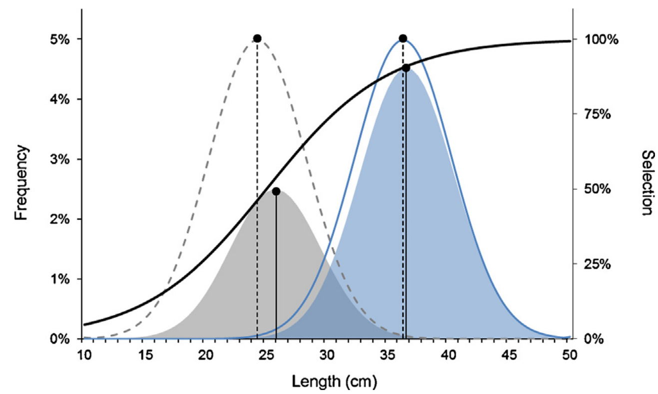

Fig. 1. An illustration of the effect of length-based selection (heavy black line) on the average length-at-age of retained fish (the two interior shaded normal distributions) compared to the population at large (the two broader distributions).

Rather than having to estimate as many parameters as there are age-classes to describe selectivity, many stock assessment models reduce the number of selection parameters by using simple functional forms to represent selection curves. Common forms include the S-shaped logistic function, which has maximum selection at the oldest age-class, and the so-called double-logistic function (Methot, 1990), which can take on a domed shape, with maximum selection at an intermediate age. Although it is common to assume that contact selection by trawl gear will have an asymptotic form, because all fish greater than some size will be retained by the trawl meshes, the largest individuals may be able to outswim the net and thereby avoid capture. Gear-types such as gillnets can be quite selective for particular sizes of fish and a bell-shaped Gaussian selection curve is often assumed (Millar and Fryer, 1999).

Another common assumption in certain age-structured stock assessment models is that selection curves do not vary from year to year. Instead, they are treated as being constant within time-blocks or for the entire modeled period. This assumption of separability (fishing mortality by age and year is the product of an age effect [selectivity] and a year effect, $F_{a,y} = S_a F_y$; Pope and Shepherd, 1982) greatly reduces the number of selection coefficients that must be estimated. However, for stocks with highly variable recruitment the fishery may tend to target the sporadic dominant year-classes, in which case one would expect to see periods of consecutive years in which there are systematic progressions in the ages of peak selection. In contrast to models that use the simplifying assumption of separability are the age-structured assessment techniques such as Virtual Population Analysis (VPA, Gavaris, 1988; Shepherd, 1999), which essentially have independent selection coefficients for each age in every year. An intermediate level of complexity is achieved by assessments that have selection coefficients constrained by smoothing functions (Aarts and Poos, 2009) or that are modeled as constrained random walks (Martell and Stewart, 2014).

2.2. Age- versus length-based selection

Because fish growth causes size and age to be highly correlated, the processes that produce selection of fish by size (e.g., retention by mesh netting) also generate selection by age. Similarly, processes that generate selection by age (e.g., gradual ontogenetic movement to deeper water) also produce selection by size. However, selection by size may not be equivalent to selection by age. Consider the simple example of a fishing process that selects fish based on a logistic function of length (Fig. 1). Fish whose lengths fall in the range where the selection is rapidly changing are more affected by selection than fish whose lengths fall in the range where selection is flat. Hence, the distributions of length-at-age of fish retained by