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Inherent bias in using aggregate CPUE to characterize abundance of fish species assemblages

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ABSTRACT

We have analyzed the practice of assessing an assemblage of fish species in a multispecies fishery on the basis of aggregate catch per unit effort (CPUE), which is the summed catch of all species per unit of effort. We show that at the onset of fishing or of a large positive or negative change in fishing effort, aggregate CPUE will be hyper-responsive, that is, relative change of aggregate CPUE will be greater than that of aggregate abundance. We also show that as the fishery reaches equilibrium, the aggregate CPUE in most circumstances will continue to be hyper-responsive, with a greater relative change from its value at the start than the aggregate abundance. However, there are less likely circumstances in which the aggregate CPUE will be hyper-stable compared to aggregate abundance. The circumstances leading to hyper-responsiveness or hyper-stability depend on the distribution of productivity and fishery vulnerability parameters among the species in the aggregation.

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1. Introduction

As the demands on fishery management have grown from consideration of a single target species harvested by a single gear to multiple species harvested by multiple gears, the challenge for fish stock assessment has grown commensurately and is evolving into notions of community or ecosystem assessment in which an assemblage of species is assessed in aggregate. A preferable strategy for evaluating the status of a community of species would be to incorporate biological and fishery information on each species into an integrated model of the community. However, in some cases, assessment of individual species and their interactions is not feasible because of the sheer number of species encountered in the fishery or because catches are not reported to species level. This difficulty predates the call for ecosystem assessment and has led to the strategy of treating the composite catch of all species as if it were the catch of a single species, for example, Marten and Polovina (1982), Ralston and Polovina (1982), Agnew et al. (2000), Halls et al. (2005), Lorenzen et al. (2006). Myers and Worm (2003) cite a rapid drop of aggregate catch per unit effort (CPUE) of large pelagic marine predator fishes in many longline fisheries in support of their claim that world-wide populations of large predatory fishes have declined to less than 10% of their abundance prior to the onset of industrial fishing.

In countering Myers' and Worm's (2003) assertion, Hampton et al. (2005) assert that aggregate catch per unit effort cannot be a valid index of aggregate abundance. Furthermore, Maunder et al. (2006) claim that declines in aggregate CPUE tend to exaggerate declines in aggregate abundance. Our purpose here is to show that such a bias exists even in the ideal situation where the CPUEs of individual species are valid indices of their individual abundances.

2. Analysis

In the assessment of single species, CPUE is often taken to be an index of abundance on the assumption that catch is proportional both to abundance and to fishing effort, i.e.

$$C_i = q_i E N_i \tag{1}$$

where C_i is catch of species i, q_i is the proportionality constant, or "catchability", E is effort,[1] and N_i is the abundance, whence it is easy to see that CPUE, C_i/E, would be an index of abundance for species i under the assumptions that catchability is constant in time and

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[1] Note that effort in aggregate CPUE must be identically defined for all species. Therefore, E is not indexed by species. Species specific aspects of the gear are relegated to the units of q_i.

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effort is a good measure of the effective magnitude of deployed fishing gear. Both assumptions are questionable unless the effort data have been appropriately standardized to account for variation in effective magnitude of fishing gear and other departures from Eq. (1). But assuming that the data are well standardized and Eq. (1) is true for individual species, we want to examine if the proportionality in (1) still holds for aggregate catch given by

$$C^{\mathrm{T}} = \sum C_i = \sum q_i E N_i \tag{2}$$

and therefore whether aggregate CPUE given by

$$\mathrm{CPUE_A} = \frac{C^{\mathrm{T}}}{E}$$

is a valid index of aggregate abundance $N^{\mathrm{T}} = \Sigma N_i$. Eq. (2) can be written analogously to (1) as

$$C^{\mathrm{T}} = (\Sigma q_i p_i) E N^{\mathrm{T}} \tag{3}$$

where $p_i = N_i/N^{\mathrm{T}}$ is the abundance of species i as a proportion of N^{T}. It is evident that the proportionality holds only if $\Sigma q_i p_i$ is constant, and because the q_i are presumed to be constant, the p_i would also have to be constant, i.e. the distribution of abundance across species would have to remain stable as N^{T} changes. This would require the proportional rate of change to be the same for all species. We maintain that the only reasonable way this could happen is if the q_i are the same for all species.

Assume a simplified situation in which all species vulnerable to a fishery are at equilibrium with zero fishing effort. Then at a point in time when a level of fishing effort E is applied, the instantaneous rate of change for any species would be simply the catch C_i because all other forces driving the population are at equilibrium. The proportional rate of change for a particular species would then be

$$\frac{C_i}{N_i} q_i E$$

and the only way for it to be the same for all species is if q_i is the same for all i. With time following onset of fishing, forces of growth and mortality other than fishing come into play. It is possible to imagine that these forces would always precisely balance the differing values of q_i in such a way that the distribution of abundances across species would remain constant while aggregate abundance is changing, but such a supposition is extremely fanciful. In the development of industrial fishing it has been noted that the larger fish species have declined faster and sooner than the smaller species (Pauly et al., 1998). This is both because the larger fishes are preferentially targeted and because they tend to have slower production processes than the smaller fishes. It is to be expected that this picture will often be reflected in single gear, multiple species fisheries where the larger species would initially decline faster than smaller ones because of preferred targeting (and therefore higher catchability), and the lower productivity of the larger species would exacerbate the decline of the larger species.

Thus it is highly unlikely that the proportionality in (3) can be maintained unless catchability across species is constant, which is itself highly unlikely. Therefore, even if the assumptions inherent in Eq. (1) are satisfied, $\mathrm{CPUE_A}$ is not expected to be a valid index of aggregate abundance. We are, however, interested in characterizing the biases to be expected if $\mathrm{CPUE_A}$ is used as such an index, i.e. whether we expect $\mathrm{CPUE_A}$ to exhibit *hyper-depletion* or *hyper-stability* as defined by Hilborn and Walters (1992).

We again envisage a simplified scenario in which a constant level of effort is applied to a hitherto unexploited mix of species and in which, prior to exploitation, all species are at equilibrium abundances which would be their respective carrying capacities. From the onset of exploitation, the abundance of all vulnerable species will decline toward new equilibrium levels (Fig. 1), as will $\mathrm{CPUE_A}$. We investigated two questions mathematically: (1) in the short term, is the initial rate of change in $\mathrm{CPUE_A}$ hyper-depleted or hyper-stable in relation to the rate of change in abundance?... and (2) in the long term as the system approaches a new equilibrium, is the equilibrium level of $\mathrm{CPUE_A}$ hyper-depleted or hyper-stable in relation to the level of aggregate abundance? We also investigated by simulation the overall hyper-depletion versus hyper-stability throughout a time series from onset of fishing towards a new equilibrium.

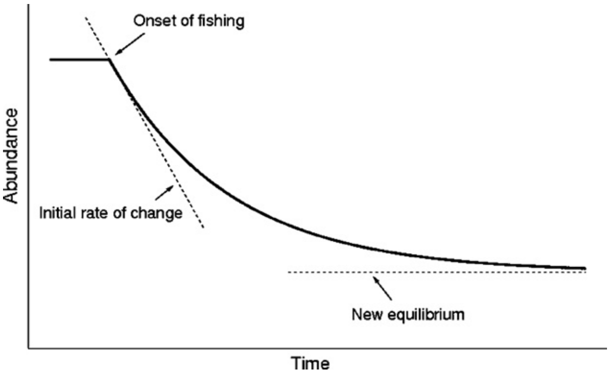

Fig. 1. Simple scenario with transition from equilibrium prior to exploitation to new equilibrium with constant fishing effort.

3. Initial rate of change

We assume that the population of each species is governed by a very general population dynamic equation

$$\frac{\partial N_i}{\partial t} = P_i(N_i)N_i - C_i = P_i(N_i)N_i - q_i E N_i \tag{4}$$

where $P_i(N_i)$ is a net production function of abundance. The functional form of P is unspecified but has the stricture that net production is zero when abundance of species i is at the carrying capacity K_i, for that species. Furthermore, P can take on different functional forms for different species. From this very general model, we find that the initial decline in $\mathrm{CPUE_A}$ in proportion to its level at the onset of exploitation must be steeper than the initial decline in N^{T} in proportion to its onset level, i.e. $\mathrm{CPUE_A}$ exhibits hyper-depletion. The proof is detailed in Appendix A, and numerical examples are shown for a simple two-species case in Fig. 2a and b. Also, in the case where a mix of fish populations is held at some equilibrium level by constant fishing effort and is then subjected to increased effort, Appendix A shows the same result of steeper proportional decline in $\mathrm{CPUE_A}$ than in N^{T}. Furthermore it is shown that when fishing effort is reduced, the recovery of $\mathrm{CPUE_A}$ is steeper than that of N^{T}. Numerical examples are in Fig. 2c and d. It is thus to be expected that fishery driven fluctuations in aggregate CPUE would exaggerate fluctuations in aggregate abundance. Since the exaggeration works in both directions, we could define this property as *hyper-responsiveness*.

4. Equilibrium depletion level

In examining the eventual equilibrium of $\mathrm{CPUE_A}$ in relation to the eventual equilibrium abundance with application of constant effort E, we find that the results do not generalize as well as they do for the initial rate of decline. We have found that it is impossible to say with certainty how the aggregate CPUE at equilibrium will relate to aggregate abundance at equilibrium. This is because the