Estimating and Testing Non-additivity in Fishing Mortality: Implications for Detecting a Fisheries Collapse

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Abstract: Common in many fisheries collapses is a disproportionate increase in fishing mortality at younger ages. One mechanism by which this increase could occur is sufficient depletion of the population at older ages due to strong overfishing, which leads to targeting of younger fish. Thus it is essential for assessments to estimate and test for a change in selectivity in the fishery. We introduce a simple and powerful approach based upon Tukey's (1949) one degree of freedom test for non-additivity. This approach can be applied within any statistical age-structured population model that estimates selectivity. We illustrate the approach with data from Atlantic cod from St. Pierre Bank, Canada. The results show significant non-additivity in fishing mortality which translates into an increase in selectivity on younger ages when fishing mortality is high. This approach also can be applied to the output of an age-structured model that assumes catch-at-age is known without error or to any survey or catch per unit effort data for which estimates of abundance are made by year and age. We believe this approach should be routinely applied in assessments, particularly when overfishing has led to depletion of the overall population or to truncation of the age structure.

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Introduction

Most of the spectacular, rapid collapses of fish populations due to overfishing share a characteristic change in fishery selectivity: there was a reduction of the mean age of selectivity by the fishery as the population collapsed. This is evident in the collapse of herring stocks in the North Pacific (Hourston 1980) and the North Atlantic (Saville 1980), and the cod stocks in the Northwest Atlantic (Myers et al. 1997). This process of targeting younger fish occurs across a wide range of gear types.

A good illustration of this phenomenon is the collapse of the walleye in Lake Erie (Shuter et al. 1979) (Figure 1, upper panel). The population plummeted in the 1950's as overall fishing mortality increased. More interestingly, the selectivity pattern changed, because fishers targeted younger fish as older fish were depleted (Figure 1, lower panel). First the relative fishing mortality on three year olds increased, and later the relative fishing mortality on two year olds increased.

This change in targeting is a key factor in a rapid collapse of a population, because harvesting at a sustainable rate can, with a small change in age of selectivity, become unsustainable, leading to commercial extinction of the stock (Myers and Mertz 1998). This rapid collapse can occur in any fishery if the mean age of selectivity to the fishery decreases below the mean age of maturity, because fish have a relatively small maximum reproductive rate in spite of their high fecundity (Myers et al. 1999). Attempts to harvest a constant quota from a declining stock are especially apt to cause increases in selectivity of younger fish (through alteration of gear or changes in fishing grounds when there is spatial segregation of fish by age). Risk evaluations based on simulations of population trajectories apparently never include this phenomenon, despite the likelihood of its occurrence during stock declines. Realistic evaluations of the risk incurred by employment of a given strategy should not ignore this effect.

Furthermore, statistical age-structured assessment models (Quinn II and Deriso 1999) often make the assumption that fishing mortality is separable into age and year effects. That is, after log transformation fishing mortality can be consider the sum of a year effect and an age effect. This the an assumption of additivity, and is often necessary to reduce the number of parameters sufficiently for reliable estimation. However, this assumption is criticized frequently as being unrealistic. One solution is to make selectivity (or fishing mortality) a random walk process, in which selectivity in one year is equal to that of the previous year plus a random error (Gudmundsson 1994; Ianelli 1996). A large number of additional parameters for these errors must be included, thereby increasing the complexity of the model greatly. A simpler solution would be advantageous in terms of model parsimony.

The purpose of this paper is to provide a simple and powerful approach to estimate and test for an increase in gear selectivity at younger ages associated with increased fishing mortality that can be easily incorporated into almost any age-structured assessment model. Such a solution was developed for two-way tables in the field of statistics more than 50 years ago by the famous statistician John Tukey!

Approach

The fishing mortality associated with any fishery can be separated into an effect of age (i.e., the selectivity of the fishery) and an effect of year (i.e., the intensity of the fishing mortality) (Fournier and Archibald 1982; Deriso et al. 1985). If the fishing mortality in year y on age a is denoted $F_{y,a}$, then the separability assumption is that $F_{y,a} = E_y S_a$, where E_y is the year effect and S_a is the age effect (Quinn and Deriso 1999, section 8.2.5). Usually S_a is set to 1 for those ages of maximal selectivity, so that E_y is the full-recruitment fishing mortality.

If we log transform fishing mortality, and let lower case letters correspond to logarithms (e.g., $\log S_a = s_a$), we can write this multiplicative relationship as an additive relationship, i.e. $f_{y,a} = e_y + s_a$. We are interested in testing a particular systematic departure from this pattern, i.e. we expect that as total fishing mortality goes up that s_a should increase for younger ages.

Tukey (1949) considered a slightly nonlinear function as an alternative to the additive form and showed that a suitable approximation for one degree of freedom for non-additivity (abbreviated ODOFFNA) involves the crossproduct of the deviations of the additive terms from their mean values. In our situation, the log transformed fishing mortality should display a simple form of non-additivity that can be described by a simple addition

$$[1] \qquad f_{y,a} = e_y + s_a + \gamma \tilde{e}_y \tilde{s}_a,$$

where γ is Tukey's (1949) ODOFFNA parameter and the tilde's denote deviations from their means. The ODOFFNA parameter γ can be thought of as a simple control on the age-specific selectivity as the average fishing mortality increases. For ease in implementation, we reparameterize equation (1) as

$$[2] \qquad f_{y,a} = \mu + \tilde{e}_y + \tilde{s}_a + \gamma \tilde{e}_y \tilde{s}_a,$$

where μ is the average log fishing mortality across ages and years. The year and age deviations are implicitly assumed to sum to 0 over their respective subscripts. Conversion of equation (2) back to original units results in

$$[3] \qquad F_{y,a} = \overline{F} \tilde{E}_y \tilde{S}_a^{1+\gamma \tilde{e}_y},$$

in which $\overline{F} = \exp(\mu)$. The latter term in equation (3) is age- and year-dependent, in contrast to the additive model in which it is simply $\tilde{S}_a$. By varying γ, one can produce non-additive patterns that range from nearly additive (when $\gamma = 0$) to those in which the trends in selectivity are completely opposite over time for some ages. Which patterns occur depends on the magnitudes and signs of the deviations and γ.

The implementation of the ODOFFNA parameter is straightforward. Separate log fishing mortality parameters are used for each fleet for a block of years (Quinn II and Deriso 1999). Then, it is a simple matter to add the ODOFFNA term using equation (3). Parameters μ, $\tilde{e}_y$, $\tilde{s}_a$, γ are estimated jointly with other model parameters for abundance, constraining the age and year deviations to sum to 0. A likelihood ratio test with the two alternative models then indicates whether non-additivity is present: $F = (\text{RSS}_a - \text{RSS}_{na})/\text{RMS}_{na}$, where RSS is residual sum of squares, RMS is residual mean square, and subscripts a and na are used for the additive and non-additive models, respectively. The test is an F-test with 1 degree of freedom in the numerator and the residual degrees of freedom for the non-additive model in the denominator (Quinn and Deriso 1999, p.152).

Also, it is often useful to examine indices of mortality from research survey estimates of relative abundance at age. Mortality can be estimated as $\hat{z}_{y,a} = -\log(r_{y+1,a+1}/r_{y,a})$, where $r_{y,a}$ is the estimate of abundance in year y at age a. The variable $\hat{z}_{y,a}$ can again be easily analyzed in a two way ANOVA with ODOFFNA. A similar analysis can be carried out with the catch-at-age data. Two-way plots can be used to visually assess the non-additivity (Morgenthaler and Tukey 2001).

Illustration

So that others can easily try out and evaluate this approach, we provide a simple example which is programmed in an EXCEL spreadsheet (go to web cite "fish.dal.ca/˜ myers/papers.html) on Atlantic cod (*Gadus morhua*) from the St. Pierre Bank, south of Newfoundland (the stock designated as 3Ps in the notation of the Northwest Atlantic Fisheries Organization (NAFO)). This is one of the cod stocks in eastern Canada that collapsed in the early 1990's; the data set is discussed in some detail in Myers et al. (1997). The data consist of catch-age data from 1978 – 1993 for ages 3 to 10+, the latter being a plus group. The Canadian research trawl survey was used for the same years, but also included age 2. Natural mortality is assumed to be 0.2 for all ages except 0.4 for age 2. A typical lognormal analysis is made with the objective function

$$[4] \qquad \text{RSS} = \sum_y \sum_a (c'_{y,a} - c_{y,a})^2 + \sum_y \sum_a \left(\log I'_{y,a} - \log Q_a N_{y,a}\right)^2,$$

where c is log catch, N is abundance, I is the research survey index, Q is the catchability of the survey as a function only of age, and a prime denotes a data value. Full-recruitment selectivity of the catch was assumed constant for ages 6 to 10+. All parameters were estimated on a log scale, and we gave equal weight to the two sums of squares for this example. This example was kept as simple as possible to focus on non-additivity; a full assessment would include other information, such as correlated errors among ages in a year (Myers and Cadigan 1995) or alternative error structure (Cadigan and Myers 2001).

The results show that abundance peaked in 1987 and decreased rapidly shortly thereafter (Figure 2a). There was an overall increase in fishing mortality onward from 1984 until the fishery was partially closed in 1993 (Figure 2a). These trends were the same for the additive and non-additive models. The estimates of selectivity on the younger ages from the non-additive model increase rapidly as shown by the increasing ratios in Figure 2b. The estimates of fishing mortality from the additive model are proportional across year by design; these are shown as flat straight lines in Figure 2b for ages 3, 4, and 5 as ratios of the full-recruitment fishing mortality at older ages. The two values of the ratios on the right side of the the graph for each age are for the two years with highest fishing mortality, 1991 and 1992. The residual sum of squares drops from 63.1 to 61.0, a highly significant difference (F-test, P=0.007). Thus, the estimate $\widehat{\gamma} = -0.36$ is statistically significant from 0, and therefore we conclude that fishing mortality is non-additive. This example demonstrates the shift in fishing mortality to younger fish as the stock declines; however, the extent is underestimated because of discarding (Myers et al. 1997).

We repeated the above analysis just for the catch-at-age data. We found a very large difference in the fit of a year by age model of the log catch ratios ($c_{y,a} - c_{y+1,a+1}$) compared to the ODOFFNA model (F-test, P< 0.001). This analysis shows that a change of selectivity can detected for this data even without the research surveys. A similar analysis of the survey data failed to show significant non-additivity, presumably because the survey variability at age was too high.

Discussion

Fishery selectivity can change for a variety of reasons. First, regulatory changes such as gear restrictions or time-area closures can influence the catching properties of the gear or the availability of fish to be caught. Second, environmental changes can alter the spatial distribution of fish or susceptibility of fish to the gear. More pernicious is the mechanism discussed in this paper: overfishing leads to depletion of the population which is not recognized in the assessment, catch remains constant because of increased effort and changes in selectivity without evidence to indicate reduction in fishing is needed which leads to increased overfishing, harvesters increasingly target younger fish to accommodate their catch needs.

Assessing changes in selectivity is often not easy due to measurement error in data sources and because alternative hypotheses may appear equally likely. The random walk model has been a useful approach for modeling changes in selectivity over a long time period, but it is not clear whether it would be able to detect recent changes in selectivity accompanying overfishing. The ODOFFNA approach may provide a parsimonious approach suitable for some assessments, but cannot deal with autocorrelation in selectivity like the random walk model can, a likely important phenomenon. However, the ODOFFNA approach can be implemented with a modicum of extra work, so we recommend its routine application.

The ODOFFNA approach can easily be incorporated into other types of age-structured assessments. In many formulations of age-structured models, the catch-at-age is assumed to be known without error, and the fishing mortality at year and age matrix is estimated separately with no or limited constraints. For these models, it is a simple matter to output the estimated fishing mortality at age, take logarithms, analyze it with a two-way ANOVA, and apply the ODOFFNA test.

Unobserved discarding may increase for younger fish as the stock collapses (Myers et al. 1997), as well as selectivity. For this reason we recommend that the ODOFFNA test be applied to any survey data as well as in the catch-at-age model, where discarding may not be well estimated. Such discarding could be confounded with an increase in natural mortality of juveniles. The ODOFFNA test on survey data detects changes in total mortality, whether due to changes in selectivity or in natural mortality. Therefore, auxiliary information would be necessary to attribute a significant test result to selectivity, natural mortality, or both.

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References

Cadigan, N. G., and Myers, R. A. 2001. A comparison of gamma and lognormal maximum likelihood estimators in a sequential population analysis. Can. J. Fish. Aquat. Sci. **58**: 560–567.

Deriso, R. B., Quinn II, T. J., and Neal, P. R. 1985. Catch-age analysis with auxiliary information. Can. J. Fish. Aquat. Sci. **42**: 815–824.

Fournier, D. A., and Archibald, C. 1982. A general theory for analyzing catch at age data. Can. J. Fish. Aquat. Sci. **39**: 1195–1207.

Gudmundsson, G. 1994. Time series analysis of catch-at-age observations. Appl. Statist. **43**: 117–126.

Hourston, A. S. 1980. The decline and recovery of Canada's Pacific herring stocks. Rapp. P.-v. Réun. Cons. int. Explor. Mer **177**: 143–153.

Ianelli, J. 1996. An alternative stock assessment model of the eastern Bering Sea pollock fishery. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea / Aleutian Islands regions, November 1996. North Pacific Fisheries Management Council, Anchorage, Alaska, pp. 81–104.

Morgenthaler, S., and Tukey, J. W. 2001. Multipolishing and two-way plots. Metrika **53**(3): 245–267 (electronic).

Myers, R. A., Bowen, K. G., and Barrowman, N. J. 1999. The maximum reproductive rate of fish at low population sizes. Can. J. Fish. Aquat. Sci. **56**: 2404–2419.

Myers, R. A., and Cadigan, N. G. 1995. Statistical analysis of catch-at-age data with correlated errors. Can. J. Fish. Aquat. Sci. **52**: 1265–1273.

Myers, R. A., Hutchings, J. A., and Barrowman, N. J. 1997. Why do fish stocks collapse? The example of cod in Canada. Ecol. Appl. **7**: 91–106.

Myers, R. A., and Mertz, G. 1998. The limits of exploitation: a precautionary approach. Ecol. Appl. **8, Supplement 1**: S165–S169.

Quinn II, T. J., and Deriso, R. B. 1999. Quantitative Fish Dynamics. Oxford University Press, New York.

Saville, A. 1980. The assessment and management of pelagic fish stocks: A symposium held in Aberdeen, 3-7 July 1978. Rapports et Proces-verbaux des Reunions, Conseil International pour l'Exploration **177**: 517.

Shuter, B. J., Koonce, J. F., and Regier, H. A. 1979. Modeling the Western Lake Erie walleye population: A feasibility study. Technical Report 32, Great Lakes Fishery Commission Technical Report.

Tukey, J. W. 1949. One degree of freedom for non-additivity. Biometrics **5**: 232–242.

Figure Captions

Figure 1: The spawner biomass (average catch per trap set of mature fish), instantaneous adult fishing mortality, and the ratio of juvenile to adult fishing mortality for walleye in the east and central Lake Erie. The ratio of juvenile to adult fishing mortality is given as the ratio of 3 year olds to the average fishing mortality on adults (ages 4+), and the ratio of fishing mortality on ages 2 to the adult fishing mortality.

Figure 2: a. Estimated abundance (solid line) and fishing mortality (dashed line) of older (age 6+) cod on St. Pierre Bank.

b. A comparison of the results from the additive (lines) and non-additive models (symbols). Ratio of fishing mortality for 1978 to 1993 for ages 3 (triangles), 4 (diamonds), and 5 (squares) to the fully recruited fishing mortality, i.e. for ages 6 and above, as a function of the fully recruited fishing mortality. The additive results for the three younger ages are the three straight lines parallel to the x-axis nearest the corresponding symbols.

Fig. 1.

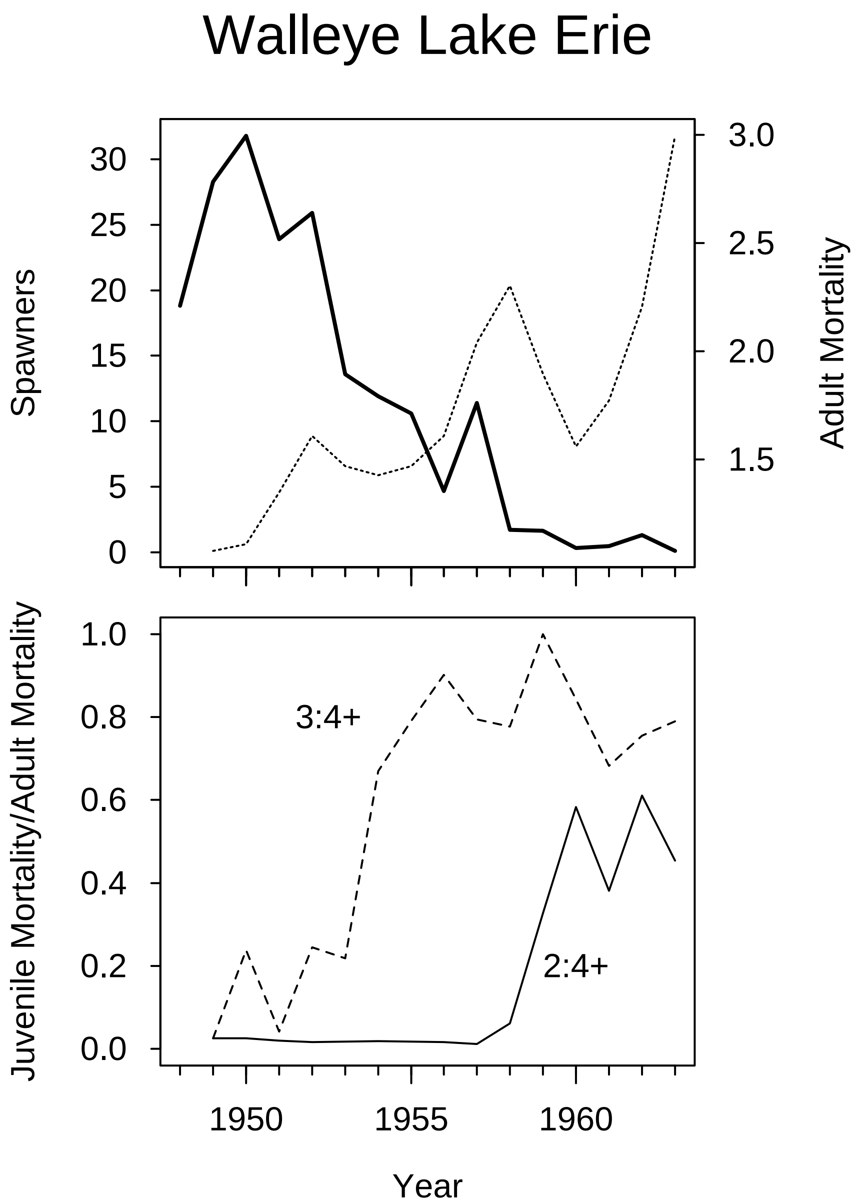
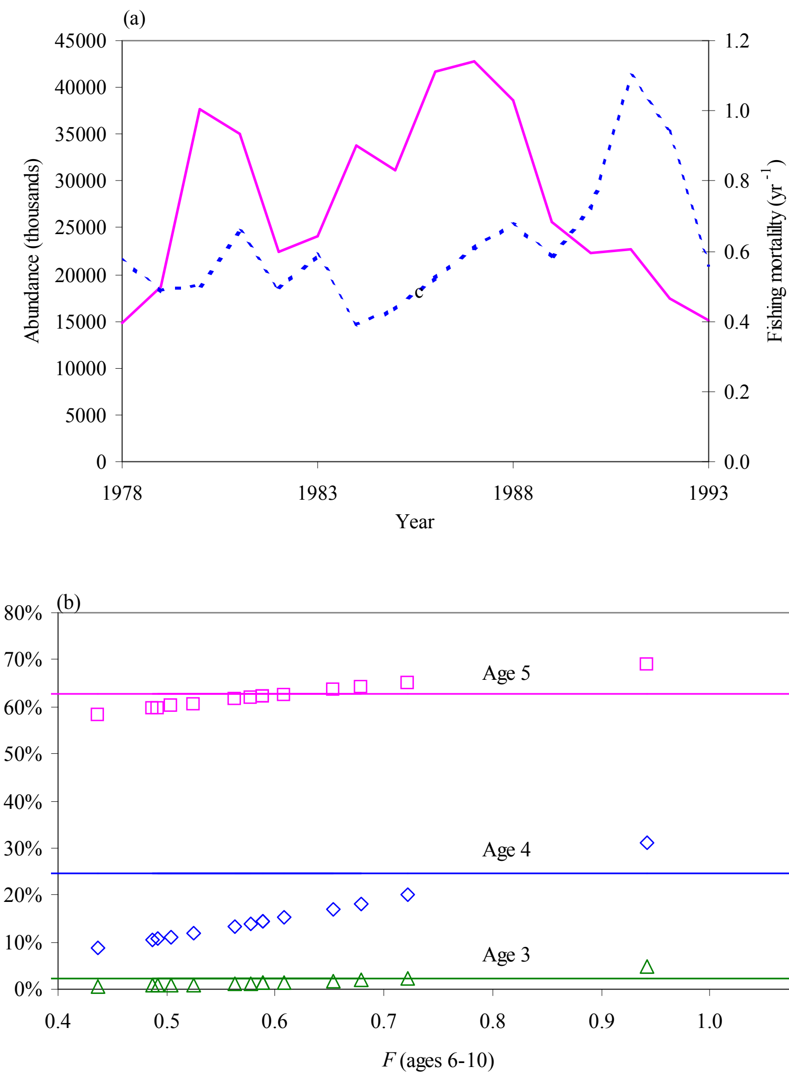

Walleye Lake Erie
Spawners
Adult Mortality
30
25
20
15
10
5
0
3.0
2.5
2.0
1.5
Juvenile Mortality/Adult Mortality
1.0
0.8
0.6
0.4
0.2
0.0
3:4+
2:4+
1950
1955
1960
Year

Fig. 2.


(a)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
Abundance (thousands)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Fishing mortality (yr⁻¹)
1978
1983
1988
1993
Year
(b)
80%
70%
60%
50%
40%
30%
20%
10%
0%
Age 5
Age 4
Age 3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
F (ages 6-10)