Estimates of large-scale purse-seine, baitboat and longline fishing capacity in the Atlantic Ocean: an analysis based on a stock assessment of bigeye tuna

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ABSTRACT

The Data Envelopment Analysis (DEA) approach for estimating fishing capacity cannot be applied effectively to tuna fisheries in the Atlantic Ocean because the available information is highly aggregated, and therefore inadequate for that purpose. This paper presents an alternative approach based on the traditional definition of fishing capacity, for which capacity is a hypothetical maximum yield that can be produced at a point in time, given the capital stock, regulations, current technology and resource abundance. The estimates of capacity obtained are based on inputs and outputs from a stock assessment of Atlantic bigeye tuna (*Thunnus obesus*) that incorporates information about age-specific selectivity and time trends in fishing efficiency. An algorithm is used to infer the potential magnitude of catches for a fishery in a given time period, assuming that the fishing mortality could be as high as the values estimated for neighbouring time periods. These are then used to infer, on the basis of the assessment results, the output capacity (in tonnes) for each fishery and for all fisheries combined. The results obtained suggest that the output capacity has exceeded the stock's potential long-term productivity since about 1992. These results are preliminary, however, as the robustness of the method should be tested, especially with regard to the level of aggregation used in the stock assessment (*i.e.* the number of fleets examined, the time steps used, *etc.*).

1. INTRODUCTION

An external Technical Advisory Committee to the *FAO Project on the Management of Tuna Fishing Capacity* has recommended that Data Envelopment Analysis (DEA; Kirkley and Squires 1999) be used to estimate fishing capacities for tuna fleets. Reid. *et al.* (2005) applied this approach to obtain estimates of fishing capacity, capacity utilization and excess capacity of the purse-seine fleet that targets tropical tunas (bigeye *Thunnus obesus*, yellowfin *T. albacares* and skipjack *Katsuwonus pelamis*) in the Atlantic Ocean. However, they found the available information to be largely inadequate because the data were highly aggregated. With the available data, it is not possible to associate the characteristics of individual vessels with their fishing effort and resulting catches at a detailed level, *e.g.*, for particular trips or months. Miyake (2005), who estimated the capacity of the longline fleets operating worldwide in recent years, also noted that the

[1] The conclusions presented in this paper do not necessarily represent the views of ICCAT.

available information for longliners in the Atlantic Ocean was highly aggregated. The situation is the same for other major gear types, such as baitboats[2]. Thus, in the absence of disaggregated data, alternative approaches to measure capacity may be necessary for the Atlantic tuna fisheries.

This paper presents an alternative approach based on the traditional definition of fishing capacity: "Capacity is ... the maximum yield in a given period of time that can be produced given the capital stock, regulations, current technology and state of the resource" (Kirkley and Squires, 1999). The estimates of capacity obtained are based on inputs and outputs from a stock assessment of bigeye tuna.

The quantitative approach presented here uses information from the assessment. Briefly, an algorithm that connects consecutive "peaks" (defined in Section 2.2) is applied to estimated fishing mortality on a fishery-by-fishery basis to obtain a time series of fishing capacity for each fishery. These are then used to infer, on the basis of the assessment results, the output capacity (in tonnes) for each fishery and for all fisheries combined. The assessment incorporates information about age-specific selectivity and time trends in fishing efficiency.

2. METHODS

2.1 The assessment and data used

The stock assessment used is a 2004 application of MULTIFAN-CL (Fournier, Hampton and Sibert, 1998) to data for Atlantic bigeye tuna. The basic data sets used and the assumptions made are described by Miyabe *et al.* (2005). The particular model run that was used in this paper was an update of the work of Miyabe *et al.* (2005), which was conducted during an ICCAT stock assessment of bigeye (ICCAT, 2005). The model considered the following:

- 3 regions (1: north of 25°N; 2: 25°N-15°S; 3: south of 15°S);
- 14 fisheries: 3 purse seine, 5 baitboat (pole-and-line and other surface), 6 longline;
- Quarterly catch-effort and length-frequency data for 1961 through 2002;
- Tagging information;
- Time trends in catchability of the fish for most fleets.

The MULTIFAN-CL model provided estimates of a large number of parameters related to abundance, movements, growth and fishing mortality. The assessment outputs used for the calculations below were: observed and predicted catches, fishing mortality and exploitable population size, by fishery, year and quarter.

2.2 Fishing and output capacity

An *ad hoc* approach is used in this paper to estimate maximum fishing mortality as a measure of "fishing capacity".

One of the MULTIFAN-CL model results obtained was estimates of fishing mortality for each of the 14 fisheries, by year and quarter. In all cases, the observed catches and the estimated fishing mortalities showed strong seasonal patterns.

Maximum fishing mortality for each fishery was estimated by assuming that, for a given quarter, the available (potential) fishing mortality should not change very much between consecutive annual peaks. A "peak" was defined as a value of fishing mortality that was greater than the preceding and subsequent values. The fishing mortality from a peak in a given year was assumed to remain available until the next peak several years later.

Let m be the time of a peak and n be the time of the next peak, y denote year, q denote quarter and g denote the fishery:

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[2] ICCAT uses the term "baitboat" for what are known as "pole-and-line" vessels by FAO and other organizations. In this paper, baitboat catches also contain minor catches made by some other surface gears, *e.g.* handlines and trolling gear.

$$\hat{F}_{y,q,g} = F_{m,q,g} \qquad \text{for } y = m \text{ to } n - 1$$

where F is the fishing mortality estimated by MULTIFAN-CL and $\hat{F}$ is the maximum fishing mortality in this paper.

Output capacity was estimated by applying the maximum fishing mortality estimates to the MULTIFAN-CL estimates of abundance (exploitable stock size for each fishery) in order to compute the potential catch that would have resulted.

2.3 Capacity utilization, MSY, excess capacity and overcapacity

Capacity utilization was estimated as the ratio of observed catch to output capacity; excess capacity was defined as the difference between output capacity and observed catch; overcapacity was estimated by subtracting estimates of maximum sustainable yield (MSY) from the overall (all gears combined) capacity output.

Although MSY is often thought of as a constant, it may vary in accordance with the fisheries that exploit the stock because different fisheries exploit fish of different age groups, and the relative intensities of the different fisheries may vary over time. In the case of Atlantic bigeye tuna, the average size of fish in the catch by all fisheries combined has decreased considerably over time. Because selectivity affects yield per recruit, and yield per recruit, in turn, affects equilibrium yield, the estimates of MSY could change substantially if the overall selectivity changes. In this paper, the approach described by Restrepo *et al*. (1994) was used to estimate MSY.

3. RESULTS

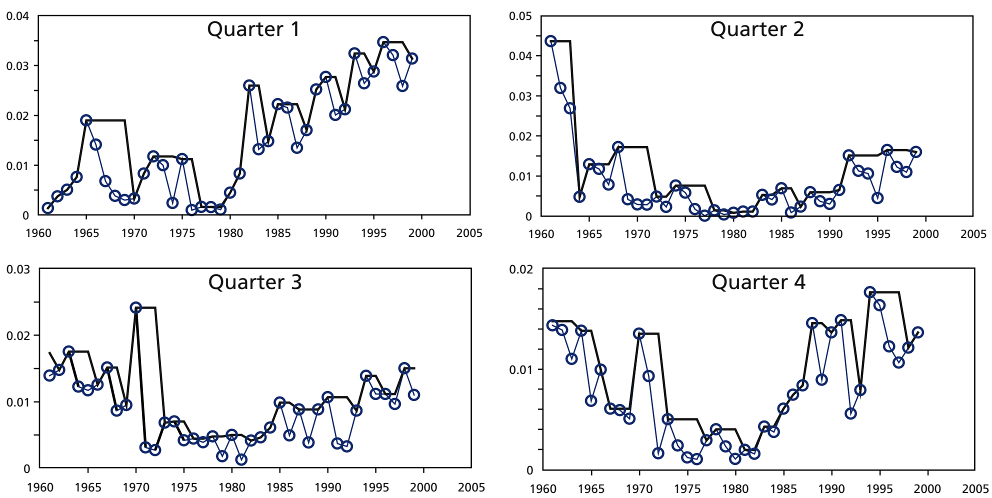
While the computations made for this study were carried out by fishery and quarter, the results were aggregated by gear type and year, which should suffice for the illustrative purposes of this paper.

3.1 Output capacity

Figure 1 illustrates how the approach used to estimate available fishing mortality was applied, using, as an example, the Japanese longline fishery in Region 2 (defined as fishery 10 in the MULTIFAN-CL analyses). Each of the panels shows the time series of relative fishing mortality for a given quarter.

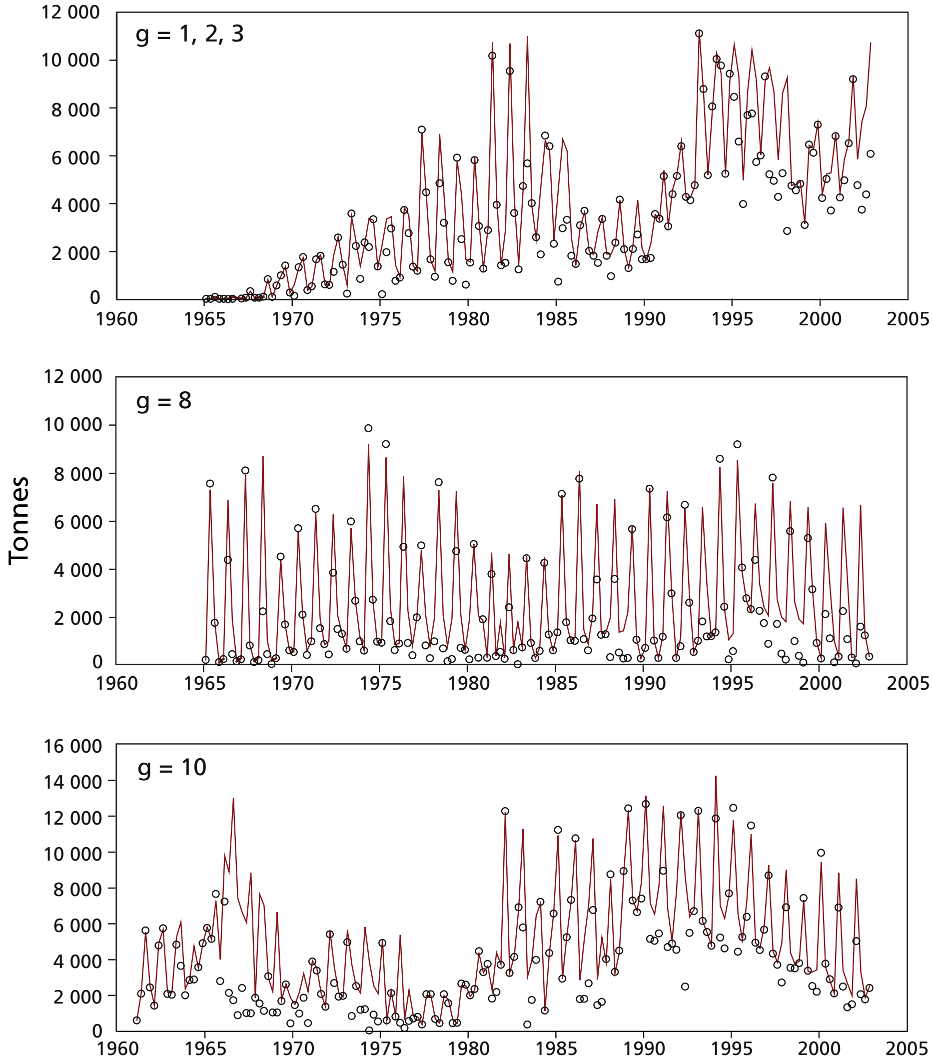
FIGURE 1

Example of how the methods to estimate fishing mortality were applied



The circles are the outputs from MULTIFAN-CL and the solid line is the maximum coefficient of fishing mortality.

FIGURE 2
Example of how the approaches applied to estimate output capacity performed for several of the 14 fisheries (g) examined



The open circles represent the observed catches, and the lines represent the estimates of capacity output. The top figure corresponds to three sequential purse-seine fisheries in Region 2; the middle figure corresponds to miscellaneous baitboat fisheries in Region 2; the bottom figure corresponds to the Japanese longline fishery in Region 2. Note that Region 2 is the area in which the majority of the catch is taken.

Figure 2 illustrates the corresponding estimates of output capacity for several of the 14 fisheries in the analyses. In all cases, the method tracked the observed seasonal pattern in fishing mortality and corresponding catches.

The estimates of capacity output are presented in Table 1, together with the observed catches.

The estimates of catch and capacity output, and the corresponding capacity utilization, aggregated by gear type and for all gears combined, are shown in Figure 3.

3.2 MSY

The relative mix of fisheries that target small bigeye and large bigeye in the Atlantic has changed considerably over time. For example, the selectivity patterns estimated by MULTIFAN-CL (all fleets combined) during the 1960s and 1990s are shown in Figure 4. The transition between predominantly longline fisheries targeting large fish

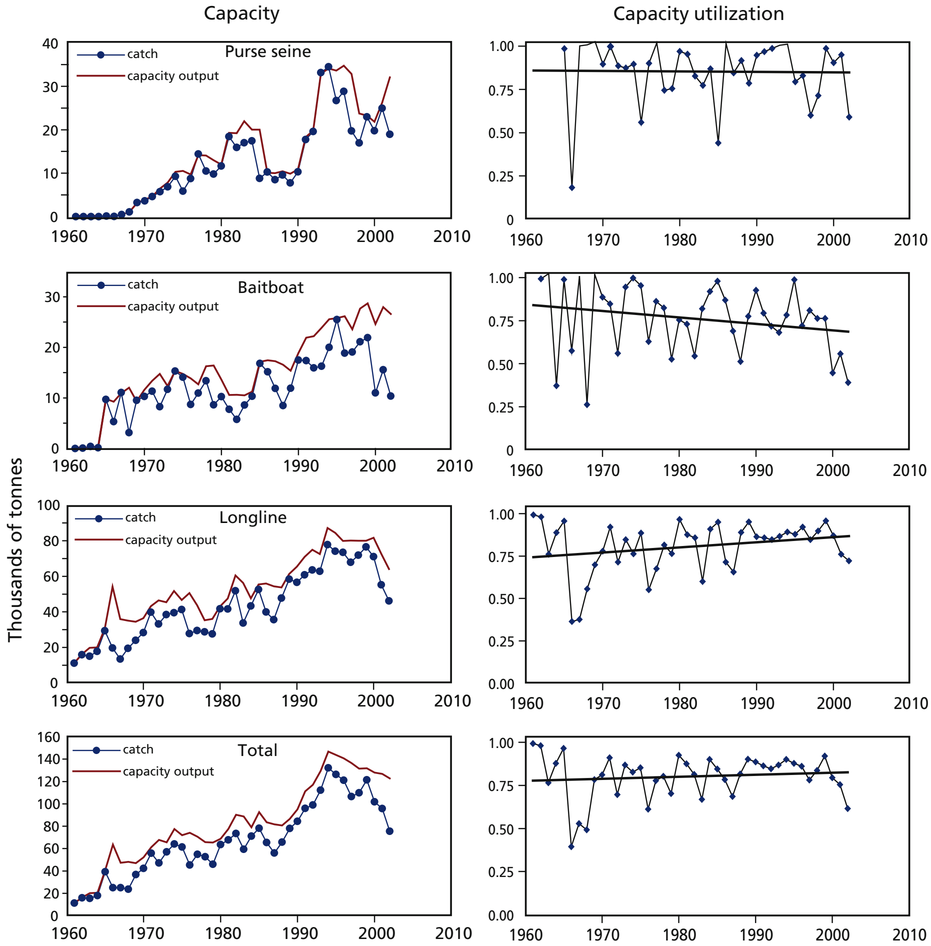
TABLE 1
Estimates of observed catch and capacity output for Atlantic bigeye tuna. The estimates are in thousands of tonnes and aggregated by gear type

Year	Purse seine		Baitboat		Longline		Total	
	Observed catch	Capacity output	Observed catch	Capacity output	Observed catch	Capacity output	Observed catch	Capacity output
1961	0.0	0.0	0.0	0.0	11.2	11.3	11.2	11.3
1962	0.0	0.0	0.1	0.1	15.9	16.3	16.0	16.3
1963	0.0	0.0	0.4	0.4	15.0	19.8	15.4	20.1
1964	0.0	0.0	0.1	0.4	17.8	20.0	17.9	20.4
1965	0.1	0.1	9.7	9.8	29.4	30.8	39.2	40.7
1966	0.0	0.1	5.3	9.3	19.7	54.1	25.1	63.5
1967	0.5	0.5	11.1	11.0	13.5	35.9	25.0	47.4
1968	1.1	1.1	3.1	12.0	19.5	35.1	23.7	48.2
1969	3.2	3.1	9.5	9.3	24.0	34.4	36.7	46.9
1970	3.6	4.0	10.3	11.6	28.4	36.5	42.3	52.1
1971	4.6	4.6	11.3	13.4	39.8	43.2	55.8	61.2
1972	5.7	6.5	8.3	14.8	33.2	46.5	47.2	67.7
1973	6.9	7.8	11.7	12.4	38.4	45.4	57.0	65.6
1974	9.3	10.3	15.3	15.3	39.5	51.8	64.1	77.4
1975	5.9	10.5	14.1	14.8	41.3	46.7	61.3	71.9
1976	8.7	9.7	8.7	13.9	27.8	50.5	45.3	74.1
1977	14.4	14.1	10.9	12.7	29.5	43.8	54.9	70.6
1978	10.5	14.1	13.4	16.3	28.8	35.3	52.7	65.7
1979	9.8	13.0	8.6	16.4	27.6	36.1	46.0	65.4
1980	11.7	12.0	10.3	13.6	41.7	43.1	63.6	68.8
1981	18.4	19.3	7.7	10.6	41.6	47.5	67.8	77.4
1982	15.9	19.2	5.8	10.6	51.8	60.5	73.5	90.3
1983	17.0	22.0	8.6	10.5	33.8	56.3	59.4	88.8
1984	17.4	20.0	10.3	11.2	43.3	47.7	71.1	78.9
1985	8.8	20.0	16.8	17.2	52.6	55.4	78.2	92.6
1986	10.3	10.1	15.2	17.5	40.0	55.9	65.4	83.5
1987	8.5	10.0	11.9	17.3	35.6	54.3	56.0	81.6
1988	9.6	10.4	8.5	16.5	47.8	53.7	65.8	80.7
1989	7.8	9.9	11.9	15.4	58.4	61.4	78.1	86.6
1990	10.3	10.9	17.5	18.9	56.5	65.4	84.3	95.2
1991	17.7	18.3	17.4	21.9	60.8	71.0	95.9	111.1
1992	19.6	19.8	15.9	22.2	63.5	75.0	99.0	117.0
1993	33.1	32.9	16.2	23.9	62.8	72.5	112.2	129.3
1994	34.5	34.1	20.0	25.5	77.7	87.1	132.2	146.7
1995	26.7	33.6	25.5	25.8	74.1	84.4	126.3	143.8
1996	28.8	34.7	18.8	26.2	73.5	79.8	121.2	140.7
1997	19.7	32.8	19.1	23.6	67.8	80.1	106.6	136.5
1998	17.0	23.8	21.1	27.6	71.8	80.0	109.9	131.4
1999	23.0	23.3	21.9	28.7	76.5	79.9	121.4	131.9
2000	19.8	21.8	11.0	24.6	71.0	81.6	101.7	128.0
2001	24.9	26.2	15.6	27.9	55.2	72.6	95.7	126.8
2002	18.9	32.1	10.4	26.6	46.2	64.1	75.5	122.7

during the 1960s and mixed fisheries that include FAD-based purse seine fisheries targeting small fish during the 1990s is evident.

When selectivity changes as much as shown by Figure 4, the MSY will change as a function of changes in yield-per-recruit values. In this study, MSY was estimated for the entire time series in the assessment, assuming that the parameters (growth, reproduction, selectivity and stock-recruitment relationship) would remain unchanged. The estimates of MSY are presented on a quarterly and annual basis in Figure 5. The figure suggests that the MSY for Atlantic bigeye tuna has dropped considerably from about 190 000 tonnes during the early 1960s, to just over 100 000 tonnes during the 1990s.

FIGURE 3
Estimated trends in catch and capacity output and capacity utilization, by gear type and for all gears combined



3.3 Excess capacity and overcapacity

In this paper, excess capacity is measured as capacity output minus observed catch, and overcapacity is measured relative to MSY each year. The estimates of excess capacity and overcapacity are presented in Figure 6. From these, it could be concluded that output capacity exceeded the Atlantic bigeye stock's long-term productivity during the early 1990s. In absolute magnitude, the estimates of overcapacity during the last 10 years for which data are available (1993-2002) average 28 000 tonnes.

4. DISCUSSION

At present, it is not possible to use DEA to estimate the fishing capacities for all of the tuna fleets that operate in the Atlantic Ocean, primarily because the data available are highly aggregated. This paper presents an alternative approach to estimating capacity, based on the results of a stock assessment.

The approach used has some advantages and disadvantages. On the positive side, it is conceptually simple, and uses information that is readily available from the stock assessment; it is not necessary to search for other types of information that may be difficult to obtain. Also, basing the analyses on the assessment may be appealing to fisheries scientists who, like the author, are already familiar with these types of data and parameters. On the negative side, the approach used to estimate maximum effort lacks a sound theoretical basis. Also, there are some alternatives that may perform more robustly, such as applying a piece-wise regression between peaks, rather than assuming that the available fishing mortality remains constant between peaks.

A key assumption with the method proposed here is that whenever a high level of fishing mortality is estimated for a given time period, the same level is also plausible in the time periods that follow immediately after it, until the next peak occurs. Thus, peaks in fishing mortality estimated by the assessment are not considered as "outliers", but rather as levels that are achievable by a given fleet in subsequent time periods. This assumption is conceptually similar to that made by DEA and other technical-economic approaches that estimate deterministic "frontiers" of maximum production. In the context of using MULTIFAN-CL for the assessment, the analyst would be able to control the level of variability in the coefficient of fishing mortality (*F*) allowed by the model, thus guarding against the possibility of abnormally high levels of *F* driving the results. Such an option was not explored in this paper, but it is reasonable to expect that lesser variability in *F* would result in lesser estimates of capacity output.

One potential problem with the method applied is that the maximum *F* levels lag behind the observed peaks in *F* (see Figure 1). A method in which the maximum *F* would be centered at the peaks might be a more reasonable alternative. One such alternative (Appendix 1) was applied. This alternative still includes the implicit assumption that whenever a high level of fishing mortality is estimated in a given time period, that high level is also possible in the time periods immediately before and after the peak.

The analyses presented here for the fleets that target bigeye tuna suggest that the output capacity has exceeded the stock's potential long-

FIGURE 4
Average selectivity patterns (all fleets combined) estimated for bigeye tuna during two decades

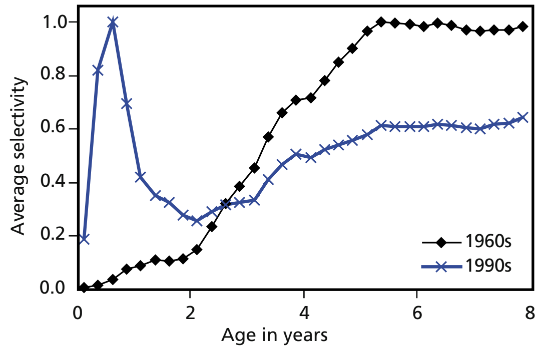
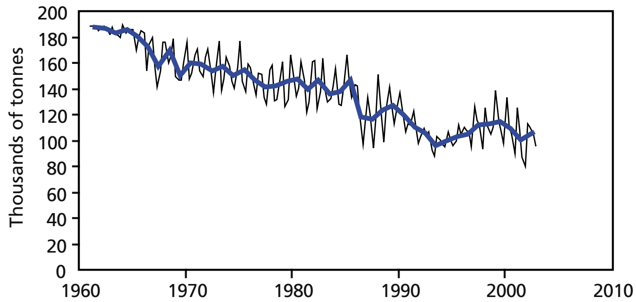


FIGURE 5
Estimated MSYs for bigeye tuna over time, assuming that the selectivity pattern during each time period remained constant over the long term



Thin line: quarterly estimates multiplied by 4; thick line: aggregated estimates by year)

FIGURE 6
Estimated excess capacity (top) and overcapacity (bottom) for Atlantic bigeye tuna fisheries (all gears combined)

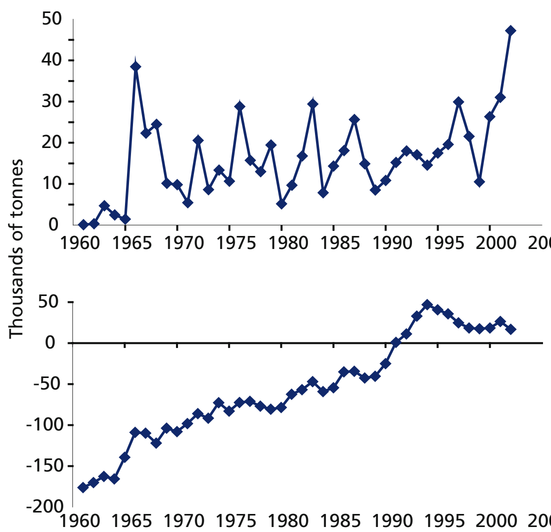
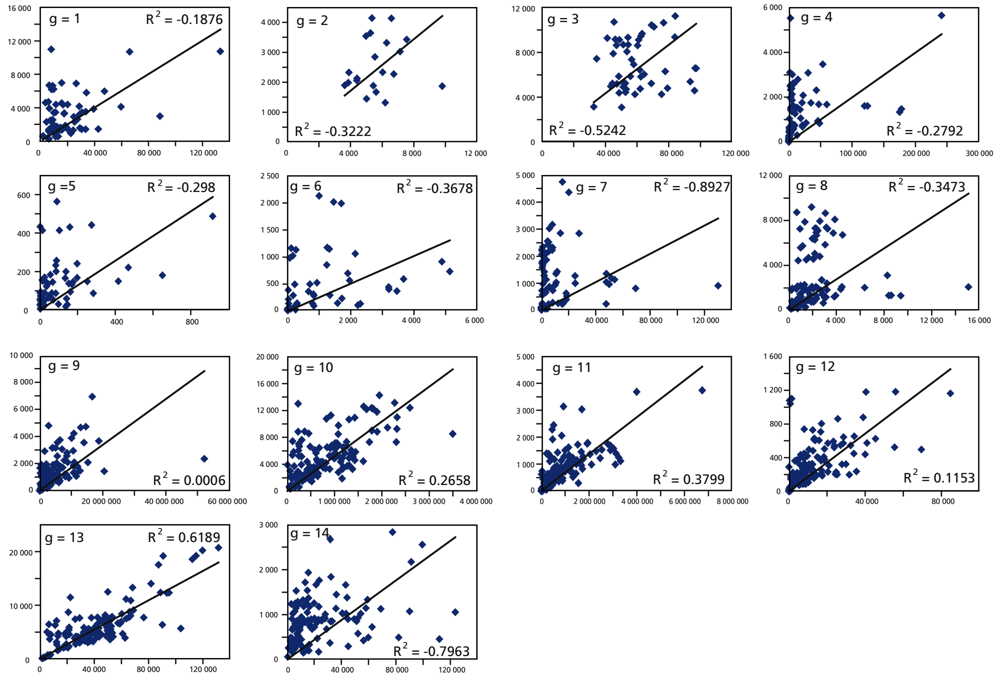


FIGURE 7

Relationship between estimated capacity output and fishing effort for the 14 fisheries (g) in the analysis



term productivity since about 1992 (Figure 6). It is interesting to note that in 1998 ICCAT adopted a binding recommendation that required all fleets catching more than 2 000 tonnes of Atlantic bigeye annually to limit their numbers of large-scale vessels that target bigeye to the average number that operated in 1991 and 1992 (*1998 Recommendation by ICCAT on the Bigeye Tuna Conservation Measures for Fishing Vessels Larger than 24 m Length Overall*). This capacity limitation was repeated in the 2004 *Recommendation by ICCAT on a Multi-Year Conservation and Management Program for Bigeye Tuna*, which implemented a comprehensive management plan that includes an overall catch limit, individual catch limits for parties, closed area-season strata and other management measures. The estimates of overcapacity in this paper appear to be in synchrony with ICCAT's decision to limit fishing capacity.

For the purpose of providing management advice, it would be useful to investigate the relationship between variable inputs (*e.g.*, fishing effort) and fishing capacity or between fixed inputs (*e.g.*, physical characteristics of the vessels) and fishing capacity. The data available for this study did not include fixed inputs. The information available in ICCAT's statistical database is mostly on nominal fishing effort (*e.g.* fishing days, number of hooks), and the level of aggregation varies by fishery. The relationship between the capacity output estimates from this study and the fishing effort series used as inputs to MULTIFAN-CL is rather poor for most of the 14 fisheries examined (Figure 7). One of the reasons for this is

that the MULTIFAN-CL model allowed for changes in catchability over time, both seasonally and annually. Thus, the underlying relationship between fishing effort and fishing mortality would not necessarily be expected to be linear. Another reason is that the estimates of capacity output in each time period are conditioned by the size of the resource at that time. In either case, on the basis of relationships such as those shown in Figure 7, at first glance it would appear difficult to draw firm conclusions about the desired changes in effort for most fisheries.

This paper deals only with the multi-gear nature of fisheries that exploit bigeye tuna in the Atlantic Ocean. A multi-species focus would be much more difficult to implement with the approach presented here because the stock assessments of ICCAT are conducted on single species.

5. REFERENCES

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APPENDIX 1

Results obtained with an alternative method to define maximum coefficient of fishing mortality

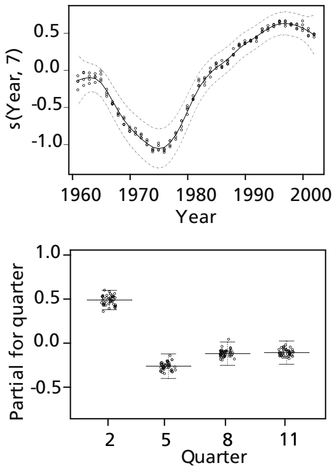
An alternative approach was used to estimate maximum coefficient of fishing mortality (*F*) so that it would be centered around peaks. This consisted of fitting a nonparametric regression model to the estimates of *F* from MULTIFAN-CL and using the results to predict fishing mortality, by year and quarter. These predicted values were then applied to the estimated stock sizes in order to compute output capacity; in cases for which the predicted catch from MULTIFAN-CL was greater, the predicted catch was taken as the value of the output capacity.

The regressions used were fishery-specific generalized additive models (GAMs) for which *F* was modeled as a spline function of year and as a factor for quarter. The degrees of freedom specified for the splines were equal to the number of years in each series, divided by 5.

$$\hat{F}_{y,q} = s(y)\,\beta q$$

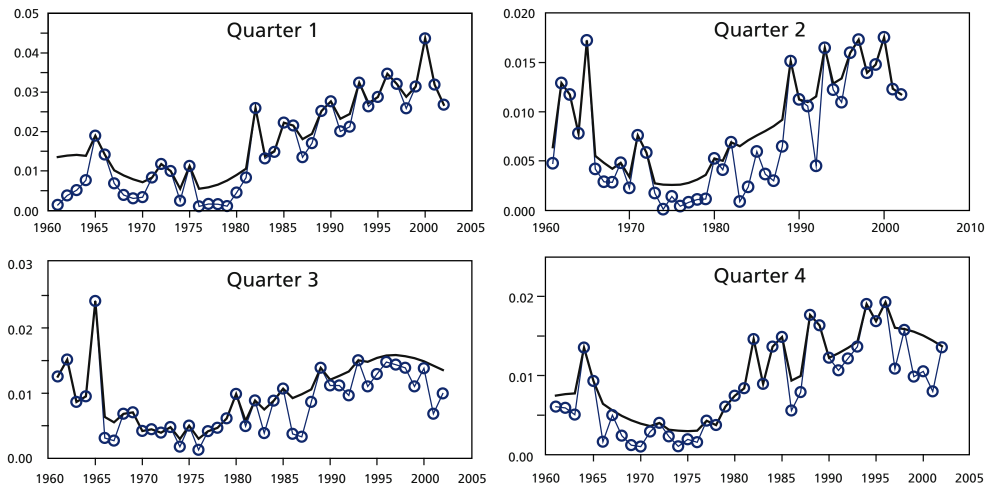
The results obtained are illustrated by Figures A1-A4. Overall, these results are similar to those obtained with the "peak" method applied in the main section of this paper. However, application of this alternative method suggests that overcapacity has been decreasing more rapidly during the more recent years than does

FIGURE A.1
Partial GAM fit plots for Fishery 10 (Japanese longline, Region 2)



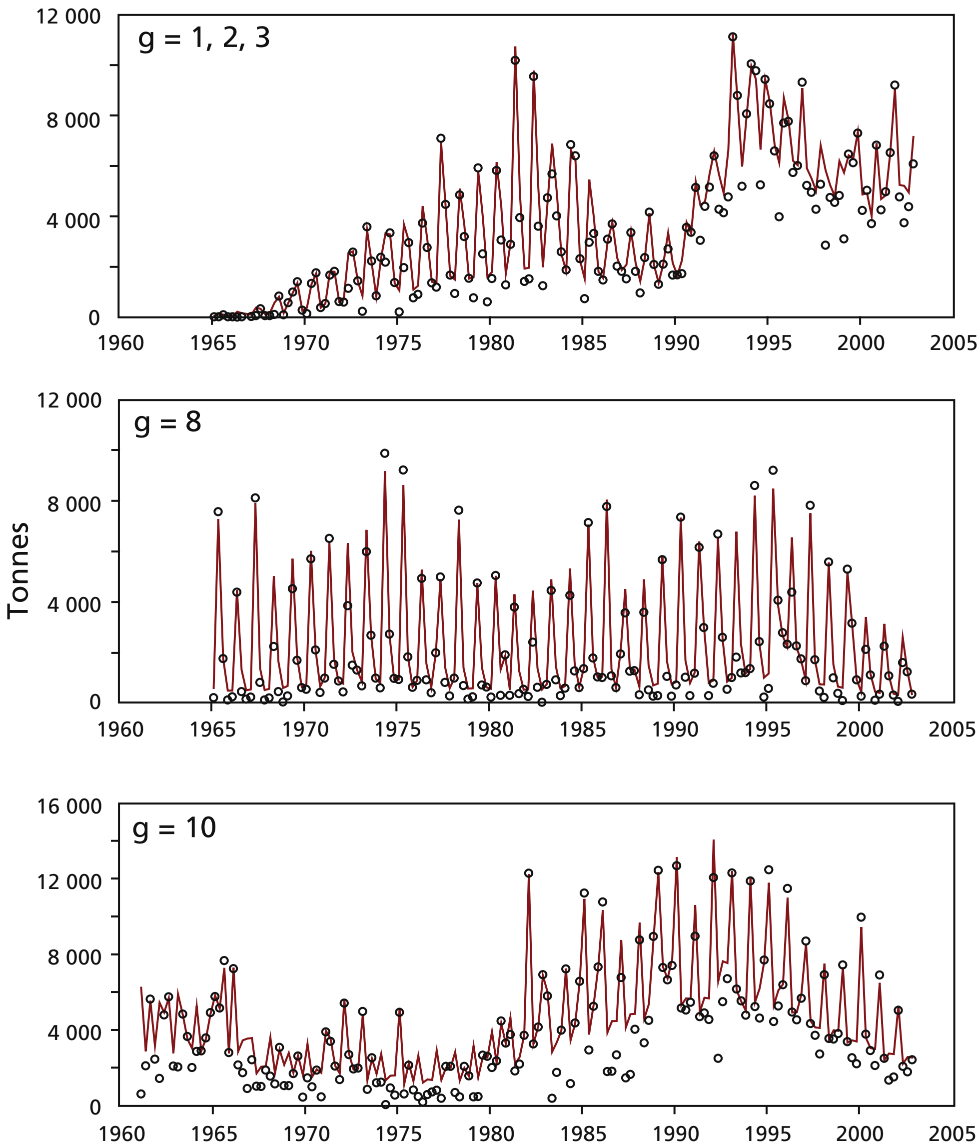
Left: smoothed nonparametric fit to the year effect; right: factor effect for quarter.

FIGURE A.2
Example of how the methods to estimate maximum fishing mortality were applied



The circles are the outputs from MULTIFAN-CL, and the solid line is the maximum of (1) fitted F from the GAM analysis, and (2) MULTIFAN-CL estimate. Data for the Japanese longline fishery in Region 2, by quarter, were used. The y axis is relative fishing mortality..

FIGURE A.3
Example of how the approach applied to estimate output capacity performed for several of the 14 fisheries examined



The open circles represent the observed catches, and the lines represent the estimates of capacity output. The top figure corresponds to three sequential purse-seine fisheries in Region 2; the middle figure corresponds to miscellaneous baitboat fisheries in Region 2; the bottom figure corresponds to Japanese longliners in Region 2. Note that Region 2 is the area in which the majority of the catches are taken.

the original method (see Figure A4). On the other hand, the most recent time period in the assessment is usually the most uncertain, so these results should be viewed with caution.

FIGURE A.4
Comparison of the results obtained with the "peak" method used in this paper and GAM approach applied in the Appendix