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An analysis of the concept of capacity limits for purse-seine vessels in the tuna fishery in the eastern Pacific Ocean was requested by Commissioners. This document was prepared by the US National Marine Fisheries Service in response to this request, since it is beyond the scope of the Commission staff to carry out such an economic analysis.

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FISHING CAPACITY AND EFFICIENT FLEET CONFIGURATION FOR THE TUNA PURSE-SEINE FISHERY IN THE EASTERN PACIFIC OCEAN: AN ECONOMIC APPROACH

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1. INTRODUCTION

Excess fishing capacity is a concern in the Eastern Pacific Ocean (EPO) tuna fisheries (IATTC 2011). Between 1993 and 2011, total purse seine well capacity increased from 117,646 to 212,315 m^3 (Table 1), potentially complicating agreement on and implementation of effective conservation and management measures. To address growing capacity and to aid in the sustainability of tuna fishing, the Inter-American Tropical Tuna Commission (IATTC) has adopted a number of resolutions and recommendations to control EPO fishing mortality levels (IATTC 2011).

The IATTC's Resolution C-02-03 on fleet capacity maintains purse-seine vessel capacity at the same level as it was at the resolution's time of adoption.[1] Currently, the Resolution sets optimum well capacity at 158,000 m^3. The Resolution also requires vessels to be listed on the IATTC Regional Vessel Register (RVR), which serves as a basis for defining purse-seine vessels that are qualified to participate in a management system.

Recommendation C-10-01 puts into place a 62-day closure to fishing tropical tunas by the purse-seine fleet plus other measures for 2011-2013. Vessels can choose to comply with the closure in each of these years in either one of two periods of the year. Fishing is prohibited in a high-seas area of the EPO between 96° and 110°W and from 4°N to 3°S, from 29 September to 29 October. The total annual longline catches of bigeye for 2011-2013 are also limited for the four principal longline fleets operating in the EPO, whose governments are tasked with ensuring that the total annual catches of bigeye tuna by their large longline vessels do not exceed country-specific limits. All other governments undertake to ensure that the total annual catches of bigeye tuna by their longline vessels in the EPO during 2011-2013 do not exceed the greater of 500 metric tons or their respective catches of bigeye tuna in 2001.[2]

Given the importance of maintaining sustainable tuna fisheries and the stated objectives of limiting fleet capacity, the analysis in this paper examines the optimum tuna purse seine fleet capacity in the EPO. Optimal capacity is defined as the minimum well capacity required to catch specified levels of yellowfin, bigeye, and skipjack tuna. In addition to calculating optimal well capacity, this study also calculates the total amount of fishing capacity in terms of metric tons of catch of tuna by EPO purse seine vessels and compares it against existing MSYs. Finally, we examine alternative levels of catch and fleet size that could arise under conservation and management policies including maximum sustainable yields (MSYs) and day-based restrictions.

The analysis flexibly incorporates environmental and economic fluctuations inherent in the study of fisheries and fish populations. The incorporation of variables such as temperature and the biomass of tuna stocks captures the changes in environmental conditions faced by vessels operating in the fishery, and the policy analysis is predicated upon satisfying existing MSYs, thereby recognizing that sustainable harvests need to rise and fall in step with the biological health of the fish stock. Under favorable environmental conditions, even in the absence of fishing pressures, fish stocks increase, and in years of less favorable conditions, fish stocks decline. There may also be regime shifts, with extended periods of higher resource productivity or periods of lower resource productivity. Management by MSYs, and more generally total allowable catches (TACs), naturally allows more fishing when conditions are favorable and cuts fishing back when conditions deteriorate and populations decline.

In short, our analysis is not predicated upon a steady-state equilibrium in which technology is fixed and fish populations are unchanging, as is generally assumed with bioeconomic modeling. Instead, the analysis accepts time-varying constraints motivated by biological conditions and also estimates the economic optimum on an annual basis that implicitly recognizes annual changes in technology. Rather than imposing spurious, long-run, steady-state equilibrium as a modeling assumption, our approach allows relatively stable patterns to emerge from the inherent variability in fish populations and economic conditions if such patterns exist.

The study, based on Kerstens *et al.* (2005, 2006),[3] determines optimal capacity in two steps: First, fishing

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[1] The IATTC measures capacity by cubic meters of well capacity. This paper will distinguish between two measures of capacity, fishing capacity (as used by the FAO and defined and discussed below) and well capacity (measured in cubic meters, m^3), with our ultimate goal of determining the optimum well capacity and corresponding vessel numbers, where optimum in this context is defined below.

[2] During the negotiations that took place to establish a capacity limitation scheme, one approach, which was extensively considered, was a system of national capacity limits. However, it was not possible to reach an agreement on this basis, and consequently that approach was abandoned in favor of a scheme that controlled vessel access via the RVR.

[3] Kjaersgaard (2010) and Yagi and Mangi (2011) provide recent fisheries applications.

capacity for each vessel is estimated by output-oriented data envelopment analysis (DEA). Second—after requiring a vessel to harvest its fishing capacity as determined in the first step and further requiring that quotas or MSYs for yellowfin and bigeye and historical skipjack catch are caught by the entire fishery—the model estimates the minimum fixed inputs for the fishery, measured here in cubic meters of well capacity.[4] The intuition is that the model says the most efficient vessels should be kept in the fleet and the inefficient vessels should be either removed or scaled to the best-practice frontier subject to maintaining total production.

The analysis employs a technical notion of capacity (physical quantity based, using only input and output information) rather than an economic notion of capacity (profit based using revenue and cost information), in part due to the absence of cost data. Moreover, we distinguish between *fishing capacity* as a maximum potential catch given fixed inputs and *well capacity* (m^3) as a measure of the physical capital stock (the vessel, gear, and equipment). The first stage analysis calculates the fishing capacity of each vessel relative to the best-practice technically efficient production frontier, and the second stage analysis calculates the optimal well capacity subject to the fishing capacity estimates from stage one.

The main restriction in the second stage model is that the fleet is required to maintain historical output or meet certain MSYs or TACs.[5] [6] Subject to this constraint, the economic optimum can be defined as the industry's efficient catch, well capacity, and vessel numbers. More broadly, economic efficiency in this paper pertains to the maximum possible catch per vessel. The economic interpretation of optimal catch, well capacity, and vessel levels presented here correspond to the optimal fleet composition that would be found under individual transferable quotas (ITQs) or group-catch quotas if optimum catch not profit was the objective.[7] Namely, it is the minimum number of vessels required to achieve a desired level of tuna catch if each vessel employs days fishing (a variable input) to reach the best-practice catch frontier, given existing levels of fixed inputs such as vessels size and exploitable biomass. The best practice frontier is defined by the highest observed levels of catch relative to the number of fixed inputs required.

We specify and estimate the baseline model by distinct modes and technologies of purse seine fishing. In the EPO, we define the two major modes of purse seine fishing to be either setting on dolphins or setting on unassociated schools and floating objects.[8] Setting on dolphins is proxied by holding a Dolphin Mortality Limit (DML). To extend the analysis and address broader social or political concerns, we further estimate the model by vessel size classes, Classes 2 and 3, Classes 4 and 5, and Class 6 for vessels that do not hold a DML and Class 6 vessels that hold a DML. Distinguishing vessels by DML holding and vessel size class accommodates the different areas north to south and closer and farther from shore. The results from the aggregate and sub-class models can be compared to assess trade-offs between keeping a diverse range of vessels in the fishery and achieving the highest level of technical efficiency.

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[4] Vessels, given their physical capital stock; the state of technology; the environment; and resource stock, produce full capacity output by either improving their technical efficiency/skipper skill or variable input (days at sea) usage. In this study, we assume technical efficiency of a vessel is stable over time, so that vessels produce at the best-practice frontier through adjusting their variable input usage, i.e. through fishing days.

[5] Additional constraints include that there is a maximum number of days that a purse seine vessel can spend at sea, that vessels cannot increase their cubic meters of well capacity, and that vessels' technical efficiency is held fixed. The state of technology, biomass, age structure of the fish stock, spatial locations of the fish stock, state of the environment (e.g. sea surface temperature, thermocline, etc.) are also assumed constant in a given year (but can change year-by-year) and form implicit constraints. For details, see sections 3 and 4.

[6] Because skipjack does not have a TAC, we use the observed skipjack catch that year as the upper bound for skipjack catch.

[7] See Allen *et al*. (2010) and Squires *et al*. (in press) for comprehensive discussions of rights-based management with international tuna fisheries.

[8] There are two types of floating objects, flotsam and FADs. The occurrence of the former is unplanned from the point of view of the fishermen, whereas the latter are constructed by fishermen specifically for the purpose of attracting fish. FADs have been widely used for about 15 years, and their relative importance has increased during this period, while that of flotsam has decreased.

The industry model developed in this paper is based upon a technical or engineering notion of capacity. As noted by Kerstens *et al.* (2006), it is unlikely that it is ever economical in terms of cost minimization or revenue and profit maximization to produce at maximal plant capacity (Morrison, 1985; Nelson, 1989, Squires 1987, 1994; Segerson and Squires 1990, 1992, 1995). [9] Depending on the exact economic capacity notion adopted, economic capacity outputs are below plant capacity outputs. Implementing the conclusions from the short-run industry model based upon plant capacity outputs will therefore normally lead to lower industry output levels than computed in the industry model, since individual firms have an obvious interest in producing below full fishing capacity.

The results from the first stage analysis indicate that average capacity utilization for the entire fishery is 0.86, indicating that total fish catch could be increased by 16% if all vessels operated on the best-practice efficient frontier. Non-DML holding vessels have an average capacity utilization of 0.83, while DML holding vessels have an average capacity utilization of 0.89, indicating that the DML holders are slightly more efficient overall. The second stage analysis—the industry model—indicates that overall well capacity could be reduced by 18% if the fishery were to improve catch efficiency. If the fishery had been restricted to fish below the TAC in each year between 1993 and 2011, then average well capacity could have been reduced by 24%. In both of these cases, the average difference between DML and non-DML vessels is slight.

In terms of actual well capacity reduction, the industry model shows that efficient levels of well capacity would have been, on average for the last 5 years, 171,000 m^3. With yellowfin and bigeye TACs and observed skipjack total catch in place, this value falls to 167,000 m^3, from an average observed level of 219,000 m^3. Overall, these results are in line with IATTC recommendations to reduce well capacity to 158,000 m^3, indicating that such a policy is close to the technically efficient level of fixed inputs for the fishery. Similarly, the model indicates vessel number reductions of 22 to 24% on average, depending on the catch restriction imposed.

Finally, the running of a disaggregated model over three different size class groupings shows that distributional concerns are not large with the fishery reconfiguration implied by the aggregate industry model. The average difference in implied minimum number of vessels between the aggregate and disaggregated models is less than 1, indicating that the aggregate model preserves a large degree of class size heterogeneity.

The rest of this paper proceeds as follows: Section 2 provides details about the notions of capacity and efficiency used in the paper, Section 3 describes the stage one model of vessel capacity, Section 4 describes the stage two model of industry fixed inputs, Section 5 describes the data and estimation method, Section 6 gives the results of the first stage analysis, Section 7 gives the results of the second stage analysis, Section 8 describes the results of the disaggregated models and compares them to the aggregate results, and Section 9 concludes.

2. FISHING CAPACITY AND EFFICIENT FIXED INPUTS

There are a number of alternative concepts of capacity and ways to measure it. To address this issue, the Food and Agriculture Organization (FAO) organized an Expert Consultancy in 1998 in La Jolla and a Technical Consultancy in 1999 in Mexico City to sort through these concepts and make recommendations for the International Plan of Action on Capacity. The resulting definition is, "Fishing capacity is the maximum amount of fish over a period of time (a year or season) that can be produced by a fishing fleet if fully utilized, given the biomass and age structure of the fish stock and the present state of technology. Fishing capacity is the ability of a vessel or vessels to catch fish (FAO 1998, 2000)." Broadly speaking,

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[9] However, as observed by Kerstens *et al.* (2006), the technical fishing capacity notion (which is based on the Johansen plant capacity notion) is estimated using empirical data that at least partially reflect changes in economic conditions. Therefore, the difference between technical and economic notions of capacity may well be much smaller in practice than imagined.

economic theory, national governments and the formal FAO definition of fishing capacity measure the capacity base by a measure of potential output or catch (Kirkley *et al.* 2002, Reid *et al.* 2005).[10] The next section discusses fishing capacity and the different methods of conceptualizing and measuring it.

2.1. Fishing capacity and fishing capacity utilization

Capacity is a short-run concept, where firms and industry face short-run constraints, such as the stock of capital or other fixed inputs, existing regulations, the state of technology, and other technological constraints (Morrison 1985). The basic concept behind capacity is that firms are confronted with short-run constraints (e.g., stocks of fixed inputs such as the vessel), and the optimal short-run or temporary equilibrium output may be different than that for a steady-state, long-run equilibrium. Capacity is defined in terms of potential output. This potential output can be further defined and measured following either a technological-economic approach or an economic optimization approach directly based on microeconomic theory (Morrison 1985, Nelson 1989).[11] What distinguishes the two notions of capacity is how the underlying economic aspects are included to determine the capacity output.

In either approach, capacity utilization (CU) is actual output divided by capacity output (Morrison 1985, Nelson 1989). In the technological-economic approach used in the fishing capacity concept, a CU value less than one implies that firms (vessels) have the potential for greater production without having to incur major expenditures for new capital or equipment (Klein and Summers 1966).

This paper, Squires *et al* (2003), Kirkley and Squires (1999), the 1998 FAO Technical Working Group (FAO 1998), and the 1999 FAO Technical Consultation (FAO 2000) focus on the technological-economic (primal, using quantities of outputs) measures of capacity to estimate fishing capacity. The paucity of cost data in most fisheries militates against estimation of cost or profit functions to derive economic measures of capacity and capacity utilization. Also, the technological-economic approach is the one used by the U.S. Federal Reserve Board (Corrado and Mattey 1998) and in most other countries to monitor capacity utilization throughout the economy.

The technological-economic capacity of a firm, used by most interpretations of the FAO definition,[12] can be defined following Johansen's (1968, p. 52) definition of plant capacity as, "the maximum amount that can be produced per unit of time with existing plant and equipment, provided the availability of variable factors of production is not restricted". Färe (1984) provides a formal proof and discussion of plant capacity.

Capacity output thus represents the maximum production the fixed inputs are capable of supporting. This concept of capacity conforms to that of a full-input point on a production function, with the qualification

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[10] In economics, there are both primal and dual measures of potential output. In other words, potential output can be measured as a maximum potential output that can be produced, given that all variables are fully utilized and given the capital stock, or it can be measured as the short-run cost-minimizing, profit-maximizing or revenue-maximizing output levels. In fisheries, the primal or maximum potential output is used.

[11] In the economics approach, capacity can be defined as that output pertaining to one of two economic optimums: (1) the tangency of the short- and long-run average cost curves (Chenery 1952, Klein 1960, Friedman 1963), so that the firm is in long-run equilibrium with respect to its use of capital, or (2), the tangency of the long-run average cost curve with minimum short-run average total cost curve (Cassel 1937, Hickman 1964), or (3) the minimum of the short-run average cost curve (Berndt and Morrison 1981, Morrison 1985, Nelson 1989). Squires (1987), Berndt and Fuss (1989), and Segerson and Squires (1990) extended the economic concept of capacity from single to multiproduct firms. These cost-based measures presume exogenous outputs. Squires (1987), Segerson and Squires (1987, 1992), and Coelli *et al.* (2002) extended this cost-minimization approach to (short-run) profit-maximizing firms with endogenous outputs and Segerson and Squires (1992, 1995), Färe *et al.* (2000), and Lindebo *et al.* (2007) extended the economic approach to revenue-maximizing firms with endogenous outputs and all fixed or quasi-fixed inputs. Segerson and Squires (1993), Squires (1994), and Weninger and Just (1997) extended the economic notion of capacity to firms under regulatory constraints.

[12] A few studies interpret the FAO definition as the maximum potential effort.

that capacity represents a realistically sustainable maximum level of output rather than some higher, unsustainable, short-term maximum (Klein and Long 1973). In practice, this approach gives maximum potential output given full utilization of the variable inputs under normal operating conditions given existing capital stock, regulations, current technology, and the state of the resource stock, since the data used incorporate the firm's ex ante short-run optimization behavior.

For fishing vessels, the measure of fishing capacity corresponds to the maximum catch a vessel can produce if variable inputs like labor are fully utilized given the biomass, the fixed inputs, the age structure of the fish stock, and the present state of technology. This concept of capacity output cannot equal the output level that can be realized only at prohibitively high cost of input usage, and hence, is economically unrealistic. The capacity output is measured relative to the observed best-practice frontier based on observed input and output levels. It is, therefore, not an absolute, technically derived number based on an engineering notion of maximum possible catch; instead, the observed input and output levels reflect changes induced by economic behavior of firms. That is, the observed best-practice frontier is established by the existing fleet and implicitly reflects economic decisions made by vessel operators.

The definition and measurement of capacity in fishing and other natural resource industries face a unique problem because of the stock-flow production technology, in which inputs are applied to the renewable natural resource stock to produce a flow of output (Squires and Kirkley 1999). For renewable resources, capacity measures are contingent on the level of the resource stock. Capacity is, therefore, 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 (FAO 1998, 2000, Kirkley and Squires 1999).

3. ESTIMATION OF FISHING CAPACITY: FIRST STAGE OF ANALYSIS

We employ DEA to estimate fishing capacity and optimum well capacity.[13] DEA is a mathematical programming approach introduced by Charnes, Cooper and Rhodes (1978).[14] The DEA approach seeks to derive the most technically efficient production frontier from either an input or an output orientation by constructing a piece-wise linear technology fitted to observed data. The estimation is restricted to a technological-economic approach in that the data are restricted to the physical quantity of inputs used in the production process and the physical quantity of output produced. The output-orientated approach of Färe (1984) is used in this study for estimating capacity. The output orientation seeks to determine the maximum expansion in outputs given fixed input levels for some factors (fixed factors) and unrestricted levels for other factors (variable factors).[15] The fixed factors limit total production. Although the variable factors are unrestricted, DEA permits the determination of variable input usage consistent with the levels determined by the fixed factors.

The original approaches of Charnes, Cooper and Rhodes (1978) and Färe (1984) provide estimates of technical efficiency (TE) consistent with Farrell's (1957) notion of maximum expansion of output, given

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[13] Primal measures of fishing capacity can also be econometrically estimated by estimating a stochastic production frontier (Kirkley and Squires 1999, Kirkley *et al*. 2002).

[14] The use of DEA to estimate capacity need not be restricted to the primal or technological-engineering concept of capacity. If sufficient data on input or output prices are available, it is possible to estimate technical efficiency, capacity, CU, and optimal variable input usage using a cost or revenue-based DEA problem. Färe *et al.* (2000) illustrate how technical efficiency, capacity, and CU for a multiproduct, multiple input technology can be estimated either directly by solving respective revenue maximization or cost minimization DEA problems or by exploiting the properties of duality. Several studies have developed DEA models that estimate either capacity or efficiency with the objective of maximizing profits rather than just the quantity of outputs. Fare, Grosskopf, and Lovell (1994) developed a long-run profit maximization DEA model that allowed outputs and both fixed and variable inputs to vary, while Coelli, Grifell-Tatje, and Perelman (2002) estimated short-run economic capacity by allowing outputs, and only variable inputs, to vary in order to maximize profits given a set of fixed inputs. Brännlund *et al.* (1998) estimated the level of output that maximized profits given the current level of both variable and fixed inputs (*i.e.* , efficient level of output rather than capacity level).

[15] Input orientation seeks to determine the minimum contraction in inputs, given a given bundle and level of outputs.

no change in inputs, for output-orientation, or maximum reduction in inputs, given no change in outputs, for input orientation. The method of Färe (1984), later modified by Färe, Grosskopf and Kokkelenberg (1989), separates the factors of production into fixed and variable inputs, and subsequently solves a mathematical programming problem that permits the determination of a piece-wise production technology or frontier, which represents the efficient levels of output, given the fixed factors of production.

The DEA approach has limitations. First, it is a non-statistical approach, which makes statistical tests of hypotheses about structure and significance of estimates difficult to perform. Second, because DEA is non-statistical, all deviations from the frontier are assumed to be due to inefficiency.[16] Third, estimates of capacity and capacity utilization are sensitive to random errors in the data that can be attributed to measurement errors and unobservable shocks such as climatic changes. The strength of the model lies in its flexible incorporation of multiple inputs and outputs, straightforward addition of policy restrictions, and its close correspondence to microeconomic theory of production.

To develop these production models formally, the production technology S transforms inputs $x = (x_1, x_2, \dots, x_n) \in R_+^n$ into outputs $u = (u_1, u_2, \dots, u_m) \in R_+^m$ and summarizes the set of all feasible input and output vectors: $S = \{(x,u) \in R_+^{n+m}: x\ can\ produce\ u\}$, where R_+^n and R_+^m are sets of all non-negative real numbers. Let J be the number of vessels, so that $j = 1, \dots, J$ indexes individual vessels. Then, u_{jm} denotes the quantity of the *m*th output produced by the *j*th producer, and x_{jn} denotes the level of the *n*th input used by the *j*th producer. The n-dimensional input vector *x* is partitioned into fixed factors (indexed by f) and variable inputs (indexed by v): $x = (x_v, x_f)$. To determine the capacity outputs and capacity utilization, either a radial or a non-radial, output-oriented efficiency measure is computed relative to a frontier technology providing the potential output given the current use of inputs: $E^0(x,y) = \max\{\theta: (x, \theta y) \in S\}$. In this study, we adopt an output-oriented non-radial Russell measure that allows each output to be expanded by a unique measure.

Assuming strong disposal of inputs and outputs[17] and variable returns to scale, a non-parametric inner-bound approximation of the true technology can be represented by the following set of production possibilities (where *x* and *u* are vectors) (Färe *et al.*, 1994, Kerstens *et al.* 2005):

$$T^\Gamma = \left\{ (x,u) \in R_+^{n+m}: x \geq \sum_{j=1}^{J} x_j z_j,\ u_j \leq \sum_{j=1}^{J} u_j z_j, z_j \in \Gamma. \right\}$$

where $\Gamma \in \{C, NC\}$

with (i) $NC = \left\{ z_j \in R_+^J: \sum_{j=1}^J z_j = 1\ and z_j \in \{0,1\} \right\}$,

(ii) $C = \left\{ z_j \in R_+^J: \sum_{j=1}^J z_j = 1\ and z_j \geq 0 \right\}$.

The acronyms NC and C denote the non-convex and convex technologies, respectively. Following the activity analysis approach, the vector of intensity or activity variables, *z*, indicates the intensity at which a particular activity (observations) is employed in constructing the piecewise linear reference technology or frontier by constructing either non-convex or convex combinations of observations forming the best-practice frontier. In general, the non-convex technology is a subset of the convex technology ($T^{NC} \subseteq T^C$). Hence, the vessel's fishing capacity catch; *i.e.*, the maximum output one can generate with unlimited variable input amounts given the vessel capital stock (measured in m^3 of well capacity), states of

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[16] When the objective is maximum potential catch or the primal problem, the inefficiency is technical inefficient and when firms optimize profit, revenue, or costs, the inefficiency is economic inefficiency comprised of technical and allocative (scale inefficiency is sometimes distinguished from allocative inefficiency).

[17] Strong disposability of outputs (inputs) implies that the producer has the ability to dispose of unwanted outputs (inputs) with no private costs.

technology and environment, and resource abundance conditions, is higher under the convex, rather than the non-convex, technology

A short-run version of this production possibilities set is simply defined by dropping the constraints on the variable input factors to form the technology underlying Johansen plant capacity, in which the availability of variable factors is not restricted (Kerstens *et al.* 2005):

$$\hat{T}^{\Gamma} = \left\{ (x,u) \in R_{+}^{n+m}: x^{f} \geq \sum_{j=1}^{J} x_{j}^{f} z_{j},\ u_{j} \leq \sum_{j=1}^{J} u_{j} z_{j}, z_{j} \in \Gamma. \right\}$$

where Γ is again defined as above. Geometrically, both of these technologies are non-convex or convex monotonic hulls enveloping all observations.

The DEA mathematical programming problem that gives an output-oriented ray measure of capacity and capacity utilization is the following (Färe *et al.* 1994):

$$\max_{z,\theta,\lambda} \theta$$

subject to:

$$\theta u_{jm} \leq \sum_{j=1}^{J} z_{j} u_{jm}, m = 1, \ldots, M$$

$$\sum_{j=1}^{J} z_{j} x_{jn} \leq x_{jn}, n \in F_{x}$$

$$\sum_{j=1}^{J} z_{j} x_{jn} = \lambda_{Jn} x_{jn}, n \in V_{x}$$

$$z_{j} \geq 0, j = 1, \ldots, N$$

$$\lambda_{jn} \geq 0, n \in V_{x}$$

where θ is the proportion by which outputs can be expanded to yield the capacity output (e.g., if the reported output equaled 100 units and θ equaled 1.5, the capacity output would equal 150 units); u_{jm} is the m^{th} output of the j^{th} producer or observation as before; x_{jn} is the *n*th input for the *j*th producer as before; *Fx* and *Vx*, respectively, indicate vectors of fixed and variable factors; λ is a measure of the optimum utilization of the variable inputs, i.e. a measure of the proportional expansion or contraction of the variables inputs V_x to reach capacity frontier; and *z* is a vector of intensity variables that define the reference technology (i.e. the best-practice production frontier) by taking convex combinations of the data. If the value of θ is 1.0, production is efficient and output cannot be expanded, and if $\theta > 1.0$, the potential output may be expanded by $\theta - 1.0$. Problem [1] imposes constant returns to scale but variable returns to scale is allowed by imposing the constraint $\sum_{j=1}^{J} z_{j} = 1$.[18] Mathematically, the technology is a convex monotonic hull enveloping all observations.

The output constraint given by the second line of equation (1), $\theta u_{jm} \leq \sum_{j=1}^{J} z_{j} u_{jm}, m = 1, \ldots, M$, states

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[18] Variable returns to scale imposes the assumption that increasing all inputs by the same proportion will cause outputs to change by varying proportions (*e.g.* if all input are doubled, output levels might increase by a factor of 2, less than 2 or more than 2). The important aspect of variable returns to scale is that it permits varying rates of change in output levels, given different rates of change in input levels.

that capacity output is less than or equal to the piecewise linear best-practice reference technology relative to which capacity is measured. The fixed input constraint given by the third line of equation (1), $\sum_{j=1}^{J} z_j x_{jn} \leq x_{jn}, n \in F_x$, states that optimal usage of the fixed factor must be less than or equal to actual usage (since the optimal usage of the fixed factor may differ from actual usage) (Färe, Grosskopf and Kokkelenberg, 1989). The variable input constraint given in the fourth line of equation (1), $\sum_{j=1}^{J} z_j x_{jn} = \lambda_{Jn} x_{jn}, n \in V_x$, allows the variable inputs to be unconstrained, so that variable inputs do not limit output (Färe, Grosskopf and Lovell, 1994). The term $\lambda_{jn} \geq 0$ allows the bounds on the variable inputs to vary, since the intensity vector *z* is not restricted in $\sum_{j=1}^{J} z_j x_{jn}$ by this constraint.

Global constant returns to scale, a highly restrictive assumption, is imposed in the above model. Adding $\sum_{j=1}^{J} z_j = 1$, a convexity constraint which allows variable returns to scale, is more general, and is determined by the data rather than *a priori* assumed and imposed, which would otherwise be the case for constant returns to scale. The constraints in the last line of equation (1), $z_y \geq 0, j = 1, \ldots, N$, and $\lambda_{jn} \geq 0$, are non-negativity constraints.

For the analysis presented here, the above model is augmented with slack variables on outputs and fixed inputs, an additional constraint allowing for variable returns to scale technology, and constraints on the intensity variable that allows the data envelopment to be non-convex. The full model is

$$\max_{z,\theta,\lambda,s,e} \theta$$

subject to:

$$\theta u_{jm} = \sum_{j=1}^{J} z_j u_{jm} - s_m , m = 1, \ldots, M$$

$$\sum_{j=1}^{J} z_j x_{jn} + e_n = x_{jn}, n \in F_x$$

$$\sum_{j=1}^{J} z_j x_{jn} = \lambda_{Jn} x_{jn}, n \in V_x$$

$$\sum_{j=1}^{J} z_j = 1$$

$$z_j \in \{0,1\}, j = 1, \ldots, N$$

$$\lambda_{jn} \geq 0, n \in V_x$$

$$e_n \geq 0, n \in F_x$$

$$s_m \geq 0, m = 1, \ldots, M$$

The first and second constraints are modified with slack variables in order to calculate non-radial optimal values for each of these variables. The slack variables are constrained to be positive. The fourth constraint imposes variable returns to scale as discussed above. Finally, the intensity variable, z_j, is constrained to be either zero or one, which imposes non-convexity on the final solution. The above model is run once for each observation in the data.

The outcome of this output-oriented radial model is a scalar, θ, indicating the amount by which the production of each vessel's catch can be expanded relative to the observed production levels in order to reach the best-practice frontier. Because this is a radial model, all outputs are kept in fixed proportions (equal to those observed), and the expansion is radial.

The vector of intensity variables z defines the reference technology given the observed inputs and outputs, giving the intensity levels at which each of the J vessels operate. The z vector allows a radial decrease or increase of observed production activities (input and output levels) to construct unobserved but feasible activities. The intensity variables z_j are the weights that relate the target vessel (i.e. activity or observation) to its set of peers in the data set (*i.e.*, the vessels against which it is compared, including itself) (Färe, Grosskopf, and Kokkelenberg, 1989; Färe, Grosskopf, and Lovell, 1994). Thus, these variables comprising the vector of intensity variables z join the observed inputs and outputs to form the piecewise linear best-practice reference technology relative to which capacity is measured (i.e. the technology constructed by DEA). From a geometric viewpoint, this short-run industry model is a set consisting of a finite sum of line segments. The activity vector, z, indicates which portions of the line segments representing the vessel capacities are effectively used to produce outputs from given inputs. The best-practice capacity frontier is comprised of piecewise linear segments for each vessel grouping (e.g. the total fishery, Class 2 & 3 vessels, Class 4 & 5 vessels, Class 6 vessels, DML holders, and non-DML holders). Capacity is estimated separately for each vessel in these different groupings.

Capacity utilization (CU) is the ratio of observed output to capacity output, given by:

$$CU = \frac{u}{\theta u} = \frac{1}{\theta}.$$

CU = 1 means that observed output equals capacity output and that production lies on the best-practice frontier. CU < 1 means that observed output is less than full capacity output (that lies on the frontier), which can be due to insufficient variable input usage and/or technical inefficiency. The approach outlined above provides a ray measure of capacity output and CU, in which the multiple outputs are maintained in fixed proportions when they are expanded or contracted (see Segerson and Squires (1990) in a parametric context). This ray measure corresponds to the Farrell (1957) measure of output-oriented technical efficiency, due to the radial nature of the output expansion (in which outputs are kept in fixed proportions as the outputs produced are expanded or contracted).

Taking the inverse of the CU measure, i.e. $\frac{1}{CU} = \frac{1}{1/\theta} = \theta$, gives the amount by which current catch can be expanded to reach the capacity output. Thus if CU = 0.75, then $\theta = \frac{1}{0.75} = 1.33$.

In the technological-economic approach to capacity, observed output may differ from capacity output due to technical inefficiency or low levels of variable inputs (Färe, Grosskopf and Kokkelenberg, 1989).[19] Thus, in equation (1), the parameter θ, which measures the extent to which output must increase to reach the 'best practice' full capacity, includes the effects of both low variable input usage and technical inefficiency. In fisheries, technical efficiency corresponds to fishing skill (Kirkley, Squires, and Strand, 1998; Squires and Kirkley, 1999), and because DEA is deterministic, deviations from the frontier can also be due to luck, weather, vessel break-downs, and other random events. In addition, the technological-economic approach to capacity is predicated on 'normal practice' or 'normal operating conditions' among the vessels, which involves a range of efficiency in the fleet. To remove the effects of differences in technical inefficiency (fishing skill) and solely focus on the level of variable inputs, an alternative measure of capacity output can be constructed by purging θ in equation (1) of technical inefficiency (fishing skill), so that a comparable new measure only reflects low levels of variable inputs. This new problem is found by considering both the variable and the fixed inputs in the analysis (i.e. allowing

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[19] Technical efficiency from an output orientation indicates the maximum potential levels by which all outputs could be increased with no change in input levels. A technical efficiency score of 1.0 indicates technical efficiency. The value of θ is restricted to ≥ 1.0. If $\theta > 1.0$, production is inefficient and output levels could be increased by $\theta - 1.0$.

variable inputs to potentially bind) and estimating a new variable θ_2, where technical efficiency is $1/\theta_2$. In equation (1), the variable input constraint becomes $\sum_{j=1}^{J} z_j x_{jn} \leq \lambda_{Jn} x_{jn}, n \in V_x$, i.e. the "equality" = becomes the "less than or equal to" $\leq$. The difference between capacity output and technically efficient output is that variable inputs are fully utilized in the capacity output and are utilized at the observed levels (which could be fully utilized) in the technically efficient output.

The new fishing capacity utilization rate is estimated by (Färe *et al*. 1989):

$$CU_2 = \frac{\theta u}{\theta_2 u} = \frac{\theta}{\theta_2}$$

This CU measure purges the capacity indicators of the amount that is due to technical inefficiency (Färe, Grosskopf and Kokkelenberg, 1989), i.e. the effects of differences in fishing skill. This CU measure of Färe *et al*. (1989) permits an assessment of whether deviations from full capacity are because of inefficient production or less than full utilization of the variable and fixed inputs. Dividing the observed output by θ_2/θ, i.e. $u_{jm}/(\theta_2/\theta)$, gives an estimate of capacity output in which deviations from full capacity are solely due to low variable input usage and do not include the effects of technical inefficiency or mis- or un-measured production conditions, such as adverse weather, mechanical breakdowns, or other standard operating limitations.

The technically efficient output vector is θ_2 multiplied by observed production for each output. Total industry output for a species can be found by aggregating the firm-level technically efficient output for a species $\theta_2 u_{jm}$ over firms or vessels. Further summing over all species gives the total fishery catch. Likewise, the aggregate industry capacity output for a species (capturing both technical efficiency and variable input use) can be found as the sum of firm-level capacity outputs θu_{jm} and further summing over all species gives the total industry capacity output over all species. We stress, however, that summing over each vessel presents a lower bound for the industry or fleet level of capacity (i.e., the industry or fleet level of capacity is greater than or equal to the sum of the vessel levels of capacity).

As observed by Clark (1976), non-convexities in fisheries can arise due to indivisibilities, such as lumpy fixed factors. Because fixed factors also lead to the capacity issue, non-convex production possibility sets may be a recurring feature in empirical analyses of Johansen plant capacity and the short-run Johansen industry model in fisheries. There can also be difficulties in achieving convexity in multiproduct technologies. On a practical basis, the linear piece-wise best-practice capacity frontier given by convexity can be inflated because more of the observations interior to the convex frontier are enveloped by the frontier running from observations that may be somewhat dissimilar, but with non-convexity some of these previously interior observations now form the frontier. That is, the frontier now more closely follows observations and fewer "in between" observations are left isolated in the interior of the frontier. Capacity utilization is lower when convexity is imposed, which in turn leads to higher excess and over-capacity at the industry level.

Moreover, it is common practice to estimate DEA and industry models over subsets of the data. In fisheries, for instance, many authors choose to break DEA estimates down by flag-state under the assumption that technology is largely homogenous within a single flag-state but not between states. This method of breaking down the sample before DEA estimation is essentially an ad-hoc method of de-convexifying the production frontier. By using an explicitly non-convex frontier, the model is allowed to weight each observation appropriately while optimizing the objective function.

For reasons discussed in the preceding paragraphs, we do not impose convexity, and instead allow for a non-convex frontier in which the capacity frontier more closely follows individual observations that lie in between (but not below) adjacent observations that are higher output but are comparatively dissimilar in input values. The frontier is still best practice and linear piece-wise, i.e. with linear frontier segments running between the observations that are best practice, but now more observations form the best-practice frontier and there is less linear interpolation between observations that are comparatively dissimilar in input usage. Geometrically, instead of a convex frontier of piece-wise line segments enveloping the observations, the non-convex frontier still consists of piece-wise line segments enveloping the best-practice observations, but more observations are now best-practice and connected, giving some line segments that are shorter and a sawtooth appearance. More technically, the activity vector z indicates which portions of the line segments representing the best-practice frontier are used to generate capacity output from inputs, and when non-convexity is allowed different optimal solutions z^* are obtained than when convexity is allowed.

4. EFFICIENT FLEET CONFIGURATION IN WELL CAPACITY: SECOND STAGE OF ANALYSIS

Horizontally summing the vessel-level capacity outputs across vessels gives a measure of aggregate industry capacity output. Comparing this aggregate industry capacity output to current industry catch provides a measure of the *excess capacity* of the industry given the existing stocks of physical and natural capital and states of the environment and technology. Comparing aggregate industry capacity output to maximum sustainable yield or any other sustainable target catch level provides a measure of the *over-capacity* of the industry given the existing stocks of physical and natural capital and states of the environment and technology. Nonetheless, the fishing capacity measure does not allow reallocation of inputs and outputs across firms. This, in turn, does not allow assessment of the industry's optimal restructuring and configuration. The fishing capacity measure instead implicitly assumes that production of capacity output is feasible and that the necessary variable input, days, is available. In renewable resource industries, such as fishing industries, the resource stock(s) and notions of sustainable exploitation must be incorporated, since total production of the fishery is constrained by the productivity of the resource stock(s). Sustainable target yields, such as Total Allowable Catch (TAC), are typically imposed to ensure a sustainable supply of fish and protect the resource stocks from overexploitation. The TAC thus imposes social constraints on the activities of private firms.

Accounting for TACs or other catch limits in the approach of Dervaux, Kerstens, and Leleu (2000), adapted to fisheries by Kerstens *et al.* (2006), the optimal industry configuration is found by minimizing the total use of fixed inputs given that each firm cannot increase its use of fixed inputs, and the production of the industry is at least at the TAC level. The output level of each firm in this short-run Johansen sector model, extended to renewable resource industries, is the capacity output estimated from the firm-level capacity model, conditional upon the resource stocks and environmental parameters and state of technology.

The second step employs the "optimal" vessel-level, best-practice frontier measures of capacity output and capacity variable and fixed inputs as parameters in the industry model. In particular, the industry model minimizes industry use of fixed inputs such that total production is at least at the current total level (or at a quota level when the renewable resource model is extended to incorporate TACs) by reallocating production among vessels. These reallocation decisions are based on frontier production and input use of each vessel. In the short run, it is assumed that current capacities cannot be exceeded either at the firm or industry level.

In the first stage, the model thus computes an optimal activity vector z_j^* for each vessel j. Using z_j^*, the vector of capacity output and its vectors of optimal use of variable and fixed inputs can be computed by:

$$u_j^* = \sum_{j=1}^{J} u_j z_j^*, x_j^{f*} = \sum_{j=1}^{J} x_j^f z_j^*, x_j^{v*} = \sum_{j=1}^{J} x_j^v z_j^*$$

When the first-stage model is non-convex, the optimal activity vector for each vessel, z_j^*, is computed under this assumption.

The second stage, industry model may be specified as:

$$\min_{\theta,w,X_v} \theta$$

subject to

$$\sum_j \hat{u}^*_{jm} w_j \geq U_m, m = 1, \ldots, M$$

$$\sum_j x^*_{fj} w_j \leq \theta X_f, f = 1, \ldots, F$$

$$-X_v + \sum_j x^*_{vj} w_j \leq 0, v = 1, \ldots, V$$

$$U_m \leq \hat{U}_m, m = 1, \ldots, M$$

$$x^*_{vj} w_j \leq FD_{max}, j = 1, \ldots, J \; v = 1$$

$$0 \leq w_j \leq 1,$$

$$\theta \geq 0$$

The variables in this model over which the objective function is maximized are the weights (w_j) associated with each vessel *j*. Rather than reflecting a returns-to-scale hypothesis, the *w* variables now indicate which vessels' capacity shall be utilized and by how much. That is, the activity vector *w* indicates which portions of the line segments representing the vessel capacities are effectively used to produce outputs from given inputs. The components of the activity vector *w* are bounded above at unity, so that current capacities can never be exceeded. These weights take on a different role to those in the earlier DEA models, as a value of 1 implies that the vessel remains in the fishery and a value of 0 implies that the vessel leaves the fishery.

The first constraint $\sum_j \hat{u}^*_{jm} w_j \geq U_m, m = 1, \ldots, M,$ prevents total production by a combination of vessel capacities from falling below the current level, U_m, where $U_m = \sum_m^J u_{jm}$. That is, the first constraint is that the sum of the catch of each species (i.e. $u^*_{jm} = \theta_2 u_{jm}$), made by the remaining vessels (i.e. $w_j \geq 0$) must be no greater than the observed total catch for that species.

The second constraint $\sum_j x^*_{fj} w_j \leq \theta X_f, f = 1, \ldots, F,$ means that the total use of fixed inputs (right-hand side) cannot be less than the total use by a combination of firms, where $X_f = \sum_{j=1}^J x_{fj}$. This constraint ensures that final fixed input use does not exceed current fixed input use (which cannot happen in any case since $w_j \leq 1$) (Tingley and Pascoe 2005).

The third constraint $-X_v + \sum_j x^*_{vj} w_j \leq 0, v = 1, \ldots, V,$ calculates the resulting total use of variable inputs. The total amount of variable inputs, $X_v = \sum_{j=1}^J x_{vj}$, is a decision variable.

The fourth constraint $U_m \leq \hat{U}_m, m = 1, \ldots, M,$ indicates that catch for each species *m*, *m = 1,…, M*, cannot exceed the species quota $\hat{U}_m$.

The fifth constraint $x^*_{vj} w_j \leq FD_{max}, j = 1, \ldots, J \; v = 1,$ indicates that each vessel is limited to a common number of days per vessel given that the fishing days are indexed by v equal to 1 (i.e. the first and in our case only variable input).

The objective function $\min \theta$ is a radial input efficiency measure that solely focuses on the fixed inputs. This input efficiency measure has a fixed-cost interpretation at the industry level. The optimal solution to this simple mathematical programming problem gives the combination of vessels that can produce the same or more outputs with less or the same use of fixed inputs in aggregate. The objective function is minimized by insuring that the constraints are satisfied by first utilizing the boats that are operating at full efficiency (*i.e.*, TE_j = 1), and by removing vessels with low levels of economic technical efficiency (Tingle and Pascoe 2005).

Individual vessel quotas for different species may also be used to manage fisheries. An individual vessel quota for species m (say bigeye) leads to the following additional constraint to the basic industry model:

$$u_{jm}^{*} w_j \leq \bar{u}_{jm},$$

where $\bar{u}_{jm}$is the same for all vessels or can be adjusted by vessel size class (i.e. vessel-size-class specific values).

Technical inefficiency may be purged all or in part from the capacity output measure as discussed above.[20] This can be modeled by adjusting the capacity output entering the second stage industry model by its current observed technical inefficiency eventually corrected by an efficiency improvement imperative (α) (Kerstens *et al.* 2006). Currently technically efficient firms need no such adjustment. Assuming this correction factor is smaller or equal to unity ($\alpha \leq 1$), the adjustment of the second stage capacity output could take the following form when technical inefficiency is (partially) accepted:

$$\hat{u}_{jm}^{*} = \frac{u_{jm}^{*}}{\max[1, \alpha\theta^{*}]}$$

When technical inefficiencies are (partially) tolerated, capacity outputs are lower and more vessels are needed within the industry. When no adjustment for technical inefficiency is accepted, then the correction factor simply equals zero ($\alpha = 0$). As the efficiency improvement imperative (α) moves away from unity, vessels are forced to move towards their maximal capacity. When technical inefficiencies are adjusted, then u_{jm}^{*} in the constraint $\sum_j u_{jm}^{*} w_j \geq U_m, m = 1, \ldots, M$ is replaced by $\hat{u}_{jm}^{*}$, giving the constraint $\sum_j \hat{u}_{jm}^{*} w_j \geq U_m, m = 1, \ldots, M$.

When non-convexity is allowed, more vessels remain in the fleet since the non-convex approach provides greater technical efficiency and a higher capacity utilization rate in the first stage (more vessels define the best-practice frontier, thereby yielding full technical efficiency by definition, and the remaining vessels interior to the frontier are more likely to lie closer to the frontier). Furthermore, not only are there more vessels under non-convexity than under convexity in the solution, but in some cases there are other vessels than those found in the convex solution. Geometrically, the short-run industry model is a set consisting of a finite sum of line segments. The activity vector w indicates which portions of the line segments representing the vessel capacities are effectively used to produce outputs from given inputs.

5. 5. DATA AND BACKGROUND TO ESTIMATION

The Inter-American Tropical Tuna Commission (IATTC) provided the annual vessel-level purse seine data from the EPO tuna purse seine fishery for the years 1993-2010. These data included landings (retained catch) for yellowfin, bigeye, and skipjack tunas, vessel gross weight and other measures of vessel size (cubic meters of well capacity, net weight, or length, weight, and depth in meters), trip lengths (days, arrival date minus departure date for trip), and number of sets. Catch is specified in metric tons (t), and estimates are based principally on data from unloadings that since 2004 have been adjusted, based on the species composition estimates. All data were differentiated by mode of fishing: (1) sets associated with dolphins and unassociated schools and (2) sets on floating objects and unassociated schools. Trips were assigned to one of these two modes of fishing by whether the vessel held a DML or not. The well

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[20] Recall from above discussion that a vessel’s catch may be less than its capacity catch (as determined by best-practice frontier) due to either technical inefficiency or inappropriate usage of variable inputs, given states of the environment, technology, and resources and fixed factors. Technical inefficiency or skipper skill is expected to be largely constant over time, leading to a purge of technical inefficiency (where technical change is captured by shifts in the best-practice production frontier over time rather than distance from that frontier).

capacity and fishing day inputs from this dataset are summarized in Table **1** and Table **2**.

TABLE 1

Total well capacity by size class and permit type

	Class 2	**Class 3**	**Class 4**	**Class 5**		**Class 6**		All Vessels
Year	Non-DML	Non-DML	Non-DML	Non-DML	DML	Non-DML	DML	
1993	1,577.0	2,667.0	3,515.0	3,646.0		39,080.0	105,171.0	117,646.0
1994	1,872.0	2,853.0	4,361.0	3,948.0		67,929.0	88,588.6	120,840.6
1995	1,727.0	4,008.0	5,508.0	4,303.0	768.0	66,339.0	96,229.0	124,022.0
1996	1,526.0	4,452.0	5,066.0	4,213.0	768.0	62,002.0	100,412.0	130,721.0
1997	1,612.0	4,938.0	3,589.0	3,538.4	768.0	116,893.1	48,033.0	147,893.4
1998	1,703.9	4,813.3	3,920.0	6,489.2		86,361.0	113,920.1	162,867.4
1999	1,068.0	5,045.9	5,154.6	6,374.0	423.8	64,078.5	150,740.7	178,822.4
2000	984.0	5,292.4	5,497.1	7,131.4		59,820.4	135,663.6	178,441.1
2001	453.0	3,992.0	5,477.0	9,114.3		100,355.7	90,913.0	188,950.0
2002	740.0	4,516.1	5,665.8	9,082.5		107,982.3	101,534.9	197,615.2
2003	676.0	3,743.0	5,922.6	8,872.7		102,775.4	110,634.9	202,135.6
2004	489.0	2,964.0	6,772.0	10,169.7		117,701.2	124,069.0	206,285.9
2005	611.0	2,568.6	6,310.1	10,360.7		89,621.2	134,664.3	209,924.1
2006	489.0	2,879.4	5,940.7	10,933.0		128,484.6	132,828.1	224,509.4
2007	514.0	3,186.0	6,603.0	10,101.7		101,064.0	141,848.5	225,982.7
2008	322.0	2,656.0	6,565.3	9,286.0		104,640.0	122,988.5	223,672.8
2009	322.0	2,628.3	5,889.0	9,143.0		116,980.1	115,213.3	223,547.7
2010	216.0	2,193.0	6,069.9	7,718.0		110,072.0	111,105.5	209,924.4
2011	224.1	2,497.0	6,233.0	7,383.0		102,447.0	115,095.0	212,315.5

Source: IATTC

Note: Measured in metric tons. Class 5 vessels holding DMLs are observed for 4 years. See the text in Section 5 for discussion of these observations.

TABLE 2

Average fishing days by size class and permit type

	Class 2	**Class 3**	**Class 4**	**Class 5**		**Class 6**		All Vessels
Year	Non-DML	Non-DML	Non-DML	Non-DML	DML	Non-DML	DML	
1993	77.6	124.1	182.9	144.7		58.0	159.1	160.0
1994	69.5	137.6	139.9	185.1		94.1	169.7	167.2
1995	66.7	131.7	158.3	160.8	259.5	77.8	166.8	167.3
1996	75.1	130.7	146.4	183.1	245.0	66.6	193.5	174.2
1997	66.9	143.3	153.3	190.3	253.0	157.8	184.1	176.7
1998	67.2	141.8	170.7	176.8		113.7	190.2	184.5
1999	97.1	125.3	112.6	170.6	153.0	53.0	165.4	157.5
2000	115.4	132.6	139.5	172.5		111.1	183.8	177.2
2001	171.6	150.0	134.1	154.5		190.7	148.5	179.3
2002	113.6	120.7	126.1	185.6		160.8	162.7	174.1
2003	86.8	126.8	129.4	191.3		172.4	187.8	189.9
2004	83.8	80.7	105.4	170.1		136.2	183.0	180.2
2005	71.8	102.8	116.2	189.7		176.6	190.1	191.7
2006	94.4	124.1	118.8	176.1		146.8	196.8	195.2
2007	55.2	132.1	116.8	163.0		158.6	199.3	187.7
2008	155.0	157.5	122.6	177.4		160.1	196.4	186.0
2009	98.0	133.2	149.8	139.4		163.2	192.3	184.8
2010	117.5	158.7	152.9	150.8		159.4	197.4	190.2
2011	133.0	123.8	160.0	153.7		158.6	187.1	180.4

Source: IATTC

Note: Simple averages are taken over reported fishing days for vessels in each category. Class 5 vessels holding DMLs are observed for 4 years. See the text in Section 5 for discussion of these observations.

Note that the IATTC data indicated that there were 74 vessel-year observations of size class 5 vessels holding DMLs. These observations resulted in the four years of class 5 DML statistics reported in all tables that are broken down into DML and non-DML. In general, vessels below class 6 do not fish on dolphins because of technical constraints that prevent small vessels from successfully setting on tuna associated with dolphins. However, some vessels below class 6 are able to set on dolphins, and in this rare occurrence, if these vessels want to set on dolphins, they must hold a DML. Due to the small number of such observations, all reported results are nearly identical with or without these vessels.

The data were also differentiated by vessel size class according to the metric tons of well capacity classifications in Table 3. Size classifications were provided by the IATTC. Although the classifications was based on metric tons of well capacity, the analysis of optimal fleet size was performed using cubic meters of well capacity, since the latter measure provides a more accurate measure of the ability for vessels to carry tuna and is consistent with the IATTC capacity program.

TABLE 3

Class ID	Short tons		Metric tons	
	From	To	From	To
1	0	50	0	45
2	51	100	46	91
3	101	200	92	181
4	201	300	182	272
5	301	400	273	363
6	401	9999	364	9999

Source: IATTC

The number of vessels of each size class is given in Table **4**. Unique total refers to the total number of vessels fishing with or without a DML across all size classes in a given year.

TABLE 4

Number of vessels by class size

	Class 2	**Class 3**	**Class 4**	**Class 5**		**Class 6**		Unique Total
Year	Non-DML	Non-DML	Non-DML	Non-DML	DML	Non-DML	DML	
1993	17	18	13	9	-	34	94	151
1994	21	19	16	10	-	64	77	163
1995	19	25	20	11	2	61	87	175
1996	17	27	19	11	2	58	89	179
1997	18	30	14	9	2	108	40	194
1998	18	29	14	14	-	76	96	201
1999	11	30	18	13	1	57	124	208
2000	10	30	19	15	-	50	110	204
2001	5	22	19	20	-	82	75	204
2002	7	24	20	21	-	87	82	215
2003	6	20	21	21	-	82	89	214
2004	5	17	24	23	-	95	99	218
2005	6	14	22	23	-	76	105	220
2006	5	15	20	24	-	103	100	224
2007	5	17	23	23	-	79	106	227
2008	3	14	22	22	-	80	94	218
2009	3	14	19	22	-	88	89	214
2010	2	11	20	19	-	85	85	201
2011	2	13	21	18	-	80	88	206

Notes: DML and non-DML fishing vessels sum to more than the unique total in a given year due to vessels that had both DML and non-DML trips within the year. No vessels smaller than class 5 engaged in non-DML fishing during this period. Class 5 vessels holding DMLs are observed for 4 years. See the text in Section 5 for discussion of these observations.

The fishing industry differs from most industries in that the normal and customary operating procedure defining the production period (e.g. number of shifts per day, number of days worked per year) and working in a relatively homogeneous environment is not relatively fixed, but instead can vary year-by-year at both the vessel and industry level. Most importantly, the number of days fishing can vary. To accommodate this time-varying normal and customary operating procedure, and following Kerstens *et al.* (2006), we specify the use of fixed inputs as flow variables, so the fixed input variables (well capacity and

HP) are both multiplied by the number of fishing days for each vessel and each year. This specification guarantees a more balanced picture of the efficiency of fishing firms, because firms are rather heterogeneous in terms of their fishing effort and service flow, i.e. the number of fishing days varies substantially. This transformation complicates the interpretation of the optimal value of the efficiency measure in model (9). It necessitates dividing the optimal scalar reduction of the fixed inputs by the optimal value of the number of fishing days (i.e. $(\theta^* x_f)/x_v^*$).

TABLE 5

Biomass		
Year	YFT	BET
1993	507,622	495,951
1994	502,826	476,341
1995	516,623	453,121
1996	509,057	436,203
1997	484,001	410,163
1998	571,572	398,397
1999	645,225	451,292
2000	758,080	503,235
2001	757,748	481,932
2002	642,148	412,019
2003	497,671	353,375
2004	389,566	348,888
2005	337,008	357,187
2006	306,171	366,236
2007	366,890	373,082
2008	409,005	383,880
2009	413,373	386,936
2010	382,209	365,009
2011	374,076	348,135

Source: IATTC
Note: In metric tons.

Fishing vessels also fish in different areas in which the resource stock conditions can vary by area. Following Kerstens *et al.* (2006), when the resource stock conditions are part of the technological constraints, then the search for more efficient combinations of production plans has to be restricted to combinations of vessels fishing in the same area. This principle can be accommodated by further delineating the model and variables by area, but is not required in our application because we specify distinct production technologies by DML or not, where vessels setting on dolphins harvest in an area geographically distinct from vessels setting on floating objects. Further spatial delineation is implicitly given by specifying distinct harvest technologies by vessel size class, where smaller vessels generally fish closer to shore than larger vessels.

The IATTC also provided biomass estimates for yellowfin and bigeye tunas, given in Table **5**. Average sea surface temperature during the trip is reported in vessel logbooks, and average values for each year and size class are given in Table **7**. Both of these variables are used to control for environmental conditions and were specified as non-discretionary or fixed inputs.

TABLE 6

MSY and TAC for Yellowfin and Bigeye

	Yellowfin		**Bigeye**	
Year	MSY	Quota	MSY	Quota
1993	269,730	232,100		
1994	269,730	219,200		
1995	269,730	238,800		
1996	269,730	250,100		
1997	269,730	256,700		
1998	269,730	264,400		45,000
1999	269,730	265,000	73177	40,000
2000	248,488	248,488	64,727	64,727
2001	275,925	275,925	70,061	70,061
2002	254,723	254,723	77,199	77,199
2003	284,979	284,979	62,849	62,849
2004	284,707	284,707	95,572	95,572
2005	287,519	287,519	105,575	105,575
2006	288,569	288,569	91,519	91,519
2007	281,902	281,902	81,350	81,350
2008	273,159	273,159	83,615	83,615
2009	264,967	264,967	90,538	90,538
2010	262,857	262,642	80,963	27,865

Source: IATTC Annual, Fishery Status and Stock Assessment Reports, various years.
Note: Quotas through 1997 are from Table 14 of the 1998 Annual Report and are measured in metric tons. For 2000 through 2009, the MSY is used for the quota.

MSY values for yellowfin and bigeye tunas were obtained from IATTC Annual Reports and are displayed in Table **6**. The MSY values were calculated by assuming there is not a stock-recruitment relationship and based on average fishing gear selectivity during multiple-year periods, where the bigeye MSY was based on an average selectivity for all fisheries combined.[21] Because skipjack are apparently not fully utilized in the EPO, there is no control proposed in the level of harvest.

Estimates of capacity outputs, allowing for variable returns to scale and non-convexity were made at vessel level for trips by mode of fishing (dolphin and unassociated schools, floating object and unassociated schools) for the aggregate fishery and then separately for each vessel size class as described in Section 3. Trips on dolphins and unassociated schools were classified by whether or not a DML was held, under the assumption that holding a DML signaled trips that set on dolphins. Trips without DMLs were classified as sets on floating objects and unassociated schools. The landings of other fish caught were negligible and hence not considered in the analysis. After vessel level capacity was calculated, the minimum well capacity to maintain observed or MSY level catch was calculated as per Section 4.

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[21] Estimates of the MSY are sensitive to the age-specific pattern of selectivity that is used in the calculations, and different allocation schemes for fishing effort among fisheries would change this combined selectivity pattern (IATTC 2011). Thus, the question of an “optimal” MSY depends to a large extent on the dominant fisheries.

TABLE 7

Average sea surface temperature by size class and permit type

	Class 2	**Class 3**	**Class 4**	**Class 5**		**Class 6**		All Vessels
Year	Non-DML	Non-DML	Non-DML	Non-DML	DML	Non-DML	DML	
1993	24.6	24.8	24.8	24.7		25.4	26.2	25.5
1994	24.6	23.9	23.7	23.7		25.3	26.4	25.1
1995	24.7	23.8	23.6	24.3	23.8	25.6	26.5	25.2
1996	24.9	24.7	24.9	25.1	25.1	25.7	26.4	25.6
1997	26.7	25.9	26.8	26.2	26.7	26.6	27.8	26.8
1998	25.9	25.5	25.1	25.2		26.8	26.7	26.2
1999	24.3	24.5	24.6	24.0	25.6	26.0	26.3	25.5
2000	25.1	24.9	24.9	25.4		25.5	26.5	25.9
2001	25.6	25.6	25.6	25.8		25.6	26.9	26.1
2002	26.0	25.1	25.0	25.2		25.7	27.3	26.0
2003	25.0	24.6	24.8	25.3		25.6	26.6	25.7
2004	24.0	24.6	24.7	24.4		24.8	26.0	25.2
2005	24.7	24.7	25.1	24.9		25.0	25.8	25.3
2006	23.9	24.6	24.2	23.9		25.2	25.7	25.1
2007	23.8	24.3	24.3	24.3		25.4	25.5	25.0
2008	24.6	25.2	25.1	24.4		25.3	25.5	25.3
2009	23.5	25.4	25.1	25.1		25.4	26.8	25.9
2010	26.0	24.8	24.5	25.1		25.8	26.4	25.7
2011	25.5	24.5	24.7	25.2		25.1	25.9	25.4

Source: IATTC

Notes: Measured in degrees Celsius. Simple averages are taken over average sea surface temperature for each set reported by vessels in each category. Class 5 vessels holding DMLs are observed for 4 years. See the text in Section 5 for discussion of these observations.

Fishing capacity and minimum well capacity were separately estimated for each year. Separate estimation yields estimates conditional upon that year's state of technology, so that differences in annual values may be due to not only changes in physical capital (measured by well capacity) but also to technical change.

The technological-economic measure of capacity output specifies full utilization of variable inputs. However, estimates of technical efficiency by DEA were made using the number of sets per vessel by each type of fishing by year as the variable input. Estimates of capacity utilization, in which deviations from full capacity utilization are due to either low variable input usage or technical inefficiency, are given by θ in problem [1]. Estimates of capacity utilization purged of the effects of technical efficiency were given by the ratio θ_2/θ_1, where θ_2 is derived from problem [1] allowing for variable inputs that are not necessarily fully utilized and θ_1 is the θ in problem [1] when variable inputs are fully utilized (Färe, Grosskopf and Kokkelenberg 1989). Thus, estimates of capacity utilization purged of the effects of technical efficiency are due to low variable input usage. As noted above, we have attempted to control for deviations from full capacity utilization due to technical change in the later years by estimating each year independently. We also attempted to control for deviations from full capacity utilization due to fluctuations in resource abundance and environmental conditions (which shift the capacity output frontier in or out) by specifying biomass and sea surface temperature.

6. EMPIRICAL RESULTS: FISHING CAPACITY AND FIRST STAGE ANALYSIS

Capacity utilization and technical efficiency are estimated by DEA. We estimate the output-oriented non-convex problem given in Section 3, so that outputs are kept in fixed proportions as outputs are expanded or contracted, while holding fixed factors constant and with full utilization of variable inputs. We separately estimate for the two unique harvest technologies for DML and non-DML fisheries and also for the full fishery.

6.1. Overall levels of fishing capacity in eastern Pacific Ocean tuna purse seine vessels

The results of the first stage analysis, shown in Table 8 and Table 9, indicate that average capacity utilization for the entire fishery is about 86%.[22] This value indicates that purse seine vessels had a catch capacity 16% greater than their observed catch. In short, tuna purse seine vessels had the fishing capacity to catch substantially more of all species over 1993-2011 than they actually caught. The largest contributor was non-DML vessels, which had an average excess capacity of 20% compared to DML vessels, which had an average excess capacity of just 13%.

There is very little inter-temporal variation, with the degree of capacity utilization reaching a minimum in the early and mid-1990s before settling between 0.8 and 0.9 for the remainder of the sample period. There is one year where capacity utilization was above 1, which is a result of the non-convexity assumption in the model. These models are also called “super-efficiency” models since it is possible for vessels to not be inefficient under non-convexity. This flexibility is another reason to prefer non-convex estimates.

TABLE 8

Average fishing capacity utilization, non-convex frontier

	Non-DML		**DML**		**All**	
Year	CU	TE	CU	TE	CU	TE
1993	0.80	0.80	0.92	0.92	0.86	0.86
1994	0.68	0.68	0.88	0.88	0.74	0.74
1995	0.84	0.84	0.93	0.93	0.88	0.88
1996	0.81	0.81	0.93	0.93	0.86	0.86
1997	0.83	0.83	0.98	0.98	0.86	0.86
1998	0.71	0.71	0.89	0.88	0.76	0.76
1999	0.80	0.80	0.88	0.88	0.86	0.86
2000	0.74	0.74	0.87	0.87	0.82	0.82
2001	0.84	0.84	0.83	0.83	0.84	0.84
2002	0.87	0.87	0.87	0.87	0.85	0.85
2003	0.89	0.89	0.90	0.90	0.89	0.89
2004	0.81	0.81	0.84	0.84	1.03	1.03
2005	0.88	0.88	0.85	0.85	0.89	0.89
2006	0.83	0.83	0.91	0.91	0.90	0.90
2007	0.83	0.83	0.87	0.87	0.85	0.85
2008	0.91	0.91	0.84	0.84	0.87	0.87
2009	0.89	0.89	0.88	0.88	0.89	0.89

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[22] As a reminder, fishing capacity is the maximum potential output possible when there is full variable input utilization, given the stocks of physical and natural capital and states of the environment and technology. This definition differs from cubic meters of well capacity.

2010	0.91	0.91	0.87	0.87	0.89	0.89
2011	0.92	0.92	0.90	0.90	0.91	0.91

Notes: Capacity utilization (CU) and technical efficiency (TE) are calculated as described in Section 3. "DML" column values are calculated over all vessels holding a dolphin mortality limit, "Non-DML" values are over vessels not holding this permit, and "All" values are calculated over unique vessels. Non-convexities in the frontier are allowed.

Table 9 breaks the capacity utilization values down by size class groups. These results will be discussed in more detail in the following sections.

TABLE 9

Average capacity utilization by size class, aggregate estimation

	Class 2 and 3		Class 4 and 5		Class 6			
	Non-DML		**Non-DML**		**Non-DML**		**DML**	
Year	CU	TE	CU	TE	CU	TE	CU	TE
1993	0.64	0.64	0.89	0.89	0.91	0.92	0.92	0.92
1994	0.57	0.57	0.68	0.68	0.74	0.88	0.88	0.88
1995	0.77	0.77	0.85	0.85	0.89	0.92	0.92	0.92
1996	0.73	0.73	0.87	0.87	0.84	0.94	0.94	0.94
1997	0.67	0.67	0.92	0.92	0.88	0.99	0.99	0.99
1998	0.45	0.45	0.73	0.73	0.87	0.89	0.89	0.88
1999	0.74	0.74	0.87	0.87	0.80	0.88	0.88	0.88
2000	0.55	0.55	0.78	0.78	0.88	0.87	0.87	0.87
2001	0.77	0.77	0.78	0.78	0.89	0.83	0.83	0.83
2002	0.76	0.76	0.86	0.86	0.91	0.87	0.87	0.87
2003	0.75	0.75	0.90	0.90	0.92	0.90	0.90	0.90
2004	0.66	0.66	0.74	0.74	0.88	0.84	0.84	0.84
2005	0.83	0.83	0.83	0.83	0.92	0.85	0.85	0.85
2006	0.88	0.88	0.86	0.86	0.81	0.91	0.91	0.91
2007	0.83	0.83	0.77	0.77	0.87	0.87	0.87	0.87
2008	0.94	0.94	0.87	0.87	0.93	0.84	0.84	0.84
2009	0.91	0.91	0.88	0.88	0.89	0.88	0.88	0.88
2010	0.90	0.90	0.90	0.90	0.92	0.87	0.87	0.87
2011	0.79	0.79	0.94	0.94	0.94	0.90	0.90	0.90

Notes: Capacity utilization (CU) and technical efficiency (TE) are calculated for each vessel within a given DML holding and year as described in Section 3 and averaged to produce the figures. "DML" column values are calculated over all vessels holding a dolphin mortality limit, "Non-DML" values are over vessels not holding this permit, and "All" values are calculated over unique vessels. Not enough vessels of class lower than 6 are observed to estimate capacity utilization for the DML technology. Non-convex frontier results are reported.

6.2. The non-DML fishery

This fishery sets on floating objects and unassociated schools and includes vessels in all size classes 2-6.

6.2.1. The Classes 2 and 3 vessels fishery

Potential catch (fishing capacity) exceeds actual catch for school sets and floating object sets for class 2 and 3 vessels, i.e. there is excess capacity, whether or not capacity output is purged of technical efficiency. Excess capacity for all set types for class 2-3 vessels has been steadily declining over 1993-2011. The vessels in this size class show the lowest average capacity utilization of any group.

6.2.2. The Classes 4 and 5 vessels fishery

Potential catch exceeds actual catch for floating object and school sets for class 4 and 5 vessels, i.e. there is excess capacity. Excess capacity for all set types has roughly trended downwards over 1993-2010, but with considerable variability. Until the final years of the sample, these vessels had the second lowest capacity utilization.

6.2.3. The Class 6 vessels fishery

Potential catch exceeds actual catch for school sets and floating object sets for class 6 vessels, i.e. there is excess capacity, with average excess capacity being 12% over the sample. Excess capacity has been non-monotonic over the sample period, first increasing, then falling.

6.3. Class 6 DML vessels

Potential catch exceeds actual catch for school sets and floating object sets for Class 6 vessels, i.e. there is excess capacity, with average excess capacity being 12% over the sample. Excess capacity has increased consistently from 1993 to 2011.

6.4. Summary and conclusions on fishing capacity and first stage analysis

Excess fishing capacity for all species combined, defined as capacity output minus observed output (landings), exists for all vessel size classes individually and combined for all set types (dolphin, school, floating objects) for yellowfin, bigeye, and skipjack tuna when measured as: (1) potential catch minus actual catch or (2) technically efficient catch. Excess capacity catch for all vessel size classes, tuna species, and purse-seine fishing methods increased from about 50,000 metric tons in 1993 to above 140,000 metric tons in 1998, before falling to about 52,000 metric tons in 2011. Prior to the year 2000, DML vessels were responsible for the majority of this excess capacity, while since 2000, the DML and non-DML vessels have each contributed roughly half of the excess capacity.

7. EFFICIENT FLEET CONFIGURATION: WELL CAPACITY

Table 10 reports the ratio of optimal well capacity to observed well capacity estimated using the non-convex capacity output frontier and aggregate catch limits on yellowfin, bigeye, and skipjack that do not differentiate between fishing with and without a DML. When the ratio of optimal to observed well capacity lies closer to one, then the closer the match between the optimal and observed well capacities, and the closer this ratio lies to zero, the greater the divergence between the optimal and observed well capacities. In the baseline case, no restrictions are placed on the industry. In the TAC case, catch limits (yellowfin and bigeye MSYs and historical catch of skipjack) are imposed.

TABLE 10

Johansen industry model fixed input capacity

	Baseline			**TAC**		
Year	Non-DML	DML	All	Non-DML	DML	All
1993	0.82	0.89	0.88	0.82	0.89	0.88
1994	0.63	0.84	0.73	0.63	0.84	0.73
1995	0.81	0.89	0.85	0.81	0.89	0.85
1996	0.79	0.88	0.83	0.73	0.87	0.81
1997	0.85	0.98	0.87	0.79	0.92	0.81
1998	0.74	0.81	0.77	0.73	0.76	0.73
1999	0.76	0.82	0.81	0.67	0.72	0.70
2000	0.73	0.81	0.76	0.58	0.74	0.66
2001	0.87	0.83	0.85	0.81	0.63	0.68
2002	0.89	0.81	0.84	0.83	0.57	0.67
2003	0.92	0.87	0.86	0.81	0.68	0.68
2004	0.84	0.72	0.76	0.79	0.66	0.70
2005	0.87	0.76	0.81	0.80	0.67	0.73
2006	0.85	0.87	0.87	0.81	0.86	0.85
2007	0.81	0.82	0.79	0.77	0.80	0.77
2008	0.84	0.81	0.80	0.82	0.79	0.78
2009	0.82	0.84	0.83	0.79	0.79	0.80
2010	0.88	0.81	0.81	0.86	0.80	0.80
2011	0.90	0.87	0.87	0.88	0.85	0.86

Notes: Reported values are the Johansen industry model θ given in Section 4 which is the fraction of optimal well capacity (m3) to observed well capacity (m3). One minus reported fraction gives amount of reduction to reach technical efficiency and minimum cost of well capacity. Baseline specification applies no additional restrictions beyond the observed catch levels. The TAC specification limits total output in the fishery to lie at or below the total allowable catch or, if the TAC is unspecified for that year, the MSY. A non-convex frontier is assumed.

Table 11 breaks down the industry efficiency estimates by size class group for the baseline and TAC models. Average minimum input efficiency differs across the classes by a maximum of 14 points (between class 4 and 5 non-DML vessels and class 6 non-DML vessels). Overall, these values indicate that fixed input utilization follows a similar pattern to capacity utilization.

TABLE 11

Johansen industry model by size class, aggregate estimation

	Class 2 and 3		Class 4 and 5		Class 6			
	Non-DML		**Non-DML**		**Non-DML**		**DML**	
Year	Baseline	TAC	Baseline	TAC	Baseline	TAC	Baseline	TAC
1993	0.82	0.82	0.82	0.82	0.82	0.82	0.89	0.89
1994	0.63	0.63	0.63	0.63	0.63	0.63	0.84	0.84
1995	0.81	0.81	0.81	0.81	0.81	0.81	0.89	0.89
1996	0.79	0.73	0.79	0.73	0.79	0.73	0.88	0.87
1997	0.85	0.79	0.85	0.79	0.85	0.79	0.98	0.92
1998	0.74	0.73	0.74	0.73	0.74	0.73	0.81	0.76
1999	0.76	0.67	0.76	0.67	0.76	0.67	0.82	0.72
2000	0.73	0.58	0.73	0.58	0.73	0.58	0.81	0.74
2001	0.87	0.81	0.87	0.81	0.87	0.81	0.83	0.63
2002	0.89	0.83	0.89	0.83	0.89	0.83	0.81	0.57
2003	0.92	0.81	0.92	0.81	0.92	0.81	0.87	0.68
2004	0.84	0.79	0.84	0.79	0.84	0.79	0.72	0.66
2005	0.87	0.80	0.87	0.80	0.87	0.80	0.76	0.67
2006	0.85	0.81	0.85	0.81	0.85	0.81	0.87	0.86
2007	0.81	0.77	0.81	0.77	0.81	0.77	0.82	0.80
2008	0.84	0.82	0.84	0.82	0.84	0.82	0.81	0.79
2009	0.82	0.79	0.82	0.79	0.82	0.79	0.84	0.79
2010	0.88	0.86	0.88	0.86	0.88	0.86	0.81	0.80
2011	0.90	0.88	0.90	0.88	0.90	0.88	0.87	0.85

Notes: Reported values are the Johansen industry model θ given in Section 4 and are calculated for each DML and year group. Baseline specification applies no additional restrictions beyond the observed catch levels. The TAC specification limits total output in the fishery to lie at or below the total allowable catch or, if the TAC is unspecified for that year, the MSY. Not enough vessels of class lower than 6 are observed to estimate values for the DML technology. Convex frontier results are reported.

From the industry model, optimal well capacity can be calculated subject to meeting existing catch levels or quotas. These values are given in Table 12.

TABLE 12

Observed and efficient well capacity (cubic meters)

	Actual			Baseline Johansen			TAC Johansen		
Year	Non-DML	DML	All	Non-DML	DML	All	Non-DML	DML	All
1993	50,485	105,171	117,646	41,065	89,044	99,229	41,065	89,044	99,229
1994	81,017	88,589	120,895	45,104	71,212	86,878	43,829	70,044	86,699
1995	81,885	96,997	124,022	62,459	84,199	101,404	62,459	84,199	101,404
1996	77,312	101,180	130,774	61,796	83,847	100,925	62,092	81,968	98,524
1997	130,624	48,801	147,946	111,330	46,132	126,632	100,408	42,702	117,531
1998	103,287	113,920	162,867	60,705	86,871	123,139	57,393	81,481	116,850
1999	81,721	151,164	178,822	65,233	123,702	142,269	52,297	111,771	129,095
2000	78,725	135,664	178,441	62,678	104,332	133,551	57,409	95,163	116,433
2001	119,392	90,913	188,950	101,129	72,589	155,410	83,880	58,160	114,811
2002	127,987	101,535	197,615	109,930	78,035	155,937	78,793	50,852	115,382
2003	121,990	110,635	202,136	106,017	91,057	169,364	85,413	73,189	130,776
2004	138,096	124,069	206,286	118,529	78,261	144,091	106,083	72,589	135,899
2005	109,472	134,664	209,924	91,000	94,087	162,742	84,676	83,740	145,248
2006	148,727	132,828	224,509	118,227	113,229	184,559	119,358	109,862	181,730
2007	121,469	141,849	225,983	92,878	106,203	165,908	95,761	100,020	159,700
2008	123,469	122,989	223,673	96,994	99,350	169,113	95,461	93,082	161,423
2009	134,962	115,213	223,548	103,635	95,006	174,890	101,625	89,750	171,477
2010	126,269	111,106	209,924	106,336	89,145	163,693	107,561	86,517	165,311
2011	118,784	115,095	212,316	105,242	98,138	180,791	101,518	94,355	177,353

Notes: All values are in cubic meters. Minimum well capacity is calculated by the Johansen industry model as the least amount of well capacity required to maintain output (Baseline Johansen) or achieve a catch limit (TAC Johansen) conditional on vessels operating on the efficient frontier. Non-convex frontier results are shown.

Both efficient and observed well capacity (measuring the physical capital stock) of all purse seine vessels increased from 1993 until recently when they have leveled off and recently declined, with observed well capacity beginning its decline in 2008 and efficient capacity in 2007. Efficient well capacity peaked at 184,559 m^3 in 2007 and observed well capacity peaked at 225,983 m^3 in the same year. The difference between observed and efficient well capacity, deemed *excess well capacity*, largely rose until peaking in 2007 and declining beginning in 2008. These temporal trends are shown in the figures below. Compared to the IATTC's goal of 158,000 m^3 of well capacity that leaves vessels at observed stages of inefficiency, our approach eliminates roughly the same amount of well capacity.

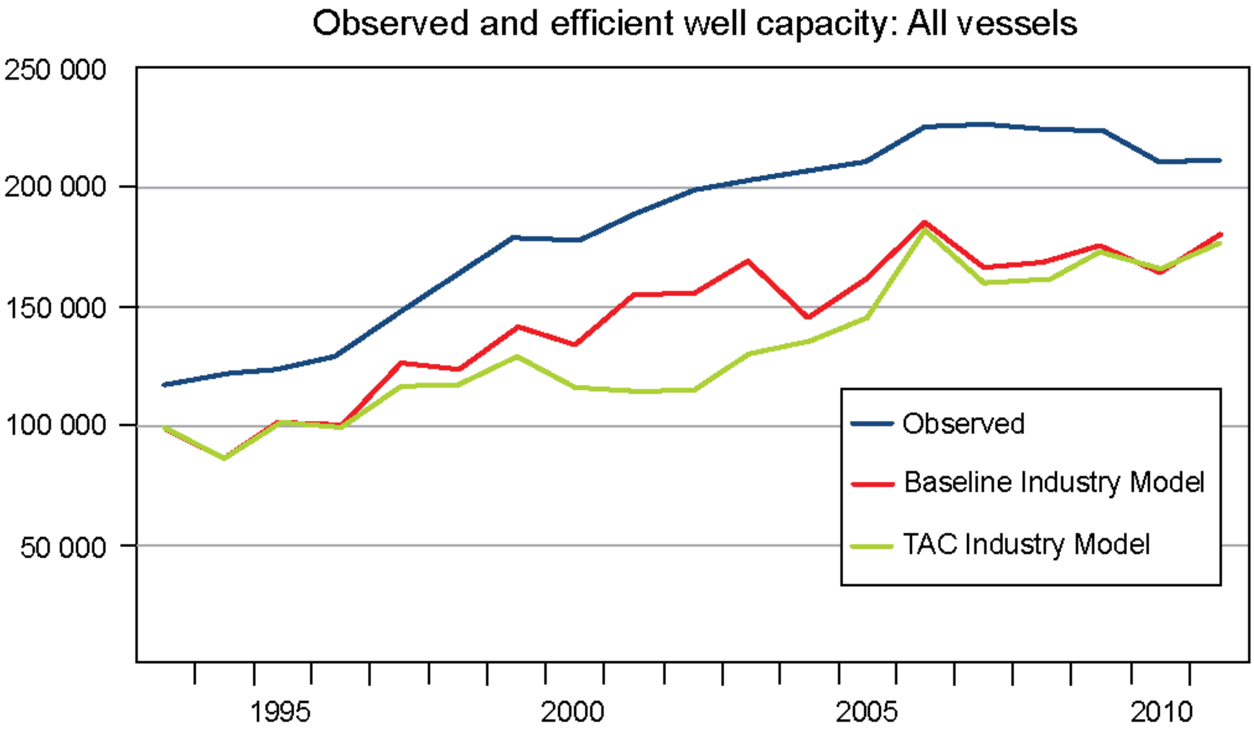


FIGURE 1

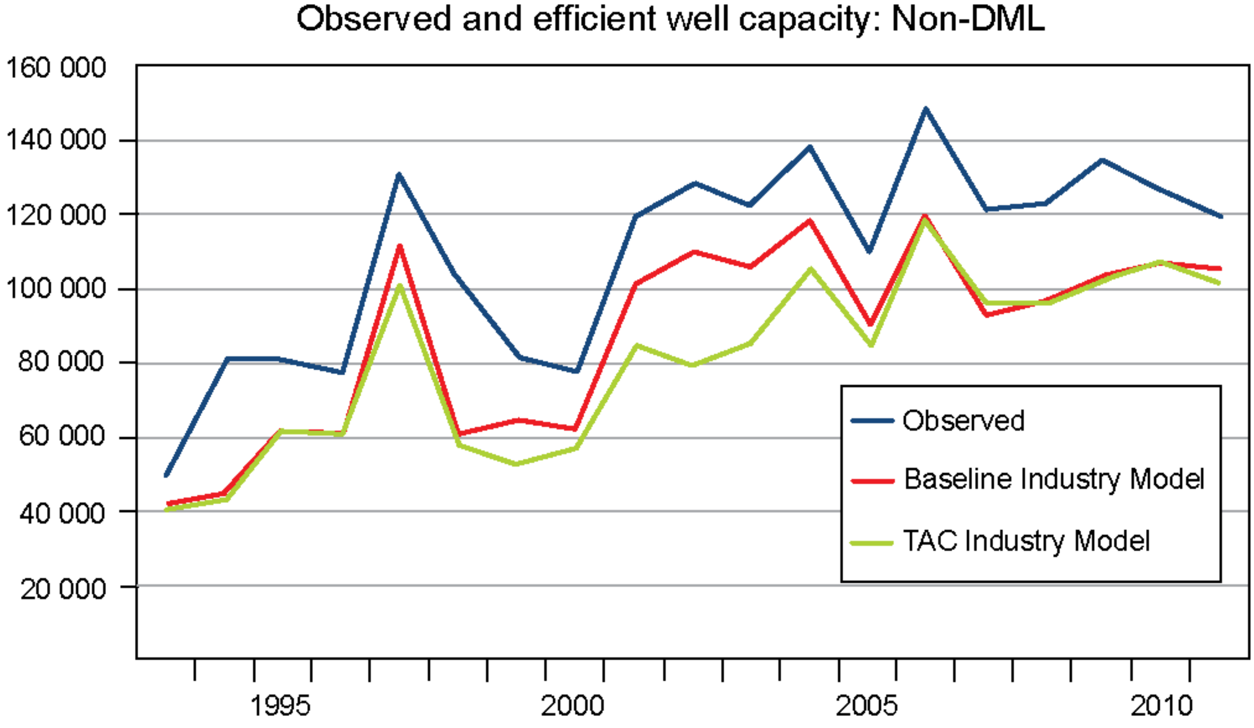


FIGURE 2

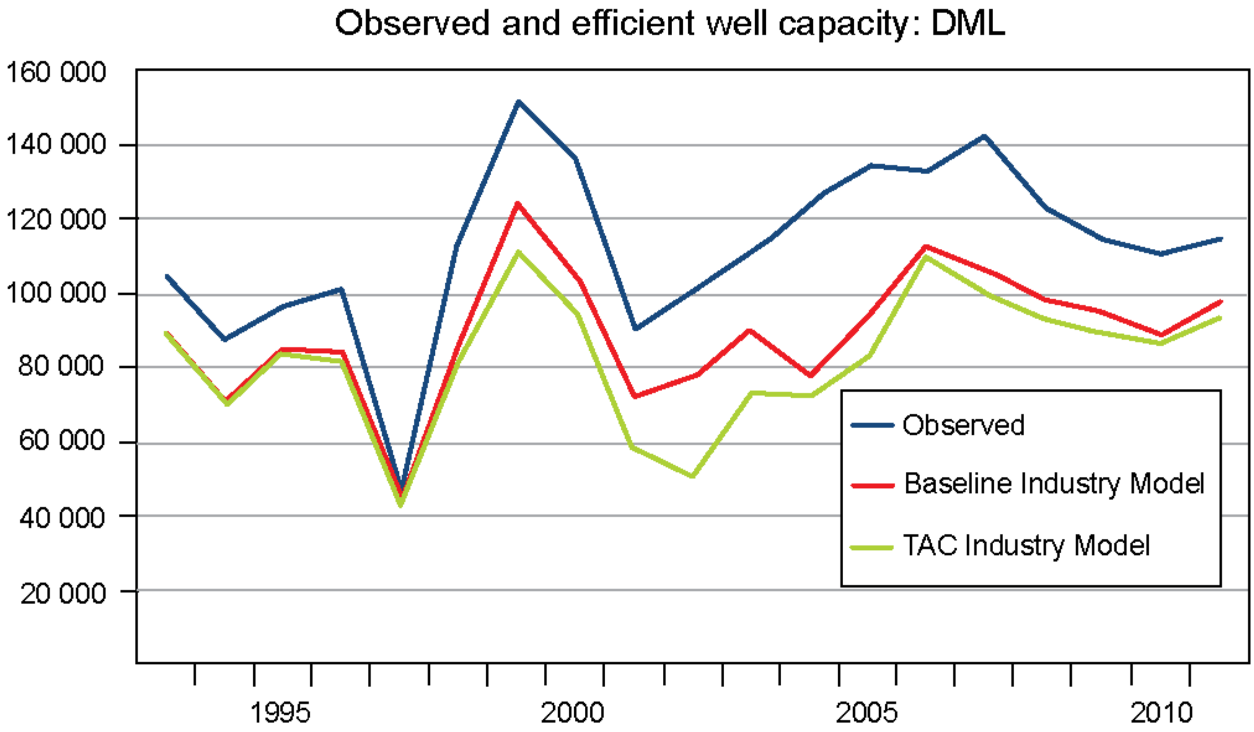


FIGURE 3

The intensity variables estimated by the industry model in Section 4 indicate whether a vessel should remain in the fishery. The sum of intensity variables is therefore a count of efficient vessels that remain after optimal industry reconfiguration. This number will be the lower bound on number of vessels, because it assumes that the least efficient vessels should be removed.

The following table and Figure 4, Figure 5, and Figure 6 give the optimum number of efficient vessels. These vessels are the most efficient vessels in the fleet, and the more inefficient vessels are removed (with a convex frontier, these vessels could be scaled) so that the efficient vessels produce capacity catch subject to maintaining total catch of skipjack tuna and TAC of yellowfin and bigeye tunas. In the first of two steps, vessels reach full efficiency by adjusting their days fished (variable inputs) with their observed technical efficiency (skipper skill) kept constant. In the second step, the most efficient vessels are kept.

Table **13** shows the observed number of vessels in the left three columns. These values are the same as those found in Table **4**. The middle three columns show the number of vessels in the baseline Johansen industry model. This model imposes no policy restrictions on the vessels or fleet. One can see that the number of vessels from this optimal capacity perspective is 42 vessels lower than observed, on average, across both fishing methods. The right three columns show the same values with a TAC imposed on the fishery. The TAC reduces the average number of vessels by another 11 per year relative to the baseline model. The figures clearly show that the TAC binds more heavily in the middle period.

TABLE 13

Observed and efficient number of vessels

	Actual			Baseline Johansen			TAC Johansen		
Year	Non-DML	DML	All	Non-DML	DML	All	Non-DML	DML	All
1993	91	94	151	74	79	128	74	79	128
1994	132	77	165	86	61	124	85	60	124
1995	136	89	175	108	77	144	108	77	144
1996	133	91	180	110	76	146	107	74	141
1997	180	42	195	156	39	170	144	37	159
1998	151	96	201	102	72	154	95	66	148
1999	129	125	208	100	102	163	86	92	150
2000	124	110	204	97	83	152	85	76	134
2001	148	75	204	127	57	169	108	47	129
2002	159	82	215	138	61	174	105	39	133
2003	150	89	214	133	72	180	112	59	141
2004	164	99	218	139	62	156	128	58	148
2005	141	105	220	119	73	172	109	65	155
2006	167	100	224	136	83	185	135	81	184
2007	147	106	227	116	79	169	114	75	164
2008	141	94	218	111	75	163	109	70	159
2009	146	89	214	111	73	166	110	69	163
2010	137	85	201	116	68	156	117	66	157
2011	134	88	206	118	75	173	115	72	172

Note: Minimum number of vessels in the non-convex Johansen industry model is the fewest vessels required to maintain current output (Baseline Johansen) or achieve a catch limit (TAC Johansen) conditional on moving all vessels to the efficient frontier, allowing for changes in input intensity. Non-convex frontier results are shown.

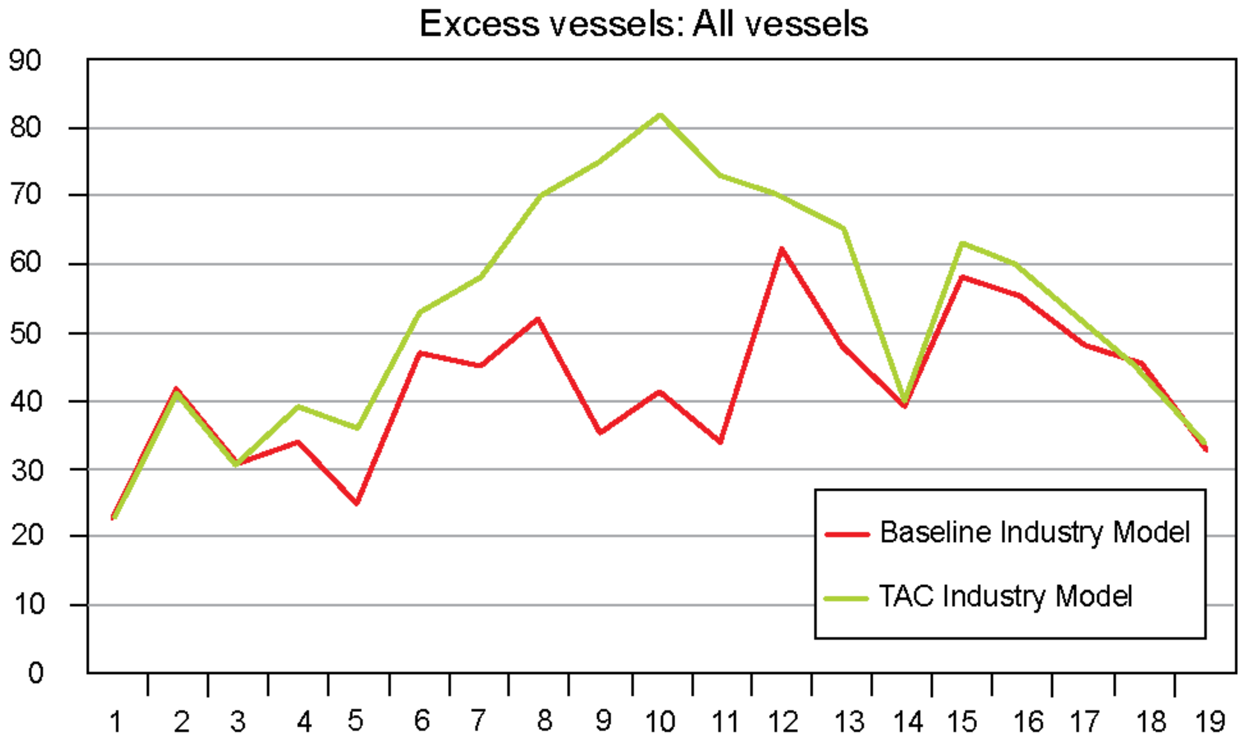


FIGURE 4

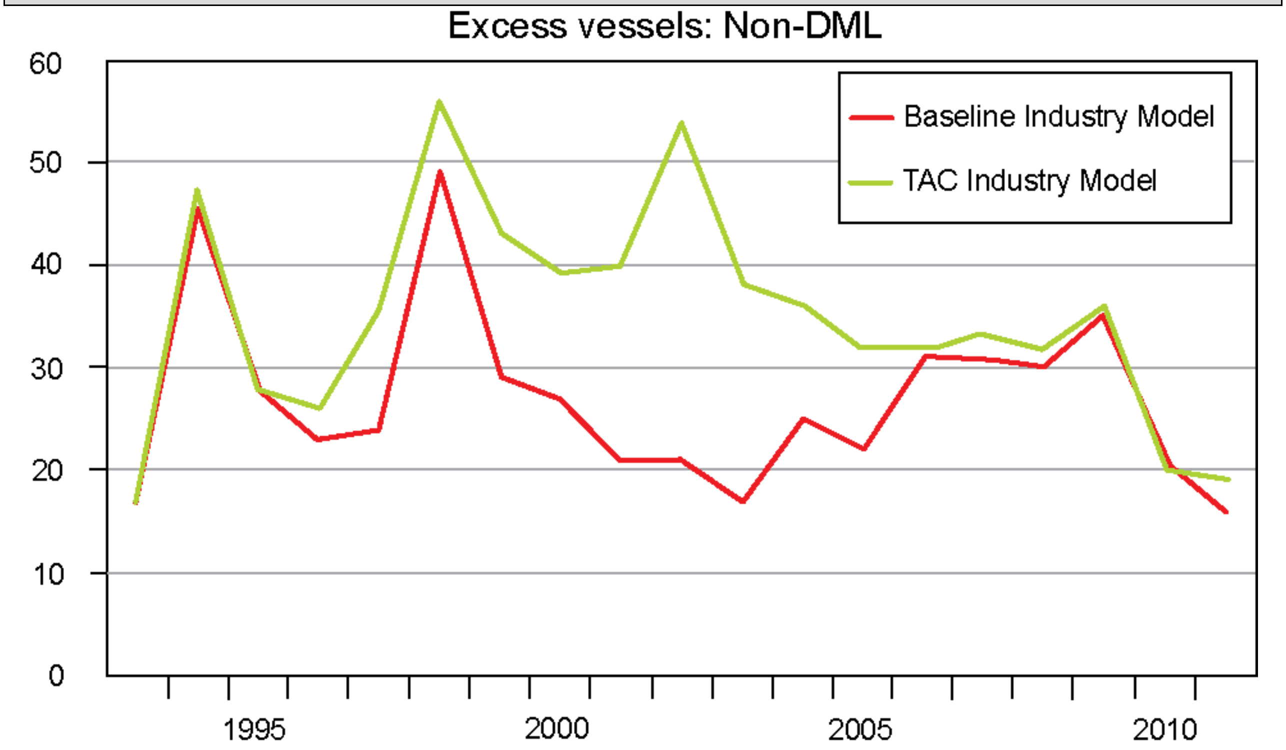


FIGURE 5

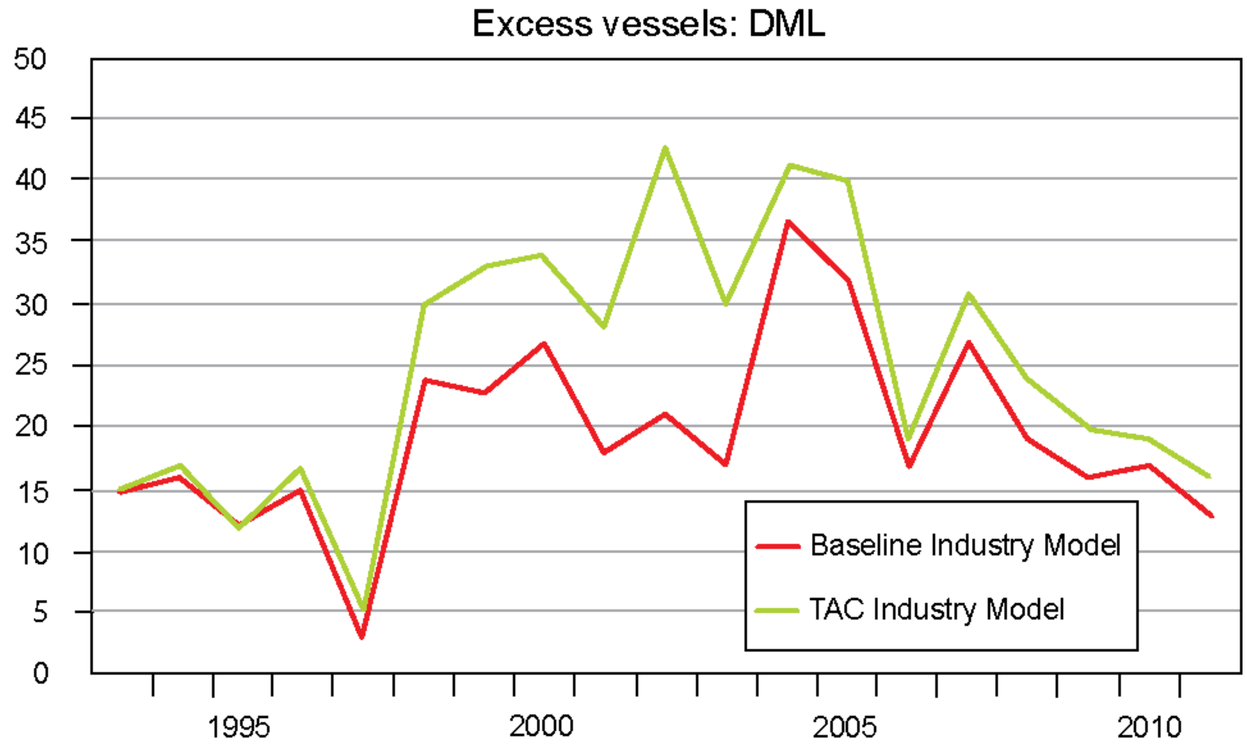
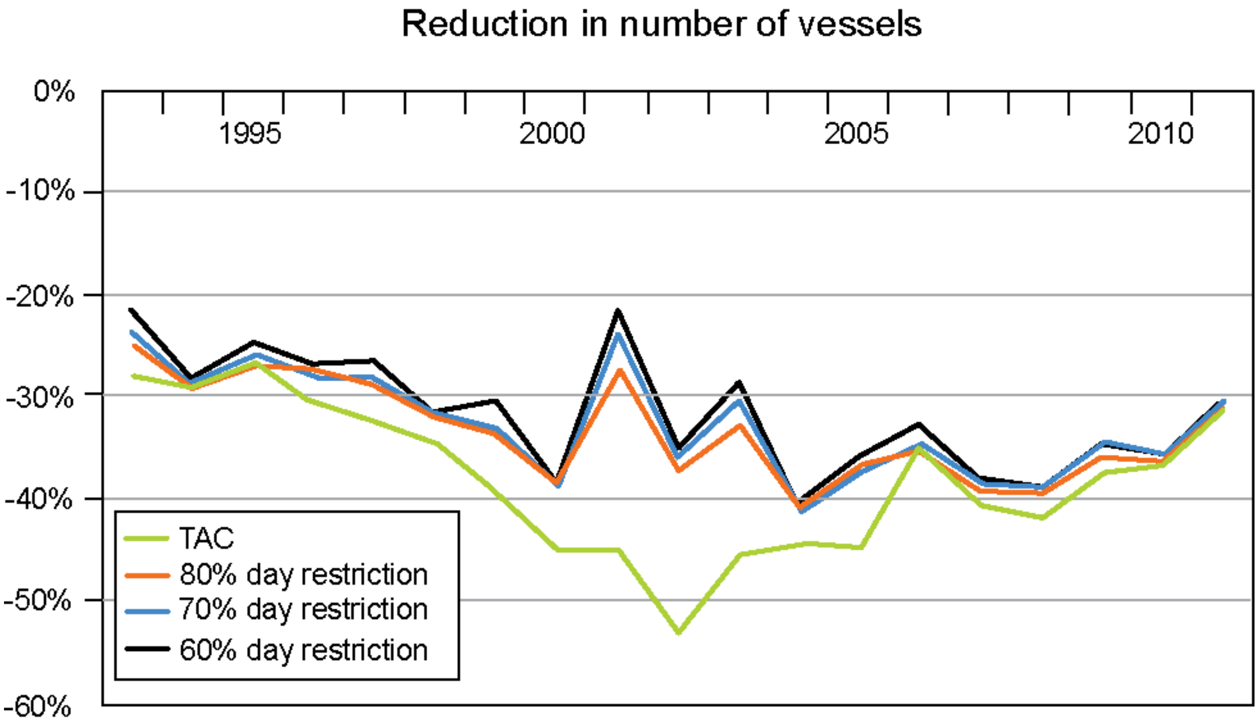


FIGURE 6

8. RESTRICTING FISHING DAYS

In addition to restrictions on total catch through TACs or individual vessel catch through Individual Vessel Quotas (IVQs), the model presented in this paper can also be used to assess the impact of restricting the number of fishing days for each vessel. The restriction is incorporated into the model by adding a constraint for each vessel's variable input (days) such that it must lie at or below a given value in the second-stage analysis. The maximum number of days allowed can be chosen by the researcher or policy maker to explore alternative policy outcomes.

Figure 7 compares three different day restriction policies to the TAC policy discussed above. To allow for flexible comparison across years with widely different vessel effort, the day restrictions are imposed as a percentage of observed maximum number of days in the fishery for each year. For instance, an 80% restriction forces all vessels to fish at most 80% of the maximum number of days recorded for that year. Thus, the 80% restriction is the loosest policy and corresponds closely to the baseline Johansen industry model. The 60% restriction is the strictest policy considered. Below 60%, the model fails to converge due to the impossibility of maintaining catch under extreme day restrictions.



Note: All values are percentage reduction in the number of vessels relative to the observed number in the fishery. "TAC" refers to the total allowable catch policy discussed above. Each day restriction line is discussed in the text. "80% day restriction" is the loosest policy and "60% day restriction" is the strictest.

FIGURE 7

One can see that the TAC reduces fleet size much more than any of the day restrictions. Also, seemingly counter-intuitively, the more restrictive day policies leave more vessels in the fishery than the less restrictive policies. This result can be explained by examining the dynamic response of the fishery to a day-restriction. When vessels are free to fish any number of days, the more efficient vessels will fish more often. Once days are restricted, vessels are no longer able to employ as much effort, disproportionally impacting the high efficiency vessels. To maintain catch levels, the total industry must compensate by either increasing the fishing days of less efficient vessels, adding more vessels, or both. Such a result is exactly what occurs under day restrictions in the Johansen industry model. The number of vessels increases relative to other policies while the average fishing intensity of the fleet falls.

9. SIZE CLASS SPECIFIC RESULTS AND ASSESSMENT OF DISTRIBUTIONAL CONCERNS

To address possible social and political concerns about fishery diversity, we also estimated the industry model over each size class group individually. Therefore, we ran separate estimates for vessel-size groups of Classes 2 and 3, Classes 4 and 5, and Class 6 for vessels that do not hold DMLs and Class 6 vessels that hold DMLs. Below, we compare the values derived from this estimation to the values calculated by the aggregate model results reported in Sections 6 and 7.

Table 14 and Table 9 show capacity utilization rates for the disaggregated and aggregated models, respectively. One can see that the values are largely similar, with the disaggregated estimates being 0.03 points higher than the aggregate estimates, on average. The largest difference is in the class 2 and 3 vessels, where average disaggregated values are 0.08 points higher. These higher values are likely due to the very small number of vessels of this size class and the relatively narrow range of outputs generated by vessels in these classes.

Table 15 and Table **11** show industry model fixed input utilization rates for the disaggregated and aggregated models, respectively. Again, the rates largely agree, with the disaggregated estimates being 0.02 points higher than the aggregate estimates, on average. The largest difference is now in class 6 non-DML TAC estimates, where average disaggregated values are 0.11 points higher.

TABLE 14

Average capacity utilization by size class, independent estimation

	Class 2 and 3		Class 4 and 5		Class 6			
	Non-DML		**Non-DML**		**Non-DML**		**DML**	
Year	CU	TE	CU	TE	CU	TE	CU	TE
1993	0.67	0.67	0.94	0.94	0.92	0.92	0.92	0.92
1994	0.64	0.64	0.68	0.68	0.83	0.88	0.88	0.88
1995	0.77	0.77	0.89	0.89	0.94	0.93	0.93	0.93
1996	0.76	0.76	0.88	0.88	0.90	0.94	0.94	0.94
1997	0.73	0.73	0.91	0.91	0.92	0.99	0.99	0.99
1998	0.51	0.51	0.78	0.78	0.90	0.89	0.89	0.88
1999	0.91	0.91	0.89	0.89	0.93	0.88	0.88	0.88
2000	0.82	0.82	0.83	0.83	0.90	0.87	0.87	0.87
2001	1.01	1.01	0.79	0.79	0.91	0.83	0.83	0.83
2002	0.91	0.91	0.88	0.88	0.93	0.87	0.87	0.87
2003	0.80	0.80	0.90	0.90	0.95	0.90	0.90	0.90
2004	0.72	0.72	0.79	0.79	0.89	0.84	0.84	0.84
2005	0.87	0.87	0.87	0.87	0.92	0.85	0.85	0.85
2006	0.89	0.89	0.90	0.90	0.82	0.91	0.91	0.91
2007	0.84	0.84	0.81	0.81	0.90	0.87	0.87	0.87
2008	0.96	0.96	0.89	0.89	0.93	0.84	0.84	0.84
2009	0.96	0.96	0.91	0.91	0.94	0.88	0.88	0.88
2010	0.98	0.98	0.93	0.93	0.92	0.87	0.87	0.87
2011	0.96	0.96	0.95	0.95	0.96	0.90	0.90	0.90

Notes: Capacity utilization (CU) and technical efficiency (TE) are calculated for each vessel within a given size class, DML holding, and year as described in Section 3 and averaged to produce the figures. "DML" column values are calculated over all vessels holding a dolphin mortality limit, "Non-DML" values are over vessels not holding this permit, and "All" values are calculated over unique vessels. Not enough vessels of class lower than 6 are observed to estimate capacity utilization for the DML technology. Non-convex frontier results are reported.

TABLE 15

Johansen industry model by size class, independent estimation

	Class 2 and 3		Class 4 and 5		Class 6			
	Non-DML		**Non-DML**		**Non-DML**		**DML**	
Year	Baseline	TAC	Baseline	TAC	Baseline	TAC	Baseline	TAC
1993	0.63	0.63	0.95	0.95	0.93	0.93	0.89	0.89
1994	0.35	0.35	0.64	0.64	0.86	0.86	0.84	0.84
1995	0.75	0.75	0.85	0.85	0.86	0.86	0.89	0.89
1996	0.73	0.73	0.91	0.91	0.90	0.88	0.88	0.88
1997	0.69	0.69	0.98	0.98	0.90	0.90	0.98	0.98
1998	0.42	0.42	0.77	0.77	0.93	0.93	0.81	0.81
1999	0.82	0.82	0.87	0.87	0.93	0.92	0.82	0.82
2000	0.81	0.81	0.80	0.80	0.92	0.90	0.81	0.81
2001	0.93	0.93	0.79	0.79	0.92	0.87	0.83	0.68
2002	0.86	0.86	-	-	0.93	0.88	0.81	0.63
2003	0.74	0.74	0.87	0.87	0.96	0.93	0.87	0.74
2004	0.79	0.79	0.74	0.74	0.91	0.91	0.72	0.72
2005	0.80	0.80	0.85	0.85	0.91	0.91	0.76	0.76
2006	0.96	0.96	-	-	0.85	0.85	0.87	0.87
2007	0.82	0.82	0.81	0.81	0.85	0.85	0.82	0.82
2008	0.99	0.99	0.90	0.90	0.84	0.84	0.81	0.81
2009	0.99	0.99	0.89	0.89	0.82	0.82	0.84	0.84
2010	0.99	0.99	0.95	0.95	0.88	0.88	0.81	0.81
2011	0.94	0.94	0.91	0.91	0.93	0.93	0.87	0.87

Notes: Reported values are the Johansen industry model θ given in Section 4 and are calculated for each size class, DML, and year group. Baseline specification applies no additional restrictions beyond the observed catch levels. The TAC specification limits total output in the fishery to lie at or below the total allowable catch or, if the TAC is unspecified for that year, the MSY. Not enough vessels of class lower than 6 are observed to estimate values for the DML technology. Non-convex frontier results are reported.

Finally, the minimum number of vessels for each class as implied by the industry model is compared in the following figure. As with the capacity utilization values and industry model estimates, these values agree highly across the different model estimations.

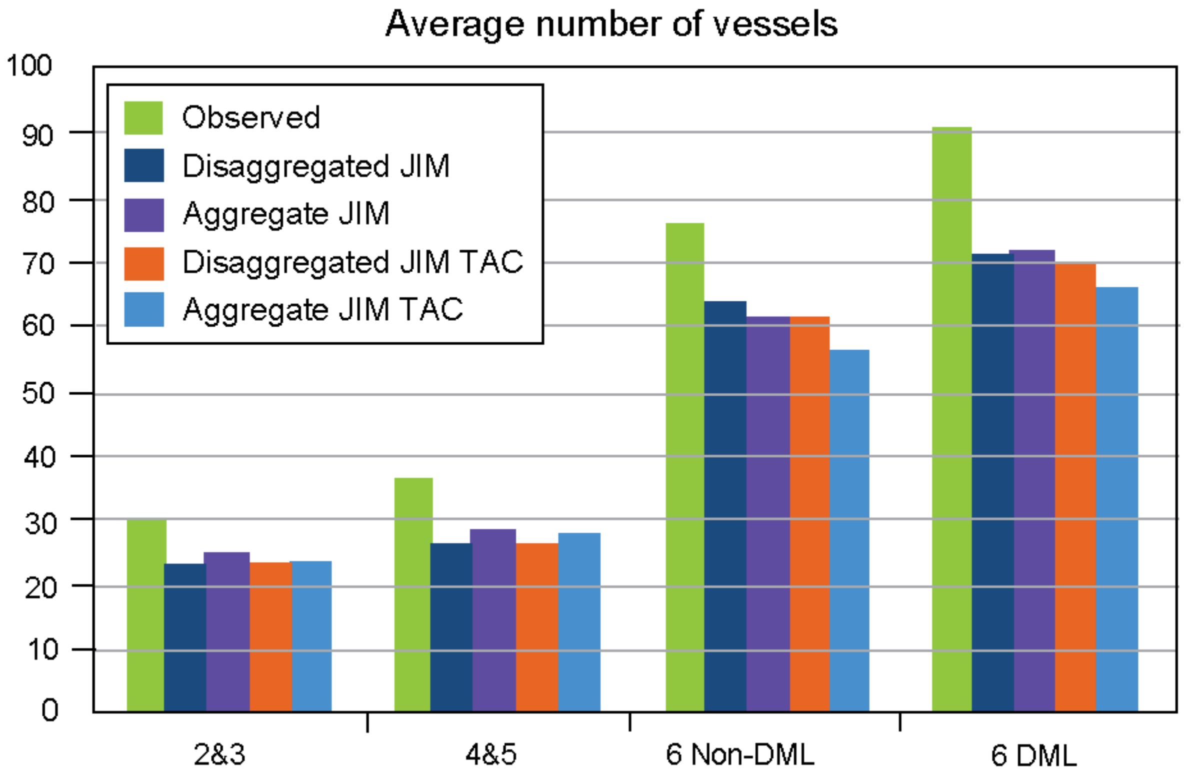


FIGURE 2

10. SUMMARY AND CONCLUSIONS

Given the importance of maintaining sustainable tuna fisheries and the stated objectives of limiting fleet capacity, the analysis in this paper examines the optimum tuna purse seine fleet capacity in the EPO. Optimal capacity is defined as the minimum well capacity required to catch specified levels of yellowfin, bigeye, and skipjack tuna. In addition to calculating optimal well capacity, this study also calculates the total amount of fishing capacity in terms of metric tons of catch of tuna by EPO purse seine vessels and compares it against existing MSYs. Finally, we examine alternative levels of catch and fleet size that could arise under conservation and management policies including maximum sustainable yields (MSYs) and day-based restrictions.

The results from the first stage analysis indicate that average capacity utilization for the entire fishery is 0.86, indicating that total fish catch could be increased by 16% if all vessels operated on the best-practice efficient frontier. Non-DML holding vessels have an average capacity utilization of 0.83, while DML holding vessels have an average capacity utilization of 0.89, indicating that the DML holders are slightly more efficient overall. The second stage analysis—the industry model—indicates that overall well capacity could be reduced by 18% if the fishery were to improve catch efficiency. If the fishery had been restricted to fish below the TACs for bigeye and yellowfin and observed total catch for skipjack in each year between 1993 and 2011, then average well capacity could have been reduced by 24%. In both of these cases, the average difference between DML and non-DML vessels is slight.

In terms of actual well capacity reduction, the industry model shows that efficient levels of well capacity would have been, on average for the last 5 years, 171,000 m^3. With a TAC in place, this value falls to 167,000 m^3, from an average observed level of 219,000 m^3. Overall, these results are in line with IATTC recommendations to reduce well capacity to 158,000 m^3, indicating that such a policy is close to the technically efficient level of fixed inputs for the fishery. Similarly, the model indicates vessel number reductions of 22 to 24% on average, depending on the catch restriction imposed.

Finally, running a disaggregated model over three different size class groupings shows that distributional concerns are not large with the fishery reconfiguration implied by the aggregate industry model. The average difference in implied minimum number of vessels between the aggregate and disaggregated models is less than 1, indicating that the aggregate model preserves a large degree of class size heterogeneity.

APPENDIX

A.1: Convex Analysis

As stated in the body of the text, we believe that non-convex frontiers are more appropriate than convex when analyzing this fishery according to fishing method. For comparison, below are tables presenting convex frontier results for both capacity utilization and the Johansen industry model fixed input scaling factor.

TABLE 16

Average capacity utilization (Convex frontier)

	Non-DML		DML		All	
Year	CU	TE	CU	TE	CU	TE
1993	0.60	0.60	0.69	0.69	0.63	0.63
1994	0.48	0.48	0.72	0.72	0.55	0.55
1995	0.61	0.61	0.76	0.76	0.66	0.66
1996	0.56	0.56	0.71	0.71	0.60	0.60
1997	0.60	0.60	0.78	0.78	0.61	0.61
1998	0.46	0.46	0.67	0.67	0.54	0.54
1999	0.62	0.62	0.68	0.68	0.62	0.62
2000	0.56	0.56	0.60	0.60	0.53	0.53
2001	0.61	0.61	0.69	0.69	0.63	0.63
2002	0.60	0.60	0.65	0.65	0.56	0.56
2003	0.67	0.67	0.64	0.64	0.64	0.64
2004	0.62	0.62	0.60	0.60	0.56	0.56
2005	0.66	0.66	0.63	0.63	0.61	0.61
2006	0.62	0.62	0.67	0.67	0.64	0.64
2007	0.61	0.61	0.64	0.64	0.59	0.59
2008	0.70	0.70	0.66	0.66	0.65	0.65
2009	0.67	0.67	0.71	0.71	0.66	0.66
2010	0.68	0.68	0.70	0.70	0.67	0.67
2011	0.65	0.65	0.70	0.70	0.66	0.66

Notes: Capacity utilization (CU) and technical efficiency (TE) are calcuated as described in Section 3. "DML" column values are calculated over all vessels holding a dolphin mortality limit, "Non-DML" values are over vessels not holding this permit, and "All" values are calculated over unique vessels. Convexity in the frontier is imposed.

From these two tables, it is clear that the convex frontier indicates about 20 points lower technical efficiency than the non-convex frontier. Similarly, the convex industry model gives an optimal reduction in well capacity about 20 percentage points larger than the non-convex industry model.

TABLE 17

Johansen industry model fixed input capacity, convex frontier

Year	Baseline Non-DML	DML	All	TAC Non-DML	DML	All
1993	0.63	0.68	0.65	0.63	0.68	0.65
1994	0.49	0.70	0.57	0.49	0.70	0.57
1995	0.60	0.74	0.68	0.60	0.74	0.68
1996	0.52	0.68	0.62	0.49	0.66	0.60
1997	0.62	0.76	0.62	0.57	0.72	0.57
1998	0.51	0.65	0.56	0.50	0.61	0.53
1999	0.55	0.63	0.60	0.48	0.53	0.50
2000	0.52	0.57	0.52	0.42	0.51	0.45
2001	0.65	0.70	0.66	0.57	0.43	0.50
2002	0.56	0.64	0.56	0.50	0.40	0.43
2003	0.68	0.62	0.63	0.60	0.42	0.50
2004	0.65	0.54	0.55	0.60	0.47	0.50
2005	0.66	0.58	0.60	0.59	0.50	0.53
2006	0.64	0.65	0.63	0.60	0.64	0.61
2007	0.58	0.63	0.58	0.56	0.63	0.56
2008	0.64	0.62	0.59	0.63	0.60	0.58
2009	0.64	0.67	0.64	0.62	0.63	0.61
2010	0.63	0.66	0.63	0.62	0.66	0.62
2011	0.63	0.69	0.63	0.62	0.69	0.63

Notes: Reported values are the Johansen industry model θ given in Section 4 which is the fraction of optimal well capacity (m^3) to observed well capacity (m^3). One minus reported fraction gives amount of reduction to reach technical efficiency and minimum cost of well capacity. Baseline specification applies no additional restrictions beyond the observed catch levels. The TAC specification limits total output in the fishery to lie at or below the total allowable catch or, if the TAC is unspecified for that year, the MSY. A convex frontier is assumed.

A.2: IVQ Restrictions

In this appendix, we evaluate the technological-economic optimum fleet fishing capacity, well capacity, and vessel numbers when vessels are subject to individual vessel quotas (IVQs) for bigeye. Two bigeye IVQs have been recommended: (1) 1.2 mt/m^3 of well capacity and (2) 0.56 mt/m^3 of well capacity. These bigeye IVQs differ from bigeye ITQs, because IVQs are not transferable, and hence there is less economic efficiency.

In the context of the model presented in this paper, IVQ restrictions amount to individual vessel restrictions on catch in the second stage. Such restrictions enter in the same was a day restrictions but are placed on vessel-level total catch for bigeye. Because the main constraint in the model requires that the total fishery meet or exceed the given catch limit, such IVQs do not reduce catch of the tuna subject to the quota or of other fish. For this reason, a model such as the one provided in this paper might not be appropriate to evaluate such a policy option.

A.3: IATTC Annual Report vessel numbers and well capacity

The two figures below are reproduced from IATTC annual reports for 2010 and 2011. They serve as a comparison to Table **4** and Table **1**.

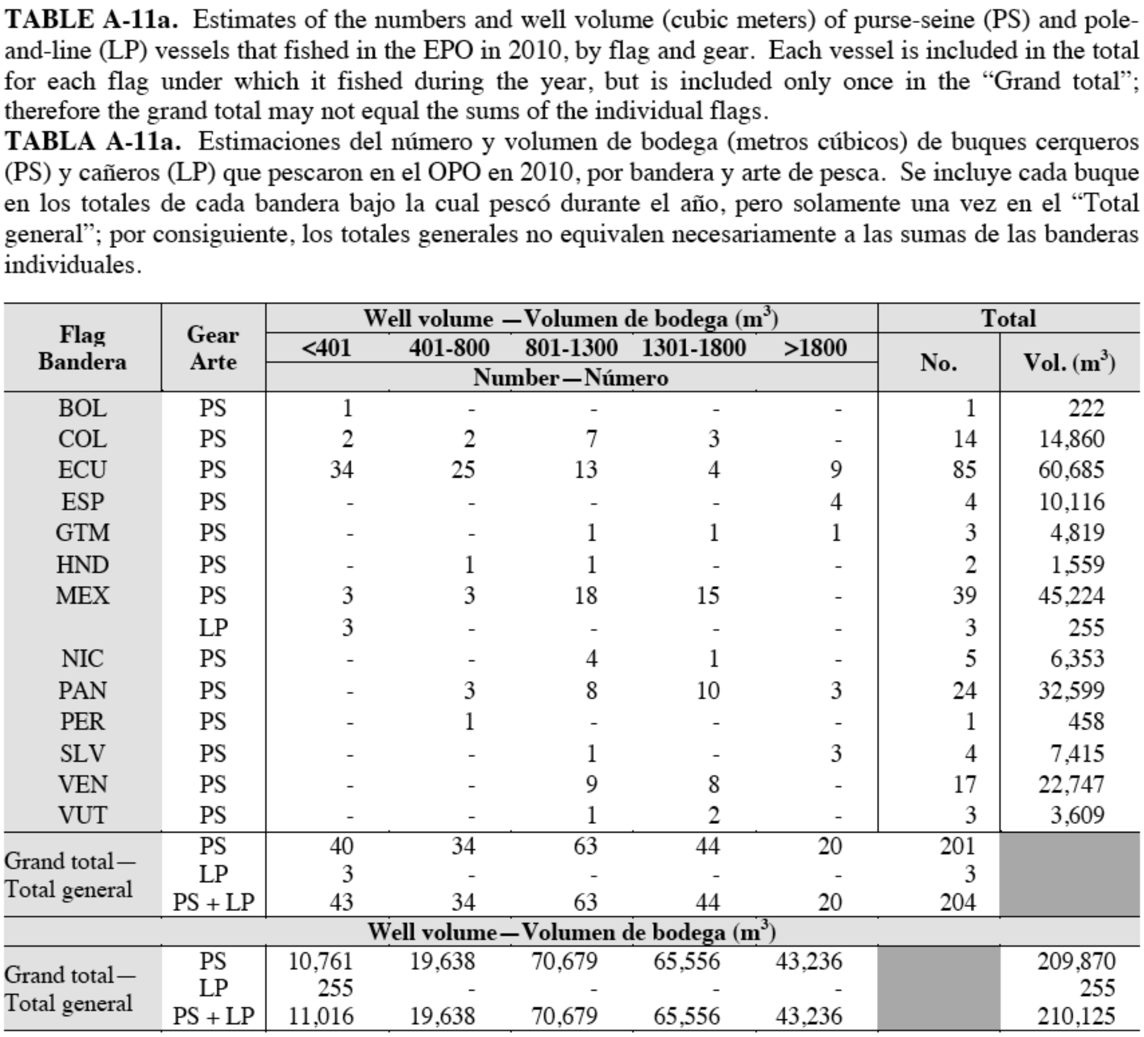


TABLE A-11a. Estimates of the numbers and well volume (cubic meters) of purse-seine (PS) and pole-and-line (LP) vessels that fished in the EPO in 2010, by flag and gear. Each vessel is included in the total for each flag under which it fished during the year, but is included only once in the "Grand total"; therefore the grand total may not equal the sums of the individual flags.

TABLA A-11a. Estimaciones del número y volumen de bodega (metros cúbicos) de buques cerqueros (PS) y cañeros (LP) que pescaron en el OPO en 2010, por bandera y arte de pesca. Se incluye cada buque en los totales de cada bandera bajo la cual pescó durante el año, pero solamente una vez en el "Total general"; por consiguiente, los totales generales no equivalen necesariamente a las sumas de las banderas individuales.

Flag Bandera	Gear Arte	Well volume —Volumen de bodega (m^3)					Total	
		<401	401-800	801-1300	1301-1800	>1800	No.	Vol. (m^3)
		Number—Número						
BOL	PS	1	-	-	-	-	1	222
COL	PS	2	2	7	3	-	14	14,860
ECU	PS	34	25	13	4	9	85	60,685
ESP	PS	-	-	-	-	4	4	10,116
GTM	PS	-	-	1	1	1	3	4,819
HND	PS	-	1	1	-	-	2	1,559
MEX	PS	3	3	18	15	-	39	45,224
	LP	3	-	-	-	-	3	255
NIC	PS	-	-	4	1	-	5	6,353
PAN	PS	-	3	8	10	3	24	32,599
PER	PS	-	1	-	-	-	1	458
SLV	PS	-	-	1	-	3	4	7,415
VEN	PS	-	-	9	8	-	17	22,747
VUT	PS	-	-	1	2	-	3	3,609
Grand total—Total general	PS	40	34	63	44	20	201	
	LP	3	-	-	-	-	3	
	PS + LP	43	34	63	44	20	204	
		Well volume—Volumen de bodega (m^3)						
Grand total—Total general	PS	10,761	19,638	70,679	65,556	43,236		209,870
	LP	255	-	-	-	-		255
	PS + LP	11,016	19,638	70,679	65,556	43,236		210,125

FIGURE 9

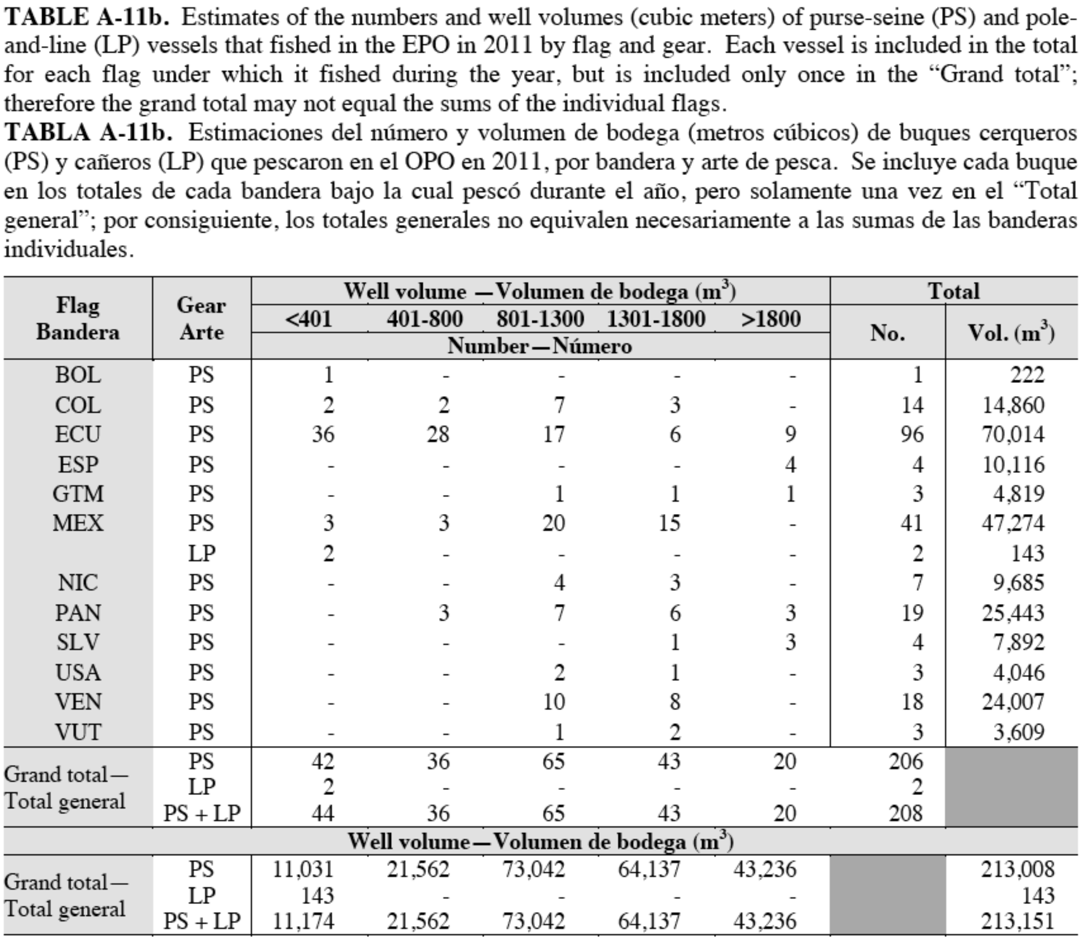


TABLE A-11b. Estimates of the numbers and well volumes (cubic meters) of purse-seine (PS) and pole-and-line (LP) vessels that fished in the EPO in 2011 by flag and gear. Each vessel is included in the total for each flag under which it fished during the year, but is included only once in the "Grand total"; therefore the grand total may not equal the sums of the individual flags.

TABLA A-11b. Estimaciones del número y volumen de bodega (metros cúbicos) de buques cerqueros (PS) y cañeros (LP) que pescaron en el OPO en 2011, por bandera y arte de pesca. Se incluye cada buque en los totales de cada bandera bajo la cual pescó durante el año, pero solamente una vez en el "Total general"; por consiguiente, los totales generales no equivalen necesariamente a las sumas de las banderas individuales.

Flag Bandera	Gear Arte	Well volume —Volumen de bodega (m^3)					Total	
		<401	401-800	801-1300	1301-1800	>1800	No.	Vol. (m^3)
		Number—Número						
BOL	PS	1	-	-	-	-	1	222
COL	PS	2	2	7	3	-	14	14,860
ECU	PS	36	28	17	6	9	96	70,014
ESP	PS	-	-	-	-	4	4	10,116
GTM	PS	-	-	1	1	1	3	4,819
MEX	PS	3	3	20	15	-	41	47,274
	LP	2	-	-	-	-	2	143
NIC	PS	-	-	4	3	-	7	9,685
PAN	PS	-	3	7	6	3	19	25,443
SLV	PS	-	-	-	1	3	4	7,892
USA	PS	-	-	2	1	-	3	4,046
VEN	PS	-	-	10	8	-	18	24,007
VUT	PS	-	-	1	2	-	3	3,609
Grand total—Total general	PS	42	36	65	43	20	206	
	LP	2	-	-	-	-	2	
	PS + LP	44	36	65	43	20	208	
		Well volume—Volumen de bodega (m^3)						
Grand total—Total general	PS	11,031	21,562	73,042	64,137	43,236		213,008
	LP	143	-	-	-	-		143
	PS + LP	11,174	21,562	73,042	64,137	43,236		213,151

FIGURE 10

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