Which Swordfish Gear is Cleanest?

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I. Introduction

A guiding principle in the regulation of production activities which generate negative externalities is to employ *cleaner* technologies – those which limit the level of environmental damage as much as possible for a given level of economic benefit. A potential Pareto improvement for the environmentalist and fishing communities is embodied in a technology which achieves a lower level of environmental damage for a given level of economic benefit.

Equivalently, the search for a cleaner technology represents an attempt to find a technology which maximizes the benefits of economic production for a stipulated level of environmental damage. The search is complicated when there is joint production of desirable outputs with undesirable outputs which are unavoidable and impose negative externalities with associated environmental damage costs.

One case which fits the above description is that of a fishery with a negative externality in the form of protected species bycatch. The Endangered Species Act (ESA) prohibits the incidental take of species which are determined to be endangered. A group of fisheries which face the problem of protected species bycatch is the commercial swordfish fisheries in the US Pacific Ocean Exclusive Economic Zone (EEZ), which

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[1] The views set forth in this proposal are the author's own, and do not represent the position of the National Marine Fisheries Service.

includes the California-Oregon drift gillnet fishery, the Hawaii pelagic longline fishery and the California harpoon fishery. Additionally, there is a current proposal to explore the viability of commercial longline fishing in the California coastal portion of the US west coast EEZ.

The question of which commercial swordfish gear is cleanest is a principle concern among consumers, fishermen and environmentalists. The selectivity profile of a fishing gear directly impacts the levels of protected species and nontarget species bycatch, with implications for economic profitability and the efficacy of a planned transition to an ecosystem management regime. To identify the cleanest gear, it is necessary to quantify the relationship between the economic efficiency of various gear types and the risk of incidental protected species and nontarget species bycatch.

On first consideration, determining which gear is cleanest would appear to be a simple matter of measuring which gear has the higher bycatch rate per unit of fishing effort. On this basis alone, a common perception is that drift gillnet fishing is more environmentally detrimental, due to higher bycatch rates per unit of fishing effort. However, this opinion ignores the heterogeneous costs across gear types, or the rates at which the target species is caught. It is conceivable that a gear with higher bycatch rates per nominal effort unit could prove far more economically and environmentally viable if this gear also had a much higher target species catch rates per unit of effort, provided that adequate environmental safeguards were used to mitigate bycatch.

In the case of alternative swordfish gear types, there are several challenges to obtaining an objective comparison to determine which gear type is cleanest:

1. Nominal measures of effort in gillnet, longline and harpoon fishing are not comparable; for instance, longline effort is normally measured by the number of hooks, while gillnet effort is typically measured by the number of sets.
2. There is more than one species of bycatch concern; for example, both leatherback and loggerhead turtle bycatch are concerns for the Hawaii pelagic longline fishery, while the California drift gillnet fishery faces problems of marine mammal and leatherback turtle bycatch, as the gear is targeted very broadly. By contrast, harpoon gear is much better targeted, but may fail on economic grounds due to a low catch rate for the time, travel and capital costs of fishing, and to a limited range of seasonal and geographic viability of harpoon fishing.
3. Different gear types face distinct bycatch rates over the species of concern, suggesting a need for an aggregate measure of environmental damage across the species of concern.
4. The feasibility of different gear types is heavily dependent on economic and environmental factors. For example, harpoon fishing is not generally feasible under the oceanic conditions north of Pt. Conception, while drift gillnet fishing typically is feasible. Similarly, drift gillnet fishing is comparatively advantaged closer to shore, while longline fishing is comparatively advantaged farther out to sea.
5. The cost structure may vary considerably across gear types, due to differences in capital prices, maintenance requirements, search costs and the risk of lost fishing opportunity due to environmental or regulatory factors.

6. There are few if any cases where observer records exist for harpoon, drift gillnet and longline swordfish fishing effort which occurred in the same season and region. This makes it difficult to empirically distinguish observed variation in target and bycatch species selectivity due to inherent properties of the gear types from selectivity variation due to possible confounding factors such as environmental variation or differences in target and bycatch species density across time and space. Similarly, it is possible that the economic return to swordfishing can vary due to environmental and stock density fluctuations across time and location.

I propose a framework for measuring the level of economic profitability of different swordfish gear types subject to a safety standard which sets the maximum allowable bycatch levels. Such a comparison is a necessary first step towards obtaining an objective determination of which swordfish gear is cleanest. Data on the rates of target species and leatherback turtle bycatch per unit of effort for longline and drift gillnet fishing will be used in conjunction with cost and earnings data to test the approach.

II. Commercial Swordfish Gear used in the U.S. west coast EEZ

The gear types used for targeting swordfish in the west coast EEZ of the U.S. include harpoon, drift gillnet and longline. These gear types are briefly described below.

Harpoon

The use of harpoon gear to catch swordfish off the North American west coast dates back nearly 3,000 years to artisanal Native American fishers who fished out of canoes with carved wooden harpoons (Coan et al). The modern-day California harpoon fishery for swordfish developed in the early 1990s, and harpoon was the primary gear for swordfish from the early 1900s to 1980. California harpoon effort began a period of decline in the early 1980, when drift gillnet fishing started. Many vessels converted to drift gillnet fishing gear or obtained permits to use both types of gear. Today, only a handful of vessels continue to participate in the harpoon fishery.

The harpoon fishery primarily targets swordfish, although small quantities of shark are also landed by harpoon gear. Swordfish landings and ex vessel revenues peaked in 1978 at 1,172 mt, decreased to a record low of 16 mt in 1991, before rising over tenfold in 1993 – 1994 and finally settling to around 80 mt over 1996 – 1999. Landings were typically less than 200 mt in most years. Sizes average 149 cm in length or 85 kg dressed weight in 1981 to 1993.

Harpoon is legal gear in California and Oregon, but is not defined as legal gear in Washington. Harpoon fishing season typically begins in May, peaks in July to September, and ends in December, coincident with the annual northwesterly movement of the North Equatorial Countercurrent and during months of calm sea conditions that harpoon fishing generally requires. Fishing usually concentrates in Southern California Bight off San Diego early in the season and shifts to areas as far north as Oregon later in the season, especially in El Nino years.

Harpoon vessels are from 6 m to 26 m in length with a 6 m to 8 m bow plank and hold capacities up to 100 mt. In order to use a harpoon to catch swordfish, it is necessary to first locate swordfish basking at the surface where the hand-held gear can be used to spear them. Swordfish are usually sighted basking at the surface of the water in temperatures between 12 degrees and 26 degrees Celsius. Harpoon vessels sometimes work in conjunction with an airplane to spot swordfish beyond binocular range from a vessel or sub-surface swordfish.

The hand-held harpoon consists of a 10 – 16 foot metal and/or wood pole attached to a 2-foot long metal shank and tipped with a 4-inch tethered bronze or iron dart. The harpoon is thrown at a surface-basking fish by a person standing on a metal pulpit at the end of a long plank at the vessel's bow. When a fish is spotted, the plank is positioned above the swordfish and the harpoon thrown from the end of the plank. After harpooning, the handle is pulled free from the dart, and the mainline, marker flag and floats are thrown overboard, leaving the fish to tire itself. The vessel then proceeds to search for and/or harpoon other fish. After the fish is tired, in approximately two hours, the vessel returns to retrieve it. The fish is stored over ice for the rest of the trip.

Drift Gillnet

The shark/swordfish drift gillnet fishery was developed in 1977 to catch barracuda and white sea bass. By 1979 fishing techniques improved, landings, and market demand for pelagic sharks increased. Fishers soon discovered that drift gillnet gear also caught swordfish, worth nearly four times the dockside value of sharks. At that time, harpoon was the only commercial gear authorized under California law for the harvest of swordfish.

Drift gillnets capture by entanglement. Drift gillnet gear required for this fishery includes a net 45 to 60 large inflatable ball buoys, a spar buoy called a "high flyer" affixed with a radar reflector and strobe light, a deck mounted hydraulically powered reel on which to store the net, and a reel mounted level wind to assist in deploying, and retrieving the net. Webbing is hung loosely, much like drapery, which gives the net its entanglement properties.

Drift gillnet trips range from one night to one month, but typically lasts 5 to 15 days. The California drift gillnet fishery now operates primarily outside of state waters to about 150 miles offshore, ranging from the U.S. Mexico border in the south to northward of the Columbia River depending on sea temperature conditions. Because of seasonal fishing restrictions, and the seasonal migratory pattern of swordfish, about 90% of the annual fishing effort occurs between August 15 and December 31. Depending on where they fish, drift gillnet vessels primarily land fish in San Diego, San Pedro, Ventura, Morro Bay, Monterey, Moss Landing, and San Francisco Bay area ports where it is sold in the fresh fish market providing high quality, locally-caught fish for the restaurant trade.

Longline Fishing

Longline fishing is the most recent addition to the commercial gear types used to target swordfish for landing in California ports. Handheld harpoon gear was the predominant commercial fishing gear from 1900 through the 1970s. Drift gillnet gear developed in the late 1970s and became the dominant gear type during the decade of the 1980s. Though longline fishing has never been permitted in the U.S. west coast EEZ, longline-caught fish were allowed to be transported through the EEZ and landed in California ports, provided they were caught outside the 200 mile coastal limit. In the early 1990s, a high-seas longline fishery developed which caught fish outside the U.S. EEZ between California and Hawaii and landed their catch in California ports. This fishery quickly became a major source of fresh swordfish catch landed on the west coast.

Longline fishing gear consists of a mainline strung horizontally across 1-100km (1-62 miles) of ocean supported at regular intervals by vertical float lines connected to surface floats. Descending from the main line are branch lines, each ending in a single, baited hook. The main line droops in a curve from one float line to the next and bears some number (2-25) of branch lines between floats. Fishing depth is determined by the length of the float lines and branch lines, and the amount of sag in the mainline between floats. The depth of hooks affects their efficiency at catching different species. When targeting swordfish, vessels typically fish 24-72 km of 600 to 1200 pound test monofilament mainline per set. Mainlines are rigged with 22m branch lines at approximately 61 m intervals and are buoyed every 1.6 km. Between 800 and 1,300 hooks are deployed per set.

Large squid are known to be used for bait, although mackerel bait has been recently introduced as an alternative that is relatively less attractive to protected sea turtles. Various colored light sticks are also used. The mainline is deployed in 4 to 7 hour and left to drift unattached for 7 – 10 hours. Radio beacons are attached to the gear for recovery. Retrieval requires 7 to 10 hr. Fishing occurs primarily during the night when more swordfish are available in surface waters. Generally, long lining gear targeting tuna is set in the morning at depths below 100m, and hauled at sunrise. A typical long line carries a crew of six, including the captain, although some of the smaller vessels operate with a four-man crew. Fishing trips last around 3 weeks. Most vessels do not have built-in refrigeration equipment, limiting their trip length. The fish are iced and sold as “fresh.”

III. The Protected Species Bycatch Problem

The introduction of modern industrial fishing technology to catch swordfish, such as the use of longline and drift gillnet gear, has raised concerns over the levels of nontarget species bycatch. Species of concern include those protected under U.S. environmental law such as sea turtles, cetaceans and pinnipeds, as well as seabirds and nontarget finfish species such as blue shark. Bycatch is costly to fishermen, as they expend time and effort handling species with no commercial value, and their allowable effort may be constrained if they bycatch is regulated by caps (quotas) which end fishing effort for the season once the cap is reached. Bycatch also may inflict long-term damage to the trophic balance of the marine ecosystem, may increase extinction risk to species that are protected or endangered and can impose external nonmarket damage costs on environmentalists and conservationists who value the continued existence of bycatch species.

Since harpoon fishing involves directly targeted effort using a hand-held spear, bycatch would not appear to be much of a concern. Longline and drift gillnet fishing are less selective than harpoon; although they offer the potential for much higher levels of swordfish catch per day at sea, this gain in technological efficiency comes at the expense of a heightened bycatch problem.

IV. Regulatory Environment Governing Commercial Fishery Take of Protected Species

The U.S. has environmental laws which govern the allowable take levels of protected species. Of primary importance to commercial swordfishing are the Endangered Species Act (ESA) and Marine Mammal Protection Act (MMPA).

Endangered Species Act (ESA)

The Endangered Species Act of 1973 (ESA) provides for the conservation of species that are endangered or threatened throughout all or a significant portion of their range, and the conservation of the ecosystems on which they depend. The ESA replaced the Endangered Species Conservation Act of 1969; it has been amended several times.

A "species" is considered endangered if it is in danger of extinction throughout all or a significant portion of its range. A species is considered threatened if it is likely to become an endangered species within the foreseeable future.

There are approximately 1,880 species listed under the ESA. Of these species, approximately 1,310 are found in part or entirely in the U.S. and its waters; the remainder are foreign species.

NOAA's National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service (USFWS) share responsibility for implementing the ESA. Generally, USFWS manages land and freshwater species, while NMFS manages marine and anadromous species. NMFS has jurisdiction over approximately 60 listed species.

The endangered Species Act of 1973 provides for the conservation of species that are endangered or threatened throughout all or a significant portion of their range, and the conservation of the ecosystems on which they depend. The leatherback turtle is a key bycatch species of concern for U.S. commercial swordfish fisheries, and has been listed as an endangered species since the enactment of the ESA in 1973. The endangered species act says that you have to protect species which have been deemed threatened or endangered against the risk of extinction. However, the ESA does not explicitly prohibit the take of endangered species, opening up the possible legal viability of commercial longline or drift gillnet fishing provided protected species take is held to acceptable levels.

Marine Mammal Protection Act (MMPA) of 1972.

All marine mammals are protected under the MMPA. The MMPA prohibits, with certain exceptions, the take of marine mammals in U.S. waters and by U.S. citizens on the high seas, and the importation of marine mammals and marine mammal products into the U.S.

Congress passed the Marine Mammal Protection Act of 1972 based on the following findings and policies:

1. Some marine mammal species or stocks may be in danger of extinction or depletion as a result of human activities;
2. These species or stocks must not be permitted to fall below their optimum sustainable population level (“depleted”);
3. Measures should be taken to replenish these species or stocks;
4. There is inadequate knowledge of the ecology and population dynamics; and
5. Marine mammals have proven to be resources of great international significance.

The MMPA was amended substantially in 1994 to provide for certain exceptions to the take prohibitions related to authorizations for scientific research to develop methods of mitigating commercial fisheries bycatch of marine mammals.

Current Regulatory Regime

Recent regulatory practice in U.S. fisheries where take of protected species are of concern has favored using some combination of (1) mandatory technology standards, (2) overall effort limits, (3) protected species take caps[2], (4) target-species catch quotas and (5) limited entry programs. All of these measures potentially limit economic opportunity to the affected commercial fishery, except to the extent they serve to mitigate the open access problem[3]. For instance, mandatory technology standards potentially reduce bycatch in exchange for a reduction in target species catch per unit of effort[4], while limited entry programs may potentially reduce the size of a fleet below the economically optimal fleet size, and may also inadvertently encourage capital stuffing and a race to fish.

Protected species take caps set a level of protected species bycatch which, if reached, results in a cessation of all fishing effort for the remainder of the fishing season. Take caps are often set at very low levels to reflect the potentially drastic effect that a small number of takes may have on the survival prospects for a critically endangered species. However, small stock sizes characteristic of endangered or threatened species give rise to a small numbers problem, where the interaction of a low take cap with a small risk may produce a large variance in the allowable effort for any one fishing season.

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[2] Take caps are defined more broadly than bycatch caps to include not only animals that were caught but also any interaction between the fishing gear and an animal.

[3] The open access problem is a well-known phenomenon where a fishery with no restriction on effort fosters new entry and additional effort up to the point where economic profits are driven to zero.

[4] Le Chatelier’s principle suggests that if the cleanest gear also offered the highest private profits, it would not be necessary to mandate its adoption, as fishermen would optimally choose it anyway.

V. A Model of Commercial Fishing under Bycatch Caps

A conceptually simple approach to objectively compare different swordfish gear with respect to the dual objectives of maximizing economic profitability and mitigating protected species bycatch is to posit a model of target species catch and protected species bycatch at constant catch rates per unit of effort. The empirical methodology employed in this paper abstracts away from the stochastic nature of protected species bycatch, as the focus is on reducing the long-term protected species take rate by choosing a cleaner gear, rather than describing the short-term fluctuation in protected species take counts. Hence estimates of long-term average CPUE for target species catch and protected species bycatch per unit of effort (BPUE) enter the model, rather than a characterization of the stochastic process which governs short term fluctuations in catch counts.

Subject to this simplifying assumption, and with estimates of target species CPUE and bycatch species BPUE plus estimated costs and commercial species prices for the fishery in question, it is possible to compare the economic profitability of the different gear types under the assumption of hard constraints on the level of effort and allowable numbers of protected species takes for each species subject to regulation.

Current regulatory practice mitigates protected species bycatch through a combination of take caps with a limit on allowable effort for the season. In addition, for a fishery with a fixed number of vessels, season length, technology and Mother Nature constrain the level of effort which could be achieved in a given season. Further, economic factors such as variation in CPUE market prices and input costs could lead to endogenous curtailment of effort before any of the regulatory constraints limit effort.

The model presented here assumes that the effort limit implied in the protected species take caps will be binding, and considers which gear type is most profitable for given allowable levels of protected species take.

Consider a representative agent model of fishing with Leontief catch technologies, $T_i(\boldsymbol{q}_i, \boldsymbol{y}_i)$ for $i = 1,2,\ldots,k$, where $\boldsymbol{q}_i$ is an m-vector of commercial species yields per unit of effort, and $\boldsymbol{y}_i$ is a p-vector of bycatch per unit of effort for protected species of concern. Further, let $\boldsymbol{b}$ represent a p-vector of binding protected species take caps[5]. Let e_i denote units of fishing effort over the course of the season using technology i. The economic parameters consist of a vector of prices $\boldsymbol{p}_i$ for which commercial catch of gear type i can be sold, an increasing[6] marginal cost per unit of effort $c_i(e_i)$ implying a decreasing profit per unit of effort equal to $\pi_i(e_i) = \boldsymbol{p}_i \cdot \boldsymbol{q}_i - c_i(e_i)$. Assuming a constant rate of protected species bycatch for each species of concern, the bycatch levels for a given level of effort are given by the vector $e_i\,\boldsymbol{y}_i$.

Bycatch may be regarded as a production externality of fishing, with the impact of environmental damage generally borne by other individuals besides fishermen and the consumers whom they supply with fish. Assume the environmental damage due to the bycatch externality is described by a continuously twice differentiable function $D(e_i) = D(y_{1i}\,e_i, y_{2i}\,e_i, \ldots, y_{pi}\,e_i)$, with first partials $D_j\,(e_i) > 0$ for $j = 1, 2, \ldots, p$ and a positive definite second derivative matrix $H = [D_{ij}\,(e_i)]$. A benevolent social planner would chose the level of effort to maximize

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[5] In practice, 100 percent observer coverage is necessary in order to strictly limit the level of protected species takes to the levels mandated by the regulatory caps.

[6] In this formulation, costs are assumed to reflect both increasing short term variable costs per unit of effort, as well as long-term fixed costs. This reflects a view that all costs are variable in the long run, and a goal of comparing gear types in terms of their potential long-term profitability.

$$V_i = \int_0^{e_i} \pi_i(x)dx - D(y_{1i}e_i, y_{2i}e_i \ldots, y_{pi}e_i)$$

The first order condition requires that

$$dV_i/de_i = \pi_i(e_i) - [D_1(e_i)\, y_{1i} + D_2(e_i)\, y_{2i} + \ldots + D_p(e_i)\, y_{pi}] = 0,$$

and the decreasing marginal profit function and positive definite second derivative matrix of the environmental damage function ensure a unique solution, provided profits net of environmental damage costs are positive at some level of effort. If e_i^* is the level of effort which maximizes the net benefit of fishing as described above, then employing bycatch caps of $e_i^* y_{ji}$ on bycatch species *j* would permit an economically efficient level of effort to occur which balanced producer surplus against the external damage costs. With knowledge of profits per unit of effort and bycatch per unit of effort for each gear type under consideration, the cleanest gear from an efficiency standpoint would be the one which maximized economic profits net of the environmental damage costs due to bycatch.

Current U.S. regulatory policy under the Endangered Species Act and the Marine Mammal Protection Act involves levels of protected species bycatch that are dictated by the regulatory authority based on biological considerations such as extinction risk which do not weigh into account economic efficiency considerations. The approach taken here to compare which gear is cleaner assumes the regulatory authority has exogenously specified permissible bycatch levels and proceeds to address the question of which gear is most economically viable subject to the regulatory constraints.

Assuming sufficiently smooth and flat profit and bycatch damage functions over the range of variation under consideration, the problem of maximizing profits for gear type *i* subject to exogenously-determined bycatch caps and effort limit may be approximated as a linear programming (LP) problem (Mas-Colell, Whinston and Green 1995) as follows:

$$Max\{e_i\}\ \pi_i\, e_i \qquad (1)$$

subject to the constraints

$$\text{s.t.}\quad \boldsymbol{y}_i\, e_i \leq \boldsymbol{b}, \qquad (2)$$

Letting Y denote a $p\ X\ p$ diagonal matrix whose diagonal entries are the components of $\boldsymbol{y}_i$. The solution to the problem is easily obtained by noting that profits are maximized for each technology by

$$e_i^* = \text{argmax}\{e_i\}\ \pi_i\, e_i \qquad (3)$$

subject to

$$Ie_i \leq Y^{-1}\, \mathbf{b}, \qquad (4)$$

where I denotes a pXp identity matrix provided that the profit per unit of effort satisfies $\pi_i > 0$. The take-cap-constrained effort level is thus given by $e_i^* = \min_j \{ b_j / y_{ji} \}$, and the take-cap-constrained profit from using technology i is given by $\pi_i\, e_i^*$.

Taking the vector of regulatory constraints $\boldsymbol{b}$ as mandated by the regulatory authority[7], a benevolent social planner's objective is to choose the technology $i \in \{1, 2, \ldots, k\}$ which maximizes allowable industry profit subject to the species protection take caps. The value of i which maximizes industry profit subject to the species protection constraint identifies the most profitable gear for a mandated safety standard.

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[7] Segerson (2007) considers alternative policies to find the optimal balance between the goals of protected species bycatch mitigation and increased fishing opportunity. This paper addresses a different issue, the choice of the cleanest gear, and hence treats the regulatory policy as exogenous rather than as a choice variable. Note that the framework posed here remains applicable if the constraints $\boldsymbol{b}$ are chosen based on efficiency considerations.

The following figure illustrates the solution to the LP problem for the case where there are two bycatch species subject to protected species take caps[8]:

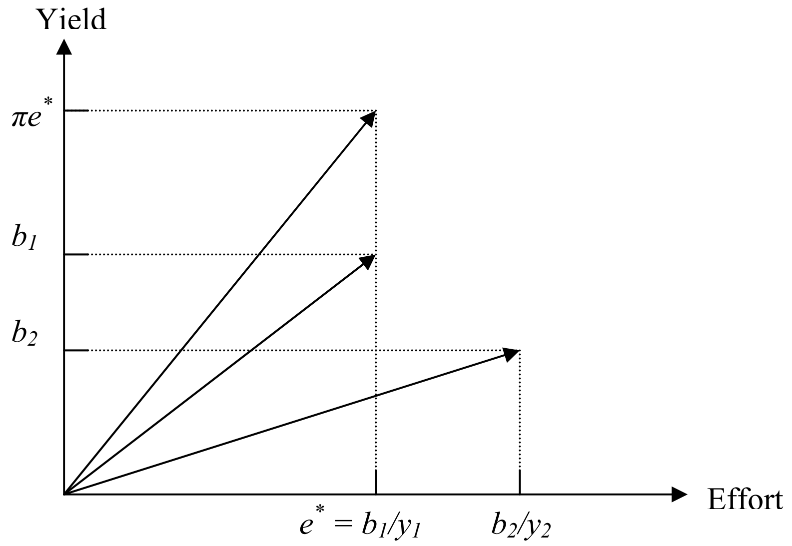

Figure 1: Bycatch Caps and Yields

Figure 1 uses a stylized figure to illustrate the effect of two protected species take caps on "yields" (bycatch and profit levels). The horizontal axis in the figure represents effort while the vertical axis represents profit and bycatch levels. The bycatch rates y_1 and y_2 for the two species of concern determine the slopes of the rays from the origin which terminate at the corresponding bycatch cap levels, b_1 and b_2.

The figure illustrates the general case where the ratio of one species' bycatch cap to its bycatch rate is smaller[9] than the corresponding ratio for the other species

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[8] The subscript *i* which references gear type is suppressed in the figure to reduce notational clutter.
[9] This situation might arise in practice if the second bycatch species were at greater risk of extinction, and hence subject to lower bycatch rates due to the smaller stock size and resulting lower interaction rate, while the more prevalent first bycatch species has a higher interaction rate which more than offset the effect of a higher bycatch cap.

($b_1/y_1 < b_2/y_2$). In this case, allowable effort will always be constrained by the bycatch cap on the first species, since allowable effort is constrained by the smallest cap to bycatch rate ratio, $e^* = b_1/y_1$. The slope of the ray from the origin up to the height πe^* is the profit per unit of effort, π, so the bycatch-cap-constrained profit level is πe^*. Note further that the nonbinding bycatch cap could be reduced from its current slack level to the point where it was just binding without further constraining allowable effort[10].

Alternatively, the problem may be posed in dual form as

$$\text{Min}\{\lambda_1, \lambda_2, \ldots \lambda_p\}\ \boldsymbol{\lambda}'\boldsymbol{b} \qquad (5)$$

$$\text{s.t.}\ \ \boldsymbol{y}_i^{\mathrm{T}}\boldsymbol{\lambda} \geq \pi_i. \qquad (6)$$

It is well-known that the components of **λ** possess a complimentary slackness property which restricts the number of nonzero components at the optimum to no more than $rank(\boldsymbol{y}_i) = 1$, and that the value of a component of **λ** at the optimum may be interpreted as the shadow value of a marginal increase in the corresponding primal problem constraint. Since the components of ***b*** are all positive and at most one of the λ_j may be nonnegative, it is straightforward to show that the minimum of the dual objective function is achieved for $\lambda^* = \text{argmin}\{\ \lambda_j\ \}\ \lambda_j b_j$ subject to the constraint that $\lambda_j = \pi_i / y_{ji}$ for each value of j under consideration. The shadow value of a unit relaxation in the binding constraint is thus given by $\lambda^* = \pi_i / y_j$ for the case where j indexes the binding constraint. Intuitively, a unit increase in the binding bycatch cap translates into an increase in allowable effort of $1/y_j$, and the corresponding increase in producer surplus is obtained by multiplying by profit per unit of effort, π_i. Since all the other components of **λ** are equal

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[10] This is the case when the bycatch rates are exactly proportional to effort. A more realistic approach is to model low levels of protected species take as a Poisson process, which introduces risk into the question of which take cap will be reached first.

to zero for a nondegenerate solution to the dual problem, it follows that only the binding constraint has a nonzero shadow value.

V. Empirical Estimation

Leatherback turtles are an endangered species subject to bycatch from both longline and drift gillnet swordfish effort. The LP approach was applied to a comparison between longline and drift gillnet gear from the standpoint of economic viability and bycatch mitigation in order to illustrate the proposed methodology in a simple case. A quadratic trend model was fit to historical price data on west coast landings of swordfish caught by longline, DGN and harpoon gear. A detailed summary of the estimation methodology for estimating swordfish prices is provided in Appendix 1; details of the LP model calculations are shown and described in Appendix 2.

The LP calculation assumes leatherback take caps of two individuals for a given season in each fishery. Under the constraint of a take cap of two leatherbacks, the estimated profit is \$728,103 for DGN effort and \$1,672,648 for longline effort, providing indication that the longline effort described by this data was cleaner with respect to leatherback bycatch mitigation than the DGN data. The respective shadow prices for a unit increase in the leatherback take cap are \$364,051 for DGN gear and \$836,324 for longline gear, reflecting a loss of profitability of longline effort for a unit decrease in the leatherback take cap.

The empirical results should be interpreted with caution. One reason is that they treat input values deterministically without taking into consideration possible estimation error. A second reason is that to the author's knowledge, no complete data set over a period of years exists for side-by-side comparison of drift gillnet to longline commercial swordfishing effort from both the economic and biological standpoints; hence the parameters used in the comparison are not likely to precisely match the comparison which would come out of a controlled experiment with side-by-side effort. A third concern is that the data do not control for the possible effect of variation in the stock sizes of swordfish and leatherback; taking these sources of variation in catch rates into account would, in principle, result in estimates which more accurately captured variation in outcomes due to differences in gear. Finally, the shadow costs of the bycatch caps only consider the tradeoff with respect to lost fishing profits, without considering the value of any nonmarket benefits which might accrue to a reduction in leatherback bycatch.

VI. Is Harpoon a Clean and Economically Viable Substitute?

Harpoon gear has been suggested as a clean alternative to longline and drift gillnet gear as targeting swordfish directly with a handheld spear will presumably result in lower bycatch rates. Although this paper does not offer empirical evidence on this question, some of the considerations to address are discussed in this section.

The question of whether harpoon gear is a cleaner substitute for drift gillnet and longline gear should take into consideration not only bycatch per unit of swordfish catch, but also the potentially higher amount of fossil fuel consumed per unit of catch when swordfish are actively hunted with boats and spotter planes and individually caught with hand-held spears versus the use of a passive technology such as longline or drift gillnet which does not require constant pursuit (and fuel consumption).

A second question concerns the economic viability of harpoon gear relative to longline and drift gillnet gear. At the advent of the California-Oregon drift gillnet fishery in the early 1980s, the level of harpoon fishing effort waned as it proved less economically viable. During the 1990s, when high seas longline effort outside the California portion of the west coast Exclusive Economic Zone (EEZ) greatly increased, drift gillnet and longline gear continually comprised the dominant portion of the catch with harpoon landings contributing a very minor portion of the total, calling into question whether harpoon is an economically viable alternative.

A third concern is whether harpoon-caught swordfish is competitive against imports. The price of harpoon-caught swordfish has remained over twice as high as the price of drift gillnet- or longline-caught swordfish over time, reflecting both a quality premium (harpoon-caught fish is fresher because it is landed sooner after when it is caught) and possibly also an efficiency disadvantage, due to lower CPUE (at least if effort is measured in days of fishing) and potentially high fuel expenses due to actively pursuing swordfish by air (spotter planes) and by water. The high relative price of harpoon-caught swordfish calls into question whether it is an affordable substitute for imported swordfish.

Finally, the notion that harpoon gear could serve as a substitute for longline and drift gillnet gear ignores the geographic and seasonal limitations of harpoon gear, and the comparative advantages of the three swordfishing gear types with respect to season and fishing area. Generally speaking, harpoon gear is best suited to near shore fishing while longline has a comparative advantage for use on longer trips farther out to sea, with drift gillnet gear providing an intermediate case with respect to proximity from the shore. Harpoon gear requires swordfish basking near the surface where they can be spotted and speared, necessitating relatively warm and calm conditions like those found in the southern California bight during the warm months of the summer. The intrinsic geographic and seasonal limitations of harpoon gear call into serious question the potential for harpoon to serve as a substitute for longline or drift gillnet gear, and make it more likely that a reduction in west coast longline or drift gillnet effort will be offset by an increase in swordfish imports from other fisheries with unknown levels of protected species bycatch beyond the reach of U.S. regulatory authority rather than by an increased level of west coast EEZ harpoon effort.

VII. Conclusions and Directions for Further Research

Drift gillnet and longline gear have been harshly criticized by the environmentalist community as poorly targeted industrial fishing methods which deliver swordfish to consumers at the price of unacceptably high levels of bycatch, including take of protected species such as marine turtles, cetaceans, sharks and seabirds. Harpoon gear has been proposed as an environmentally friendly substitute. Lost in the discussion is the question of which gear does a better job of balancing bycatch mitigation against target species catch. Bartram and Kaneko (2004) took a step in the direction of a more objective comparison across gear types by considering the ratio of bycatch per unit of effort (BPUE) to catch per unit of effort of target species (CPUE); a lower BPUE to CPUE ratio for a given bycatch species of concern is an indication of a cleaner fishery.

This paper offers an attempt to make an objective comparison between different gear types in terms of the dual objectives of economic viability and bycatch mitigation for multiple species of bycatch concern. In order to make an objective comparison, it is necessary to either consider which gear type is most profitable for a given allowable level of bycatch (the primal problem) or to consider which gear poses the lowest level of environmental damage for a given minimum level of economic profitability (the dual problem). Depending on whether the problem is respectively viewed through the primal or the dual perspective, a cleaner gear is identified as one which provides more producer surplus (profitability) for a given allowable level of protected species bycatch, or one which results in a lower level of protected species bycatch for minimum level of producer surplus. The approach is could be generalized to consider alternative specifications of the bycatch damage function such as those presented in Segerson (2007).

A linear programming approach was employed to compare drift gillnet gear to longline gear, subject to a leatherback take cap. The results provide indication that longline gear is cleaner than DGN gear, at least based on the effort which support the estimates presented herein. The estimated lost industry profits for a unit reduction in the level of the leatherback turtle take cap are \$836,324 for longline effort and \$364,051 for DGN effort.

While the results presented here illustrate a useful methodology for comparing different gear types in terms of the competing objectives of economic viability and bycatch control, they should be interpreted with caution, and as a preliminary effort in measuring which gear type is the cleanest way to target a given commercial species. The shadow price estimates which come out of this approach only take into consideration the loss in potential industry profits due to more stringent bycatch control measures, without considering the nonmarket value of reduced protected species take. While the effect on extinction risk of one additional protected species take may be small, the nonmarket external damage cost borne by environmentalists for small increases in protected species take levels may be substantial, and should be considered. For highly migratory species like endangered leatherback and loggerhead turtles, a full assessment of the shadow price of changing protected species take caps must consider the potential for a reduction in allowable effort to transfer fishing effort to other fisheries where the bycatch problem may be even worse than in the regulated fishery.

The empirical procedure presented here relies on data from disparate sources which may not accurately capture the comparison which would occur between alternative swordfish gear used in the same season and area. The shortcoming of using data from different seasons and geographic regions is that it is not possible to separate uncontrolled factors such as variation over time and space of the target species and bycatch species stock levels from those factors directly attributable the gear types which affect the catch of target species and bycatch species. The three different gear types under consideration would typically be used in different areas, with harpoon generally employed closest to shore and longline employed farther out to sea. Ideally, the comparison across gear types should be based on data for the same time periods and proximate geographical area, in order to provide a natural control on the levels of target species and bycatch species stocks, as well as economic variables such as fuel and labor costs and swordfish market prices which affect profitability of fishing.

Future research should explore the scope for obtaining contemporaneous data across gear types (including cost and earnings data as well as catch data) which better control the factors which affect bycatch rates and economic profitability. A full comparison across gear types should consider seasonal and geographic limits which bear on the potential substitutability between gear types. The effect of including additional protected species take caps besides only a leatherback cap should be explored. Ideally, the question of which gear is cleanest should be addressed within an integrated stock assessment framework (Maunder et al. 2006) that measures the tradeoff between bycatch and economic viability against a backdrop of controls on the effects of target species and bycatch species stock levels.

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Appendix 1: Quadratic Trend Model Estimation of Swordfish Prices

A quadratic trend model was used to fit a quadratic time trend model to the landed price[11] of swordfish catch by each different gear type under consideration (longline, drift gillnet and harpoon) over the period from 1991 through 2005 when a full data sample was available for west coast landings from each gear type[12]. The regression specification initially included a quadratic time trend of swordfish prices from with dummy variables to control for differences in price levels between swordfish, but the linear time term and the drift gillnet dummy variable were dropped from the specification, as doing so did not lead to a rejection of the null hypothesis in an F-test of the restriction of these coefficients to both equal 0. The restricted model was a parsimonious specification of form $p_{it} = \alpha + \delta D_i + \beta t^2 + \varepsilon_t$ where p_{it} is the average landed price per round pound of swordfish in \$2005 for each period in the data, t^2 is the square of the time variable, D_i is a dummy variable equal to 1 for harpoon prices and 0 otherwise and ε_t is a random error term. Regression results are presented in the table below. The overall regression was significant at the 1% level, as were the *t*-statistics on all three estimated coefficients. The time variable was defined so that its value equaled 0 in the last period of the data, so the estimated price of swordfish for longline and drift gillnet catch was \$1.686 per round pound for 2005. This is the value which was used for the swordfish price of longline and DGN catch in the linear programming estimate.

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[11] The price data were taken from the 2006 HMS SAFE Report produced for the Pacific Fishery Management Council.

[12] Though longline effort is not permitted in the U.S. west coast EEZ, high-seas-caught swordfish are permitted to be landed in the west coast EEZ.

Regression Statistics	
Multiple R	0.965
R Square	0.932
Adjusted R Square	0.929
Standard Error	0.303
Observations	45.000

ANOVA

	df	*SS*	*MS*	*F*	*P-value*
Regression	2	52.898	26.449	287.810	0.000
Residual	42	3.860	0.092		
Total	44	56.757			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	1.686	0.074	22.864	0.000	1.538	1.835
Harpoon Effect	2.202	0.096	22.969	0.000	2.008	2.395
t^2	0.005	0.001	6.933	0.000	0.004	0.006

Appendix 2: Comparison of Longline Gear to Drift Gillnet Gear

	DGN	LL w/std. effort	LL w/nom. Effort
(1) CPUE for Swordfish	2.989	4.509	17.16
(2) Average Swordfish Weight (dressed weight)	156.3	139.0	139.0
(3) Conversion from dressed weight to round pounds	1.45	1.45	1.45
(4) Average Swordfish Weight (round pounds) = (2) X (3)	226.635	201.550	201.550
(5) Price* for Swordfish (per round pound)	$1.686	$1.686	$1.686
(6) Revenue per Unit of Effort for Swordfish = (1) X (4) X (5)	$1,142.375	$1,532.696	$5,832.515
(7) Ratio of All Revenue to Swordfish Revenue	1.365	1.151	1.151
(8) Revenue per Unit of Effort = (6) X (7)	$1,559.574	$1,764.827	$6,715.867
(9) Estimated Cost per Unit of Effort	$435.506	$640.759	$2,438.342
(10) Estimated Profit per Unit of Effort = (8) - (9)	$1,124.068	$1,124.068	$4,277.525
(11) BPUE for Leatherback Turtle	0.00308766	0.00134406	0.00511468
(12) Leatherback Turtle Take Cap	2	2	2
(13) Constrained Effort = (12) / (11)	647.739	1488.030	391.032
(14) Annual Profit at Constrained Effort = (10) X (13)	$728,103	$1,672,648	$1,672,648
(15) Marginal increase in constrained effort for unit increase in Leatherback Take Cap = 1 / (11)	323.870	744.015	195.516
(16) Estimated Shadow Price of a Leatherback Turtle = (10) X (14)	$364,051	$836,324	$836,324
(17) Ratio of LL to DGN shadow price		2.297	
(18) Estimated Marginal Cost per Swordfish = (9) / (1)	$145.703	$142.095	$142.095

*All dollar amounts are expressed in $2005

The LP results are shown in the rightmost three columns of the table above. The center and rightmost of these three columns both present the calculation for longline gear, with the center column differing from the rightmost column by rescaling effort from nominal units (thousands of hooks) to standardized units selected to match profit per unit of effort with the DGN fishery (see row (10) of the table), which allows a direct comparison of BPUE across gear types after controlling for profitability. The indication is that leatherback BPUE standardized by profits is only about 1/3 as high for longline effort as DGN effort (row (11)).

Catch rates and bycatch rates per unit of effort were estimated from observer data from the Hawaii pelagic longline fishery for swordfish[13] and from the California drift gillnet observer database records, using the ratio of total swordfish catch count per nominal effort unit (1000s of hooks for longline, and number of sets for drift gillnet). Average dressed weight of 139 pounds for a sample of swordfish in the California high seas longline fishery was used to estimate the dressed weight of a longline-caught swordfish. Since no corresponding weight estimate for DGN caught swordfish was available, a sample average fork length of 141 cm for DGN-caught swordfish from the U.S. west coast EEZ was converted to an estimated dressed weight of 156.3 for DGN-caught swordfish using a conversion formula presented in Vojkovich and Barsky (1998), which is $DW = 1.3415 \times 10^{-7} \times CF^{2.87896}$, where CF is the swordfish fork length in millimeters and DW is the dressed weight in pounds. Estimated dressed weights of DGN- and longline-caught swordfish were multiplied by a standard California

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[13] More ideally, the comparison would be based on longline effort from the U.S. west coast EEZ versus DGN effort in the west coast EEZ, but longline effort has never been permitted within the west coast EEZ. The Hawaii longline catch and bycatch data reflects only the period since the mandatory use of circle hooks and mackerel bait went into effect to reduce sea turtle interactions.

Department of Fish and Game conversion factor of 1.45 (Hanan et al. 1993) to estimate the dressed weight of a swordfish (line (4) in the table). This was converted to revenue per unit of effort by multiplying by the price per round pound for each gear type, and then multiplied by swordfish CPUE to convert from revenue per swordfish to swordfish revenue per unit of effort (line (6) in table). Finally, to take into consideration marketable nontarget species catch, the ratio of total revenues to swordfish-only revenues taken from the 2006 HMS SAFE Report was used to gross up the swordfish revenue per unit of effort to overall revenue per unit of effort (RPUE, line (8)). Cost and earnings surveys for the California high seas longline fishery and for the California-Oregon drift gillnet fishery were used to develop costs per unit of effort (line (9)), and netting these estimates against RPUE resulted in estimated profit per unit of effort (line (10)), which was used as the estimate of π_i in the LP formulation.

The illustration of the method assumes leatherback take caps of two (line (12)) which were divided by BPUE to obtain the effort constraints (line (13)). Annual profits at the bycatch-capped effort levels were obtained by multiplying profit-constrained effort by the profit per unit of effort for each column of the table (line (14)). The estimated bycatch-constrained profit is $728,103 for DGN effort and $1,672,648 for longline effort, providing indication that the longline effort represented in this data was cleaner with respect to leatherback bycatch.

The respective shadow prices for a unit increase in the leatherback take cap are $364,051 for DGN gear and $836,324 for longline gear, reflecting a loss of profitability of longline effort for a unit decrease in the leatherback take cap.