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Accounting for undesirable outputs in productivity measurements: Application to the California-Oregon drift gillnet fishery

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Accounting for Undesirable Outputs in Productivity Measurements:

Application to the California-Oregon Drift Gillnet Fishery

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ABSTRACT

Many production activities typically produce undesirable outputs, e.g., the production of the pollutant sulfur dioxide in the generation of electricity. Traditional economic metrics may overstate the efficiency and productivity of these production activities by failing to account for the undesirable outputs. These omissions can lead to conclusions that are biased against resource conservation and protection.

Many fisheries capture their target species concomitantly with undesirable outputs such as bycatch of juvenile fish, marine mammals, sea birds, and sea turtles. One such fishery is the California-Oregon (CA/OR) drift gillnet fishery (DGNF), which incidentally takes protected species, such as sea turtles and marine mammals while harvesting swordfish and thresher shark. Beginning in August of 2001, regulatory measures to reduce the take of endangered species (e.g., leatherback sea turtles) have required the annual closure of an area located between Point Conception and 45° N. latitude, for the time period August 15 to November 15. This regulatory closure acts as a natural experiment for assessing the impact of the time-area closure on the productivity of the CA/OR DGNF.

The three primary purposes of this research were to measure the impact of the 2001 time-area closure on the productivity of the CA/OR DGNF, and to estimate the opportunity cost or shadow price of undesirable outputs. These shadow prices provide lower bound estimates of the social costs of conservation regulations intended to protect endangered leatherback sea turtles and other bycatch species.

An alternative method which models the joint production of both desirable and undesirable outputs, the directional output distance function approach, was used to estimate the efficiency and productivity of drift gillnet fishing trips, thus crediting trips with reductions in undesirable harvest and increases in desirable outputs for the time period 1996-2008. By incorporating undesirable harvest into the production process, a more appropriate measure of total factor productivity was calculated than what is provided by traditional productivity measures. The new productivity measure can be used to develop more effective policies designed to maintain or improve a fishery's economic performance.

The results indicate that efficiency and productivity measures which ignore undesirable outputs substantially misinterpret the economic performance of economic trips. The model that incorporates undesirable outputs indicates that productivity per trip has been growing by 788 pounds of swordfish over the research period relative to the base year. This is considerably lower than the average growth of 964 pounds when undesirable outputs are ignored and 878 pounds when undesirable outputs are allowed to expand. However, post-closure averages suggest that conventional estimates understate the economic performance of the observed trips. Post-closure productivity growth resulted in an increase of 334 pounds of swordfish harvest when adjusted for undesirable outputs.

Average trip shadow prices (per animal captured) revealed a conservation opportunity cost for the reduction of undesirable outputs of $2,500 for marketable discards, $6,600 for unmarketable discards, $28,800 for sea turtles, and $9,800 for marine mammals in forgone composite swordfish and thresher shark revenue.

Accounting for Undesirable Outputs in Productivity Measurements:

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SECTION I: INTRODUCTION

a. General overview of the problem

Fishing is an economic activity; therefore, detailed economic analyses of fishermen and fishery performance are critical factors in improving its management Managers are likely to be concerned about a number of economic measures including profitability, competitiveness, management quality and cost, efficiency, equity, productivity, output and input interactions, capacity, and sustainability (Grafton *et al.*, 2000).

Changes in fishery regulations can impact the metrics used to calculate these economic measures. Understanding and quantifying how regulations affect the economic measures of performance provide important feedback for managers and resource users that can be used to assess the performance of new regulations, and if necessary, provide guidance for program design modifications (Grafton *et al.*, 2000). One measure of economic performance is the productivity change of a fishery. Productivity change indicates how changes in output have responded to changes in input levels over time.

Biased or misleading estimates may result when undesirable outputs, such as the incidental take of sea turtles and marine mammals, are ignored in assessing efficiency and productivity change. Efficiency describes how close production is to the maximum potential output for a given level of inputs. An alternative notion of efficiency, but not used in this study, is how close observed input usage (e.g., days at sea) is to the minimum potential level of inputs for a given level of outputs. Productivity change refers conceptually to the combined effects of technical and efficiency change. Efficiency change describes the change in efficiency over the given period, while technical efficiency describes the change in technology that alters the relationship between given inputs and outputs. Traditional measurements of efficiency, technical, and productivity change only account for the desirable outputs and inputs which are marketable. The cost of reducing the undesirable outputs is ignored and can lead to conclusions that are biased against resource conservation and protection. This approach may provide an inaccurate picture of economic performance that can lead to misguided policy design (Färe *et al.*, 1993). Industries which provide food to the population, such as agriculture or fisheries, are subject to environmental regulations that may adversely affect their productivity. This is in part due to the cost of abatement or conservation that has typically not been included in the calculation of efficiency and productivity of the production process. The productivity indicator used in this research models the joint production of undesirable and desirable outputs, crediting fishing trips with reductions in undesirable harvest and increases in marketable species.

By incorporating undesirable harvest into the production process, more appropriate measures of total factor productivity and other economic metrics can be calculated and used to design more effective policies or improve a fishery's economic performance. One important economic metric is the shadow price for undesirable outputs. Shadow price is an opportunity cost, or an indicator of producer surplus forgone in terms of lost revenue of the production activity. Shadow prices estimates can be used to calculate a "green" gross domestic product (GDP).

Boyd (2007) defined "green GDP" as a measure of what is valuable about nature, excluding goods and services that are already captured in the GDP. "Green GDP" is a metric of "society's value" rather than the "actual value". "Green GDP" accounts for the future consequences of society's current consumption, while shadow prices represent the forgone loss in current revenue of an activity, or opportunity cost. The incorporation of shadow values in the calculation of "green GDP" should provide a better measurement of social welfare, as it captures the utility of conservation and the loss of resources due to environmental degradation from an economic activity like fishing.

Numerous fisheries have some level of bycatch or incidental take of undesirable outputs. Bycatch is defined in the Magnuson-Stevenson Fisheries Conservation and Management Act (MSA) as "fish which are harvested in a fishery, but which are not sold or kept for personal use, and includes economic discards and regulatory discards." Incidental take refers to marine mammals, sea turtles and sea birds which are unintentional captured. In fact, a major concern of management agencies is the reduction of undesirable outputs, or more specifically, undesirable bycatch. National Standard Nine of the Magnuson-Stevenson Fisheries Conservation and Management Act states, "Conservation and management measures shall, to the extent practicable (A) minimize bycatch and (B) to the extent bycatch cannot be avoided, minimize the mortality of such bycatch" (MSFCMA, 2007).

U.S. fisheries are also required to comply with other federal statutes such as the Endangered Species Act (ESA) and Marine Mammal Protection Act. Fisheries managers have reduced effort in areas or completely closed fisheries to reduce bycatch and incidental take of endangered species and marine mammals in order to comply with these federal statutes. In addition to the regulatory controls, federal agencies such as the National Marine Fisheries Service (NMFS) have funded and conducted research to examine and modify gear to reduce bycatch, with a major goal to reduce marine mammal takes. The Pacific Offshore Cetacean Take Reduction Team (POCTRT) was created in 1996 to advise and develop a plan to reduce marine mammal takes in the CA/OR DGNF.

On a global scale, the Food and Agriculture Organization (FAO) of the United Nations has sponsored numerous meetings and research to find ways to reduce bycatch in fisheries. In 1995, the FAO established the Code of Conduct for Responsible Fisheries, of which Section 8.4.5 encouraged the development and implementation of technologies and operational methods that reduce discards (FAO, 1995).

The drift gillnet fishery off of the coast of California and Oregon targets swordfish and thresher sharks, but has demonstrated bycatch of undesirable outputs, including juvenile fishes, marine mammals, sea birds, and sea turtles. The leatherback sea turtle, listed as endangered, is one of the species of sea turtles incidentally taken by the fishery.

Beginning in August of 2001, a regulatory measure, known as the Pacific Leatherback Conservation Area (PLCA), was implemented to reduce the take of leatherback sea turtles in the fishery. It resulted in the annual closure of an area located between Point Conception and 45° N. latitude for the time period August 15 to November 15. This regulatory closure acts as a natural experiment for assessing the impact of the time-area closure on the productivity of the CA/OR DGNF.

It is important to quantify the changes in the productivity metrics for a fishery that has experienced a regulatory closure. Changes in the metrics may reflect many of the production decision variables such as cost, employment, outputs, and prices within the fishery, as well as social welfare. Productivity change is also important as it may reflect changes in the scarcity or abundance of the resource stock. Fisheries managers need to understand the effects of regulations on the fishery in terms of economic losses.

Many management regulations on the CA/OR DGNF designed to protect the target stocks and bycatch species place constraints on productivity, which can lead to further misallocation of resources, reduction in profits, and in some cases, increased costs. This cost increase may also contribute to the inflation of food prices in domestic markets.

Regulations can also reduce revenues when effort has been significantly curtailed to reduce bycatch or to protect stocks. Gjertsen *et al.* (2009) found revenues from the CA/OR DGNF declined by 60 percent after implementation of the closure. This extensive revenue loss was largely driven by a combination of price declines[1] and attrition from the fishery; it does not necessarily imply vessel-level productivity decline in the fishery. The revenue loss does not include the indirect effect of declines in the supporting fishery infrastructure. However, regulations can also increase productivity. Fishermen and the fishery as a whole can become more efficient through altered fishing practices, reduction in the most inefficient vessels, or technological innovation.

Currently, no studies have been conducted to examine the effects (i.e., loss of revenue) of a regulatory closure on the commercial DGNF. Fisheries management needs to have the ability to assess the productivity pre- and post-closure accounting for undesirable harvest. The present study accomplishes this through a green-based approach that considers undesirable harvest as an output in the production process.

[1] The ex-vessel price per pound was $5.83 in 1996, but had declined to $2.96 by 2008.

The three primary purposes of this research were to measure the impact of the 2001 time-area closure on the productivity of the CA/OR DGNF, to elucidate the effects of the closure on the economic performance of the fishery, and to estimate the opportunity cost or shadow value of undesirable outputs. A directional output distance function approach was used to estimate the productivity change of the fishery pre- and post-closure for the time period 1996-2008. The production frontier was specified as a generalized quadratic. The directional distance function approach allowed for the consideration of non-proportional changes in outputs and allowed desirable outputs to be expanded while undesirable outputs were simultaneously contracted. Since one goal of fisheries regulations is to minimize bycatch and related mortality, the undesirable outputs were contracted while desirable outputs (marketable species) were expanded.

The directional output distance function was estimated using data from NOAA CA/OR DGNF logbooks. Price information from Pacific Fisheries Information Network (PacFIN) was used to calculate the revenue-based shadow price of undesirable outputs. The directional output distance function was specified as a quadratic functional form and used to estimate productivity, technical efficiency, and shadow prices for marine mammals, sea turtles, other non-marketable species, as well as discarded marketable species. The directional distance function (DDF) was specified as a deterministic function. In this case, all deviations from the frontier were attributed to technical inefficiency. Specifically, the Luenberger productivity indicator developed in Chambers (1998) was used to measure productivity, technical change, and efficiency change. Estimates of average annual shadow prices were calculated for undesirable outputs (marine mammals, sea turtles, and other non-marketable species).

The comparison between the pre- and post- closure productivity suggested that fishermen may have made changes to their fishing practices or behavior after the implementation of the closure to reduce undesirable outputs relative to desirable outputs. The productivity analysis provided evidence that the remaining drift gillnet fishermen have adapted to the closure, reflecting improvements in trip efficiency for fishermen who continued participation in the fishery after the closure.

Finally, as no market prices exist for undesirable species captured in the fishery, managers need information on marginal costs of conservation to compare the costs of conservation to the benefits of maintaining a species' abundance. The study accomplished this task by calculating the shadow price for the undesirable outputs. The shadow prices, as calculated in this study, can be interpreted as lower bound estimates of the cost to society to conserve bycatch or protected [undesirable] species caught in drift gillnets. More specifically, it represents lost revenue due to the foregone production of desirable species such as swordfish associated with reducing undesirable outputs such as sea turtle bycatch. The estimates can assist managers in the evaluation of the cost of the closure and other conservation policies as well as the effect on the fishery in terms of its overall production.

b. Commercial importance of California-Oregon drift gillnet fishery

According to the 2009 Stock Assessment and Fishery Evaluation (SAFE) report, the CA/OR DGNF landed 1,318 metric tons of seafood valued at $4.9 million in 1996. In 2008, the ex-vessel value for the fishery was $2.2 million, harvesting only 629 metric tons of seafood. Swordfish sales alone totaled $1.6 million. When put in 2008 real dollars, which adjusts for inflation, a difference of $5.6 million revealed the precipitous decline of the fishery and the extensive loss in revenue over the last 13 years (Figure 1) in what was previously one of the most valuable fisheries in the state of California. The 60 percent decline in revenue has also negatively impacted the fishing communities and supporting infrastructure (Gjertsen *et al.,* 2009). Annual fishing effort has declined from a high of 11,243 sets in the 1986 fishing season to 1,043 sets in 2005 due, in part, to more stringent state and federal regulations.

The CA/OR DGNF is a limited entry fishery that has been capped at 150 permits. In 2006, industry representatives attributed the decline in vessel participation and annual effort to regulations implemented to protect threatened and endangered marine mammals, sea turtles, and seabirds. The number of active vessels declined from 111 to 46 between 1996 and 2008 (Table 1). To keep a permit active, current permittees are required to purchase a permit from one consecutive year to the next; however, they are not required to make landings using drift gillnet gear. In addition, a general resident or non-resident commercial fishing license and a current vessel registration are required to catch and land fish caught by drift gillnet gear. A logbook is also required by the state. The fishery captures highly migratory species (HMS), defined by the MSA as "tuna species, marlin, oceanic sharks, sailfishes, and swordfish". As such, the Highly Migratory Species (HMS) Fisheries Management Plan (FMP) requires a federal permit with a drift gillnet gear endorsement for all U.S. vessels that fish for HMS within the West Coast Exclusive Economic Zone (EEZ) and for U.S. vessels that catch HMS on the high seas (seaward of the EEZ) and land their catch in California, Oregon, and Washington. Any changes in the regulatory regime could have large detrimental impacts on vessel returns and associated fishing communities. Measures of changes in productivity are, therefore, useful indicators of the impacts of changes in the regulatory regime.

Implementation of the Pacific Leatherback Conservation Area (PLCA) resulted in a reduction and redistribution of fishing effort along the central and northern California coast. Based on fishing effort data provided by the California Department of Fish and Game (CDFG), there was an overall reduction of approximately 300 DGN sets for the year following implementation of the closure. A set refers to the set and haul back of the drift gillnet and is used as the metric for effort. It is also important to note that due to area closures, vessels from more northern ports have to travel farther to reach fishing grounds, which increases fuel usage and reduces profits. Also, based on fishery observer data, it appears that the spatial distribution of fishing effort has shifted to the south compared with the areas where vessels fished prior to the implementation of PLCA. With the bulk of gillnetting operations based in Southern California ports, there is an increased strain on this region's infrastructure.

c. Research rationale

Given the importance and decline in revenues of and participation in the fishery, the management agency needs to design sound polices aimed at maintaining or increasing productivity within an appropriate timescale to assist the commercial viability of the fishery. Fisheries policies are mainly based on rebuilding population biomass and conservation of protected species. Most of these polices do not take into account effects on the impacted fishery's economic productivity. Färe *et al.* (2007a) suggest that regulations tend to initially reduce productivity, technical efficiency, allocative efficiency, undesirable outputs, and capacity utilization. Performance indicators would be one way to help fisheries managers design and implement better polices that would meet the goals of National Standards Five and Nine set forth in the Magnuson-Stevens Fishery Conservation and Management Act.

One of the key management goals of the HMS FMP is to "minimize economic waste and adverse impacts on fishing communities to the extent practicable when adopting conservation and management measures" (PFMC, 2007). However, if managers design policies to reduce undesirable outputs such as sea turtle bycatch in a fishery, while simultaneously trying to maintain productivity, they should adjust the performance measures to reflect the change in productivity due to the reduction of undesirable outputs.

To date, most studies on productivity in fisheries have failed to address the inclusion of undesirable outputs (e.g., bycatch) into the framework, and no study to date has elucidated the effects of regulatory restrictions on productivity for the drift gillnet fishery. Rather, the studies have primarily focused on specifying bycatch as an input or altogether excluding it from the calculation (Reinhard *et al.,* 2000; Walden *et al.,* 2001). Also, typical measures of productivity ignore the joint production of undesirable and desirable outputs since data on undesirable outputs are seldom available. Undesirable outputs are also ignored due to the complexity of separating the desirable and undesirable outputs in the production process. Other studies have instead treated undesirable outputs as inputs (Reinhard *et al*., 1999; Murty and Kumar, 2004; Kumar, 2006). Yet, management typically affects productivity. Bycatch problems in HMS fisheries are of major concern to NMFS; consequently, this research is focused on a HMS fishery which has had a number of regulations implemented for the direct purpose of conservation of protected resources. This study provided empirical evidence to answer the following questions: What impact does the regulatory time area closure have on productivity? How does adjusting for undesirable outputs affect the productivity measure?

This research tried to quantify the potential cost of regulations (e.g., 2001 Leatherback Area Closure) to the CA/OR DGNF and the change in productivity over the years when adjusted to reflect the reduction in undesirable outputs. The comparison between the pre- and post-closure productivity suggested the nature and magnitude of adjustments made by the fishery after the event of the closure. It also provided evidence on whether or not the surviving CA/OR DGN fishermen have adapted to the closure and made efforts to improve their efficiency.

Another problem encountered by fishery managers is the valuation of non-marketable catch such as juvenile discards and protected species. Since there is no market price for undesirable harvest, measuring the marginal cost of conservation is difficult but important to fisheries managers to facilitate the comparison of the costs of conservation to the benefits of maintaining a species' abundance. The study accomplished this task by calculating the shadow price of undesirable outputs.

The results of this study should assist policy makers, specifically the Pacific Fishery Management Council, as they design new regulations. The study demonstrated the impact of protected species conservation measures on affected fisheries and the affected communities. The study also determined what additional data are needed to conduct further research.

d. Research objectives

The overall objectives of this study were to introduce an alternative method for assessing productivity when undesirable outputs are present, to measure the changes in productivity as a direct result of a regulatory closure in the CA/OR DGNF, and to estimate shadow prices for the undesirable outputs. The empirical results will help policy makers evaluate regulatory restrictions, and the methodology should assist fisheries economists to develop alternative models for assessing productivity change. The specific objectives were as follows:

- To introduce an alternative method of calculating productivity change when undesirable outputs are present.
    - Use of a (non-stochastic) production frontier to assess productivity change when undesirable outputs are present.
    - Estimate the frontier using the generalized quadratic functional form.
    - Use of the directional distance vector to measure the distance from the frontier.
- To assess productivity change, technical change, and efficiency with and without adjusting for undesirable outputs.
    - To provide a measure of productivity change due to leatherback regulatory time-area closure based on comparing pre- and post- 2001 productivity.
- To compute shadow prices for sea turtles, marine mammals, and other non-marketable species.
- To provide policy implications of the area closure and recommend other possible frameworks for assessing productivity change.

- To determine what additional data are needed to conduct future research.

To address these objectives the following research questions were investigated:

1. What was the productivity change and efficiency level of the fleet pre-closure? Did the fleet experience productivity change or efficiency before the closure?
2. What was the productivity change and efficiency level of fleet post-closure? Did it improve or deteriorate over the five-year period following the closure?
3. What are the possible explanations for the differences in pre- and post-closure productivity change and efficiency levels? Did reduced bycatch play a significant role in accounting for such differences? Did the fleet's efficiency increase to adapt to the loss of fishing grounds?
4. When accounting for bycatch in the model, were the productivity change and efficiency scores significantly different than those calculated using a model that did not incorporate bycatch?

To answer these research questions, several hypotheses and their alternatives were evaluated:

H_{1o}: There was no change in the mean efficiency level between the pre- and post closure periods.

H_{1a}: The mean efficiency level in the pre-closure period was significantly higher than post-closure.

H_{2o}: There was no change in the mean productivity between the pre- and post closure periods.

H_{2a}: The 2001 area closure significantly improved post-closure productivity.

H_{3o}: Incorporation of bycatch into the model had no significant effect on measured post-closure productivity or efficiency.

H_{3a}: Post-closure productivity and efficiency were significantly higher when the model accounted for bycatch.

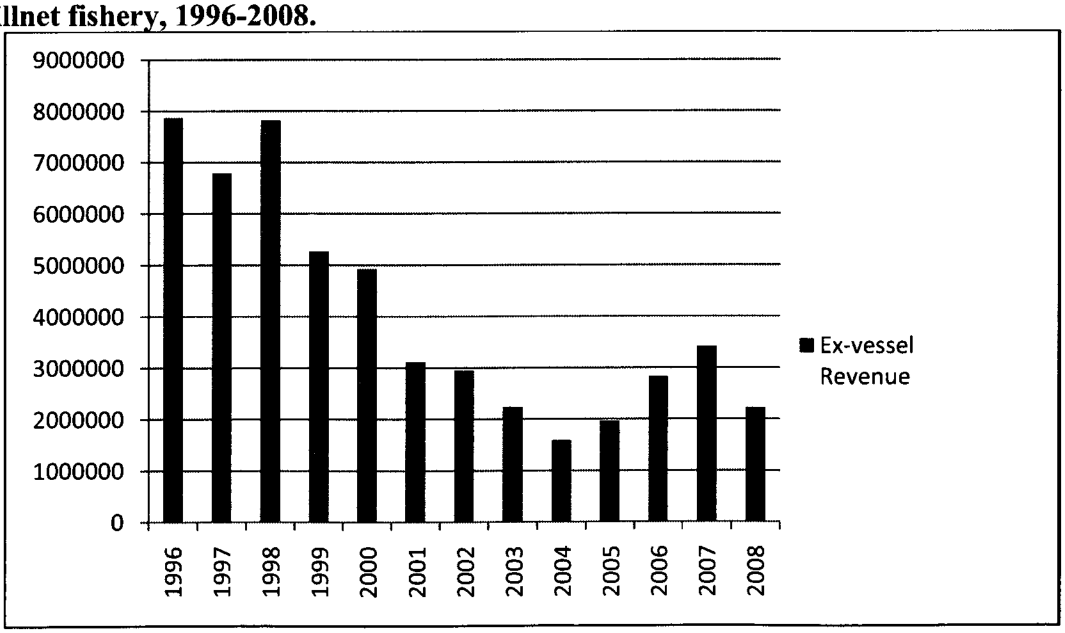
The research focused on efficiency and productivity and adds to the fisheries economic performance literature by departing from the conventional approach of estimating efficiency and productivity change. The Luenberger Productivity Indicator first developed in Chambers (1998) was employed to decompose productivity into efficiency and technical change. The approach was adapted from the work of Färe *et al.* (2007b) and Vardanyan and Noh (2006), and accounted for the simultaneous expansion of desirable outputs and contraction of undesirable outputs that mirrored the goals of fisheries managers. The approach also allowed for the calculation of shadow prices.

The remainder of the dissertation is organized as follows: Section II provides a review of the literature focusing on the drift gillnet fishery and the directional distance function approach used to calculate efficiency, productivity, and shadow prices; Section III describes the Methodology; and Section IV presents and discusses the results of the research, and recommends future research. Conclusions are provided in Section V. A glossary of terms can be found in the appendix to assist the reader in economic terminology found throughout this dissertation.

Table 1. Annual drift gillnet permits issued, the number of active vessels, and the number of observed vessels in the CA/OR Drift Gillnet Fishery for years 1996–2008.

Year	Permitted	Active	Observed
1996	167	111	52
1997	120	108	72
1998	148	98	66
1999	136	84	62
2000	127	78	55
2001	115	69	36
2002	106	50	33
2003	100	43	27
2004	96	40	23
2005	90	42	25
2006	89	45	26
2007	86	46	24
2008	84	46	25

Figure 1. Real commercial ex-vessel revenues (2008 dollars) for the CA/OR drift gillnet fishery, 1996-2008.



Industry revenue data from the 2009 West Coast HMS Safe Report.

SECTION II: LITERATURE REVIEW

a. California/Oregon drift gillnet fishery

i. Description of fishery and gear

The California/Oregon drift gillnet fishery (CA/OR DGNF) is a limited-entry fishery that operates in the coastal waters offshore of California and Oregon with the primary fishing effort historically concentrated in the south and central portions of California between San Diego and Cape Mendocino (NMFS, 2006). The CA/OR DGNF target species include swordfish (*Xiphius gladius*) and thresher shark (*Alopias vulpinus*), whereas non-target bycatch include species such as striped marlin (*Kajikia audax*), mola (*Mola mola*), and blue shark (*Prionace glauca*) (Table 2).

Drift gillnet gear consists of a net, a set of large inflatable ball buoys, a spar buoy called a "high flyer" (which is affixed with a radar reflector and strobe light), a deck-mounted hydraulic reel on which to store the net, and a reel-mounted level wind to assist in deploying and retrieving the net (Figure 2). Nets are custom made from many parts that are often purchased separately from different suppliers. Net components include the webbing, leadline, floatline, and buoyline, with seizing twine used to attach the net together. The leadline is made with a small diameter lead-cored braided line. The floatline is a large diameter braided or three-stranded buoyant line while the buoyline is made of a small diameter braided hollow-cored ply of line.

The net is constructed with one size of twisted nylon strand meshes. Typical stretch mesh measures between 18-22 inches from the opposing knot. The depth of the webbing can range from 80 to 160 meshes (90 to 170 feet).

The net length varies from 3000 to the maximum allowed 6000 feet (500 to 2000 fathoms). The net dimensions are chosen by the fisherman based on size of the net reel on the boat and the amount of instability the net would cause by the weight of the net when it is wet (PFMC, 2007).

The net is hung vertically in the water column with the buoyline at the top and the weighted line at the bottom. The net is suspended below the surface of the water by the ball buoys and the buoyline at a required minimum of 36 feet (11 meters). Drift gillnets capture by entanglement; the net is hung loosely in the water to give it that property.

The net is deployed at sunset and hauled back in before sunrise. Each such deployment, soak and haul of the net is referred to as a set, used as a nominal measure of effort. At most one set is made per day. Drift gillnet trips can last from one night to one month, but typically encompass five to 15 days at sea. Vessels typically land in ports close to the fishing grounds. The main ports include San Diego, San Pedro, Ventura, Morro Bay, Moss Landing, Monterey, and San Francisco Bay. These ports are known for their associated processors' ability to sell high-quality, locally caught fish in the restaurant trade or fresh fish markets.

Set location is often dependent on the occurrence of temperature fronts between cooler and warmer water masses, or turbidity fronts between green and blue water masses. Fishermen also look for aggregations of bait fish such as sardines or anchovies. Fishermen often communicate in coded messages with other members of loosely organized "code groups" that share information on amount of catch and location (PFMC, 2007).

ii. History of the fishery

In the early 1970s, near shore small mesh drift netters first noticed an occasional catch of sharks in their nets while targeting California barracuda (*Sphyraena argentea)* and white seabass (*Atractoscion nobilis)* (Carretta *et al.*, 2003). Fishermen began to modify their nets and techniques to catch a wider range of species such as California halibut (*Paralichthys californicus)*, California flying fish (*Cypselurus californicus),* and various sharks. Modification of the nets for use in deep waters further expanded the fishery and its targeted catch (PFMC, 2007).

The drift gillnet fishery continued to develop rapidly in the late 1970s offshore of the coast of southern California. According to state records, 40 vessels participated in the fishery in 1979. The fishery originally targeted the common thresher shark (*Alopias vulpinus)*, swordfish (*Xiphias gladius),* and the shortfin mako shark (*Isurus oxyrinchus)*, soon became an important component of the catch. The successful development of the fishery have been attributed to greater fuel efficiency, pelagic shark resource abundance, consumer acceptance and demand for shark as a food fish, and perseverance of fishermen pursuing a new source of livelihood (PFMC, 2007). As the techniques and gear improved, market demand for sharks increased which resulted in an increase in the issuance of new permits. In 1980, the California legislature established a non-transferable, limited entry permit system, and required an observer to be placed on board and logbooks to be recorded and submitted. Permits were issued to 165 fishermen who had landed at least one thresher or mako shark with a drift gillnet in either 1978 or 1979, or who had made a significant investment in the fishery prior to May 20, 1980 (Hanan *et al.*, 1993). By the early 1980s, there were approximately 200 permits issued for drift gillnetting in California (PFMC, 2007).

Fishermen were catching swordfish with a greater frequency in their nets, which had a dockside value four times that of sharks (Bedford, 1987; Holt, 1988). The high demand for the more desirable swordfish encouraged the expansion and development of the fishery with approximately 10,000 sets in 1982, moving into waters further offshore and northward into the states of Oregon and Washington (Hanan *et al.*, 1993). As of 2008, Oregon only has 10 DGN permit holders. It should be noted that all of the Oregon permit holders are also permit holders in the state of California. Washington no longer permits the landing of swordfish or sharks (PFMC, 2007).

iii. Regulatory history

The CA/OR DGNF is one of the most strictly managed net fisheries in the world. It is managed under various state laws (time/area closures, limited entry, mesh size, logbooks) and federal regulations (net depth, acoustic pingers, observer program) under the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) designed to sustain the populations of target species as well as protected species taken incidentally in a fishery, under Marine Mammal Protection Act regulations to limit marine mammal interactions, and in compliance with Endangered Species Act regulations to control incidental takes of endangered leatherback and loggerhead sea turtles. Numerous state and federal regulations on the fishery have been implemented over the last several decades (Table 3).

Under the State of California Department of Fish and Game Code, the CA/OR DGNF is closed within 200 nautical miles (nmi) of the coastline from February 1 through April 30 that was established around the Channel Islands to protect pinnipeds. From May 1 through August 14, drift gillnets cannot be used in ocean waters within 75 nmi from the mainland coastline, under a regulation which is designed to protect the migration of female thresher shark. A vessel operator, however, may land swordfish or thresher shark if the fish were taken in waters more than 75 nmi from the mainland shore. In 1985, California adopted a closure within 25 nmi of the mainland coastal line from December 15 through January 31 to protect grey whales during their northern migration through this area. From August 15 through January 31, swordfish can be taken within 75 nmi of the mainland. The majority of the fishing effort takes place from October through December of each season.

Beginning in 1980, the California state legislature enacted AB 2564, directing California Department of Fish and Game (CDFG) to implement a non-transferable limited entry program for the CA/OR DGNF with a target cap of 150 permitted vessels. Permits were issued to 165 fishermen, with 94 using dual gear (harpoon and gillnet). Legislation authorized the permitted fishery to retain swordfish. The legislature required the CDFG to conduct a study of the impact on shark resources to ensure that overfishing would not occur. It was at this time that the legislation also required mandatory observers and logbooks (Hanan *et al.*, 1993).

In 1990 the federal government assumed control of the observer program for the entire fishery from Washington to California. The National Marine Fisheries Service (NMFS) began requiring observers to be placed on vessels to monitor marine mammal bycatch.

Under section 118 of the MMPA the NMFS is required to place all U.S. commercial fisheries into one of three categories based on the level of incidental serious injury and mortality of marine mammals in each fishery (16 U.S.C. 1387 (c) (1)). A "List of Fisheries" is published each year in the Federal Register that determines whether the fishery participants are subject to registration, observer coverage, or take reduction plans. A fishery is classified into one of three categories depending on the level of incidental takes relative to the Potential Biological Removal (PBR) for each marine mammal stock. The MMPA defined PBR as the maximum number of animals (not including natural mortality) that may be removed from a marine mammal stock while allowing that stock to reach or maintain its optimum sustainable population. A Category I fishery is defined as one which the annual level of incidental take of one or more stocks is greater than or equal to 50 percent of the stocks PBR; a Category II fishery is defined as one which the annual takes of one or more stocks are greater than one but less the 50 percent of the PBR; a Category III fishery has an overall serious injury and incidental take of all marine mammals stocks, across all fisheries that interact with these stocks, of less than 10 percent of the each stock's PBR level. The CA/OR DGNF has been classified as category I throughout the research period.

In 2001, under the Endangered Species Act section 7, NMFS required new restrictions to avoid jeopardizing leatherback sea turtles. Beginning in 2001, the Pacific

Leatherback Conservation Area (PLCA), which encompasses the area between Point Conception and 45° N latitude, was closed to drift gillnet fishing from August 15 through October 31 to reduce impacts on the leatherback sea turtle population (Figure 3). The PLCA is bounded by straight lines connecting the following coordinates in the order listed:

(A) Point Sur (36°18.5' N.) to 34°27', N. 123°35' W.;

(B) 34°27' N. 123°35' W. to 34°27', N 129° W.;

(C) 34°27' N. 129° W. to 45° N., 129° W;

(D) 45° N., 129° W. to the point 45° N. intersects the Oregon coast.

The PLCA was designed around the possible migration patterns of leatherback turtles and the oceanographic features of the California coast. To date, there has been a single leatherback turtle take in the CA/OR DGNF since the establishment of the PLCA (September 26, 2009, California Gillnet Database); the turtle was released alive.

If an El Niño condition is predicted to occur, or is determined to be occurring, the area south of Point Conception is closed to drift gillnet fishing from August 15 to October 31 and during the entire month of January to reduce loggerhead sea turtle impacts (Figure 4). To date, this area has never been closed since the adoption of this regulation in 2001.

iv. Physical environment

The CA/OR DGNF is associated with hydrographic structures of the water column (e.g., the marine pelagic and mesopelagic zone and convergence boundary areas between currents and major features such as the thermocline) (PFMC, 2007). The physical oceanographic features are dependent on time-space variability patterns of the solar and atmospheric forces that are unique to the region in which the fishery exists.

The west coast of North America from the Straights of Juan De Fuca to the tip of Baja, California is part of the eastern boundary complex known as the California Current System (Hickey, 1998). The U.S. West Coast EEZ encompasses one of the major coastal upwelling areas of the world where waters provide a nutrient-rich environment and high densities of forage for highly migratory species, especially from the Columbia River mouth to the Southern California Bight. The areas of upwelling are a direct effect of the sea-air exchange of heat and moisture by the Ekman transport and vertical mixing. This affects the distributions in sea surface temperature, sea surface salinity, depth of the mixed layer, and the strength of the thermocline (Fiedler and Talley, 2006). At-sea and coastal upwelling, fronts, and eddies are generated by the oceanographic feature known as Ekman pumping driven by wind and eddy fluctuations, which can inject areas with nutrient-rich water that supports biological productivity. It is in these areas that large marine animals such as sea turtles and swordfish come to feed. The region is influenced by the various currents and water masses that affect the occurrence and distribution of the various highly migratory species targeted and bycatch species incidentally caught in the DGN fishery seasonally and annually.

Large-scale currents along the coast of California and Oregon include the surface-flowing California Current and the Inshore Countercurrent (Davidson Current), and the subsurface California Undercurrent. The region houses two major freshwater river plumes (Columbia River and San Francisco Bay), several smaller estuaries, numerous submarine canyons, and the complex borderland of the Southern California

Bight with its offshore islands, undersea ridges and deep basins (Hickey, 1998; Lynn and Simpson, 1987)

Weather systems, seasonal change, and periods of large-scale, oceanic regime shifts, such as El Niño Southern Oscillation, ENSO can affect the oceanographic features such as the direction and strength of flow. El Niño is a climatic fluctuation in which the east-west slope in the sea-surface and thermocline collapse, and warm water spreads across the tropical Pacific, along with areas of vigorous convection and heavy rainfall (Mann and Lazier, 1996). Specifically, the California Current generally flows southward year round, with strong flows in spring and summer. The southward flows may be reversed in shallow water by the seasonal appearance in the fall and winter of the subsurface poleward-flowing Inshore Countercurrent (Lynn and Simpson, 1987) and in response to storm wind (Ogston *et al.,* 2004). The California Undercurrent primarily intensifies in late spring and summer as a narrow ribbon of high-speed flow that presses northward at depth against the continental slope, generally beneath the equatorward-flowing upper layers (Lynn and Simpson, 1987).

Coastal upwelling of cold, salty, nutrient-rich water is driven to the surface by prevailing winds through Ekman pumping primarily in spring and summer in California and into early fall off the shore of Oregon. During El Niño periods, however, flow in the southward California Current is weakened while the Northward California Undercurrent is intensified. This decreases upwelling and reduces productivity. The water in the upper 500 meters of the water column is anomalously warm during the episodic period (Chelton and Davis, 1982).

The Southern California Bight (SCB) differs considerably from the regions to the north and south. The major geomorphic differences include the very narrow (< 10 kilometers) continental shelf, and the presence of a number of deep (>500 meters) basins offshore. This area is generally warmer and more protected from wind, waves, and storms than areas to the north, especially inshore of a line roughly drawn from San Miguel Island to San Clemente Island. In contrast to the SCB, the area from Point Conception northward to offshore of Cape Flattery, Washington, has a coastline that is relatively unprotected with rugged waters. For this reason, a majority of smaller vessels stay within the more sheltered SCB during the winters even though the swordfish continue to migrate northward (Chelton and Davis, 1982; Lynn and Simpson, 1987).

El Niño and La Niña events are climatic patterns that occur across the tropical Pacific and ware characterized by warming (El Niño) or cooling (La Niña) of surface waters (Mann and Lazier, 1996). These climatic fluctuations may affect the direction and strength of current system which may also affect the occurrence and distribution of organisms and the short-term productivity of the region. It has been reported that during El Niño episodic or persistent warm periods, the more tropical species such as striped marlin, thresher shark, dolphin fish (dorado), and tropical tunas (e.g., yellowfin, skipjack) may become more abundant within the EEZ, along with some of the more tropical prey species (Leet *et. al.,* 2001). The diminishing primary production, however, makes it increasing difficult for the higher trophic level species to survive in the region. In contrast, during La Niña, a climatic fluctuation in which there is a shoaling of the thermocline and nutricline, cool surface water is distributed across the tropical Pacific.

This may increase the primary production and increase the abundance and survival of higher trophic species.

Physical oceanographic features play a major role in the location of the fishery. A fisherman's choice of where to set his gear is dependent upon the occurrence or knowledge of these features such as frontal zones, and upwelling areas, as signaled by sea surface temperature, salinity and primary productivity. The success and failure of the fisherman to harvest a species is, therefore, dependent upon the ability to locate the physical oceanographic features that are correlated with populations of economically important fish.

b. Natural experiment

In general, a natural experiment is a naturally occurring event or situation, which can be exploited by a researcher to help answer a research question (Grafton *et al.*, 2006). Such occurrences are considered to be "quasi-experiments" in that the experimenter has little or no control over the situation that is being observed. Given an occurrence of an isolated change in one aspect of the economic environment, an economist can study the effects of that change as if it were an experiment, with the assumption that every other exogenous input used in the production process was held constant (Meyers, 1995).

Natural experiments have obvious limitations and drawbacks. The researcher has little-to-no control over the situation being observed, and there is the possibility that some other unobserved, uncontrolled factor could possibly influence the dependent variable. A natural experiment cannot unequivocally determine causation in a given situation; however, it can be a useful method for researchers. If used with caution, it can provide additional data which otherwise would not have been available to answer the research questions (Meyers, 1995).

Calculation of various performance metrics is one alternative approach to analyzing natural experiments. Provided appropriate data are available, measures of changes in technical efficiency and productivity can be developed to evaluate the potential ramifications or various regulatory regimes designed to reduce bycatch.

One such metric is productivity change, which indicates how changes in output have responded to changes in input levels over time. That is, how has the relationship of outputs to inputs changed over time? More importantly for this research, how has the relationship changed when adjusted to reflect changes in the level of undesirable outputs?

c. Productivity

The concept of productivity has long been examined and can, in its most basic form, be defined as the ratio of an output (or collection of outputs) to an input (or collection of inputs) in a production process (Grafton *et al.*, 2006). This definition, although fairly concise, is problematic when applied to assess productivity change in fisheries. The production process and daily operation of fishing have multiple inputs, such as labor and capital, which are used to capture various outputs such as swordfish and thresher shark (desirable) and sea turtles (undesirable). Due to the multi-output and input nature of the production process, there are several concepts of productivity. Two widely used concepts at partial factor productivity and total (overall) factor productivity (Squires, 1992).

The partial factor productivity measure generally relates a firm's output to a single input factor (e.g. labor). Although partial productivity is relatively easy to compute, it does not measure the entire production process and can be misleading. Total factor productivity (TFP) measures the multi-dimensional process (e.g. labor, capital, etc.). There is growing literature on measuring performance of fisheries using TFP (Kirkley, 1984; Squires, 1988; Squires, 1992; Jin *et al.*, 2002, and Hannesson, 2007, Kirkley *et al.,* 2010).

Managers who are interested in the assessment of the overall productivity of fisheries find TFP to be a more useful tool. The measure considers that distinct vessels or fisheries face different economic conditions and therefore may use input factors in varying proportions. There are several methods for deriving the TFP measure including growth accounting (Squires, 1992) and production based measures (Jin *et al.*, 2002).

Kirkley (1984) was the first economist to consider the application of various methods of productivity measurement to fisheries production. His early work provided an assessment of fisheries productivity at the national level. Squires (1988) used total factor productivity to analyze the Pacific coast trawl fleet productivity. Squires (1992) further expanded the field of fisheries productivity analysis by using a growth accounting approach which accounted for changes in the fish stocks in the Pacific coast trawl fleet. Following the work of Squires (1992), the New England groundfish fishery productivity was measured using the growth account approach. While these approaches all assessed productivity, none of them accounts for the presence of undesirable outputs.

Kirkley *et al.* (2010) provided a review of five general approaches that have been used throughout the productivity literature which account for undesirable outputs. Most of the approaches have been used in the pollution literature and more recently have been expanded into fisheries. The five approaches are (1) Data Envelopment Analysis (DEA)

(Färe *et al.,* 1989); (2) DEA to estimate directional distance function (DDF) (Chung *et al.*, 1997); (3) DDF using a translog specification (Färe *et al.*, 1993; Huang and Leung, 2007); (4) DDF using hyperbolic DEA (Färe *et al.* 1989) and (5) DDF using generalized quadratic specification (Färe *et al.,* 2005).

The estimation approaches to measuring productivity fall into two categories, parametric or non-parametric, which is discussed in the next section. Each approach has its advantages and disadvantages. Applicability of the various approaches is usually dependent on the availability of data. Previous studies (Chung *et al.,* 1997; Färe *et al.*, 2004; Kumbhakar and Lovell, 2000; Kwon and Lee, 2004; Huang and Leung, 2007; Felthoven and Paul, 2009; Kirkley *et al.,* 2010) have been conducted in the area of resource economics to estimate productivity changes using a parametric model. For the purpose of this study the parametric approach is discussed in more detail.

d. Parametric approach and functional form

The directional distance function measures the distance between a point in the output set and the efficient frontier in a direction of increasing productivity. It can be estimated using at least two different approaches, parametric or non-parametric. A non-parametric method, such as data envelopment analysis (DEA) has been used to estimate efficiency in the literature (Färe *et al.,* 1989; 1994; 2005; Färe and Grosskopf, 2004; Coelli *et al.,* 2005). This method employs a piecewise linear combination of all the observed inputs and outputs to construct the production possibility set. This method, while useful for obtaining estimates of efficiency, does not lend itself to the estimation of shadow prices. In order to estimate shadow prices, the model requires a parametric specification of the directional distance function that is differentiable (Färe *et al.,* 2005, Vardanyan and Noh, 2006).

In this study, a deterministic parametric approach was used to estimate efficiency, productivity change, and shadow prices. The frontier production function was first estimated, which provided estimates of the technically efficient, defined as the largest output level given some level of inputs. An indicator of productivity change was then constructed based on the works of Färe *et al.* (2001) and Chambers (1996).

When using a parametric approach, the technology is specified using an assumed functional form. Flexible functional forms or second order Taylor-series approximations are widely used in the productivity literature. The two most commonly used specifications are the translog (Färe *et al.,* 1993; Huang and Leung, 2007) which is a logarithmic transformation and, more recently, the generalized quadratic (Färe *et al.,* 2005). The generalized quadratic can be written as:

$$\vec{D}_o(x_k, y_k, b_k) = \alpha_o + \sum_{n=1}^{N} \alpha_n x_{nk} + \sum_{m=1}^{M} \beta_m y_{mk}$$
$$+ \sum_{i=1}^{I} \gamma_i b_{ik} + \frac{1}{2}\sum_{n=1}^{N} \sum_{n'=1}^{N} \alpha_{nn'} x_{nk} x_{n'k} + \frac{1}{2}\sum_{m=1}^{M} \sum_{m'=1}^{M} \beta_{mm'} y_{mk} y_{m'k}$$
$$+ \frac{1}{2}\sum_{i=1}^{I} \sum_{i'=1}^{I} \gamma_{ii'} b_{ik} b_{i'k} + \sum_{n=1}^{N} \sum_{m=1}^{M} \delta_{nm'} x_{nk} y_{mk}$$
$$+ \sum_{n=1}^{N} \sum_{i=1}^{I} \eta_{ni'} x_{nk} b + \sum_{m=1}^{M} \sum_{i=1}^{I} \mu_{mi} y_{mk} b_{ik} \qquad (1)$$

The translog takes a similar form to the quadratic, except the independent variables (x,y,b) are transformed logarithmically:

$$\vec{D}_o(x_k, y_k, b_k) = \alpha_o + \sum_{n=1}^{N} \alpha_n \ln x_{nk} + \sum_{m=1}^{M} \beta_m \ln y_{mk}$$
$$+ \sum_{i=1}^{I} \gamma_i \ln b_{ik} + \frac{1}{2}\sum_{n=1}^{N} \sum_{n'=1}^{N} \alpha_{nn'} \ln x_{nk} \ln x_{n'k}$$
$$+ \frac{1}{2}\sum_{m=1}^{M} \sum_{m'=1}^{M} \beta_{mm'} \ln y_{mk} \ln y_{m'k}$$
$$+ \frac{1}{2}\sum_{i=1}^{I} \sum_{i'=1}^{I} \gamma_{ii'} \ln b_{ik} \ln b_{i'k} + \sum_{n=1}^{N} \sum_{m=1}^{M} \delta_{nm} \ln x_{nk} \ln y_{mk}$$
$$+ \sum_{n=1}^{N} \sum_{i=1}^{I} \eta_{ni} \ln x_{nk} \ln b_{ik} + \sum_{m=1}^{M} \sum_{i=1}^{I} \mu_{mi} \ln y_{mk} \ln b_{ik}$$
(2)

where $\vec{D}_o(x_k, y_k y, b_k)$ is the direction vector, x_k represents the N factors of production (inputs), y_k is a vector of M desirable outputs, and b_k is a vector of I undesirable outputs. All other variables (e.g. α_o) are parameters to be estimated

The choice of functional form for the production estimation is very important as it can affect the estimates of productivity change and shadow prices for undesirable outputs (Vardanyan and Noh, 2006).There are a variety of functional forms that have been used in past empirical analysis including the Cobb-Douglas (Battese and Coelli, 1992, 1995), translog (Färe *et al*., 2004; Cuesta *et al*., 2009), and the quadratic (Färe *et. al.,* 2004; Vardanyan and Noh, 2006). Researchers typically chose a functional form based on trade-offs between ease of estimation and interpretation compared to the amount of flexibility the form allows.

The Cobb-Douglas, one of the most popular forms, is linear in logarithms and is the easiest to estimate. The Cobb-Douglas imposes restrictions on the relationships between the inputs and outputs, rather than imposing restrictions such as the regular hyperbolic isoquant of the functional form. An isoquant is defined as a curve or line that represents the same level of output, but that is produced with different input combinations. A more detailed listing of the restrictions imposed by the Cobb-Douglas on the underlying technology can be found in Battese and Coelli (1995), Coelli and Perelman (1999) and some basic production texts.

The translog provides flexibility by allowing the data to determine almost every aspect of the production relationship instead of including a priori constraints. The translog has various problems, specifically its inability to adequately deal with zero-valued observations, which typically occur in data for multi-species production operations. Also, the translog is translation invariant, which means that it is not the best choice when used to estimate shadow prices.

The translog and Cobb-Douglas functional forms, while easy to estimate, do not accommodate cases where there are zero inputs or outputs. This restriction makes these two functional forms inapplicable to the fisheries applications where bycatch is present in the production process. Some researchers typically have overcome this by substituting a small value less than one for the zero values. The substitution has a numerical impact, however, and complicates the analysis of the results.

The strengths of the quadratic include allowing for third stage production (where marginal products can become negative) and concavity (diminishing marginal products). Marginal products can be defined as the extra output or product that is obtained from a marginal change in a give input. Concavity is imposed by regularity conditions[2] on the

[2] A sufficient condition to guarantee concavity is that the coefficients of the quadratic terms describe a negative semi-definite coefficient matrix in the corresponding quadratic form.

signs and relative magnitudes of the estimated parameters on the second order terms in Equations 1 and 2. Other studies that estimate productivity and/or shadow price of undesirable outputs using the production frontier approach have used the quadratic form (Färe *et al.*, 2005; Färe *et al.*, 2006; Vardanyan and Noh, 2006). The quadratic production function was therefore used in this research; it overcomes the weaknesses of the Cobb-Douglas and the translog functional forms, and has been used in other various empirical applications involving undesirable outputs.

e. Shadow price

Shadow price is an opportunity cost, or an indicator of producer surplus forgone in terms of lost revenue of the production activity. Shephard (1970) was the first to develop the idea of using duality to derive shadow price outputs and input distance functions. From Shephard's work, Färe *et al.* (1993) computed shadow prices using directional distance functions (Murty *et al.*, 2007). The use of shadow pricing of undesirable outputs has been thoroughly investigated in the environmental economics literature (Färe *et al.*, 1993; Färe *et al.*, 2001; Färe *et al.*, 2005; Vardanyan and Noh, 2005). The main application of shadow pricing has been used to measure pollution abatement in electricity generating power plants. Several papers have used shadow price to estimate lost revenue of catch yields a fishery (Haraden *et al.,* 2004; Huang and Leung, 2007; Pradhan and Leung, 2008).

The shadow price reflects the trade-off between desirable and undesirable output on the boundary P(x) where the directional output distance function takes the value zero. Shadow prices have been explicitly or implicitly used to measure productivity change derived from estimates of the technology set (Rezek and Perrin, 2004). Implicitly using the shadow prices to weight the desirable and undesirable output is appropriate because consumer relevant prices (i.e. market values) are not available for the undesirables such as sea turtles, marine mammals and other non-marketable species.

The duality between the distance function and the revenue function is exploited for deriving the shadow price of outputs for the directional output distance function. Pittman (1983) presented one of the first studies to adjust productivity performance estimates for undesirable outputs, calculating shadow prices from abatement costs to adjust the productivity index for a sample of pulp and paper mills. Using Pittman's data, Färe *et al.* (1989) were the first to begin adjusting productivity performance for environmentally bad outputs by explicitly including effluents in the technology set. They used a non-parametric approach known as data envelopment analysis (DEA) to calculate the environmentally-adjusted efficiency scores for the pulp and paper mills. Färe *et al.* (1993) furthered this area of research by using a translog output distance function to represent the technology and a non-stochastic linear programming technique developed by Aigner and Chu (1968) to estimate the function. Färe *et al.* (1989) used a hyperbolic approach while a radial approach was used in Färe *et al.* (1996). Several other studies on shadow price differ from Färe's work in the choice of the directional vector on the output of the function (Chambers *et al.*, 1996; Chung *et al.*, 1997; Boyd *et al.*, 1996). All of these studies focused on different industries and different levels of reduction and therefore cannot be used as comparison for this study. The most relevant research that can provide a reasonable comparison is the work of Huang and Leung (2007) that used a translog directional output distance function to calculate shadow price of conservation cost of sea turtles in the Hawaiian longline fishery.

Table 2. Condensed list of species captured in the CA/OR DGNF.

Desirable	**Undesirable**
Target	**Marine Mammals**
Swordfish	Short-beaked common dolphin
Bigeye thresher shark	Long-beaked common dolphin
Common thresher shark	California sea lion
Pelagic thresher shark	Northern elephant seal
	Dall's porpoise
Non-Target	Cuvier's beaked whale
Albacore	Grey whale
Bluefin tuna	Sperm whale
Skipjack tuna	Pacific whiteside dolphin
Yellowfin tuna	Northern right whale
Shortfin mako shark	
Bullet mackerel	**Sea turtles**
Opah	Leatherback sea turtle
Louvar	Loggerhead sea turtle
Oilfish	
Pacific bonito	**Regulated Finfish Species**
Pacific mackerel	Striped marlin
Pacific pomfret	Basking shark
Yellowtail	Soupfin shark
Pacific hake	Salmon shark
White seabass	
Spiny dogfish	**Other**
California barracuda	Blue shark
	Bat ray
	Common mola
	Pelagic stingray
	Remora
	Manta

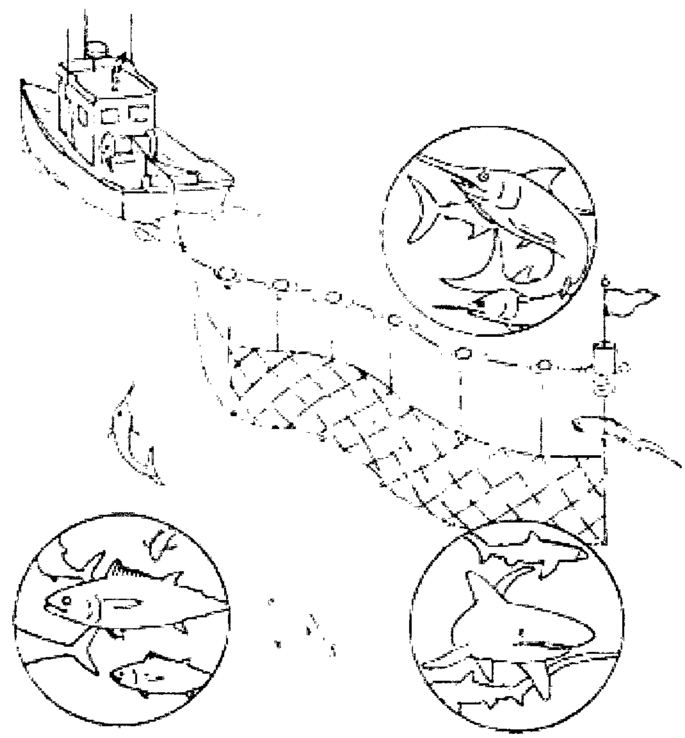
Table 3. Regulatory history of CA/OR DGNF

Year	Regulatory Body	Regulation
1977	CDFG	Exploration by 15 vessels using large mesh drift gillnets operation in nearshore waters of the Southern California Bight for pelagic sharks, which resulted in expansion of the fishery.
1980	CDFG	AB 2564, Directed CDFG to implement a non-transferable limited entry program with a target of 150 permitted vessels. Permits were issued to 165 fishermen with 94 using dual gear (harpoon and gillnet). Legislation authorized the permitted fishery to retain swordfish. Study of the impact on shark resources was conducted by CDFG. Legislation required mandatory observers and logbooks. Net length was set a maximum of 6000 feet.
1981	PFMC	Billfish and ocean sharks Fisheries Management Plan (FMP)
1982	CDFG	SB (1537) Moratorium on new DGN permits 230 permits were issued and monitored by CDFG Season Closed February 1 through April 30 Time/Area Closure established around Channel Islands to protect pinnipeds. Quota of 50% shark and 50% swordfish established
1983	ODFW & WDFW	Oregon and Washington issue experimental permits for thresher shark fishery.
1984	CDFG	Additional 35 permits issued to DGN fishermen in Northern Region AB (3387) with cap of 265 permits. Area closure established off San Francisco, and within 12 miles of shore.
1985	CDFG	Shark – Swordfish quota removed.
1986	CDFG	DGNF season closed June 1 through August 15 within 75 miles of mainland to protect migrating thresher shark. Area closed December 15 through January 31 within 25 miles to protect migrating gray whales.
1988	ODFW &WDFW	Experimental fishery ends.
1988	NMFS & PFMC	PFMC directed to draft Coast-wide Management Plan for sharks under Inter-jurisdictional Fisheries Act of 1986.
1989	ODFW & WDFW	Closure of DGNF due to marine mammal and sea turtle interactions.
1990	PFMC	Harvest guideline established for thresher shark (340 metric tons).
1990	NMFS	Fisheries Observer Program established under Marine Mammal Protection Act
1990	CDFG	DGN fishing prohibited within 75 miles of mainland from May 1 through August 14 to conserve thresher shark population.

1994	CDFG	Cap on permits, only transfer allowed for DGN permit holders.
1995	ODFW	Ban lifted on Swordfish DGN landings. Established closure within 75 miles of coast May 1 through August 14. August 14 through December 31 no fishing permitted in depths less than 1000 meters.
1996	NMFS/POCTRC	Pacific Offshore Cetacean Take Reduction Team develops (TRP).
1997	NMFS	Implementation of TRP which required use of Acoustic Pingers and 36 foot extender lines to be used to reduce interactions with Marine Mammals and Pinnipeds.
1998	CDFG	North and South permits combined into overall state permit program.
1999	ODFW	Direct targeting of thresher shark with DGN prohibited with allowance of incidental catch (ratio of 1 to 2 of thresher to swordfish)
2000	WDFW	Thresher shark fishing prohibited in adjacent waters to coast and landings consistent with OR ratio.
2001	NMFS	MMPA permits issued to DGNF to authorize the take of marine mammals. Two area closures established. Closure North of Point Conception implemented to protect Leatherback sea turtles and closure and area south of point conception implemented to protect Loggerheads during El Nino years under ESA section seven consultation.
2002	CDFG	Elimination of minimum landing requirement for DGN permit renewal.
2004	NMFS	PFMC FMP for US West Coast Fisheries for Highly Migratory Species (HMS FMP) approved.

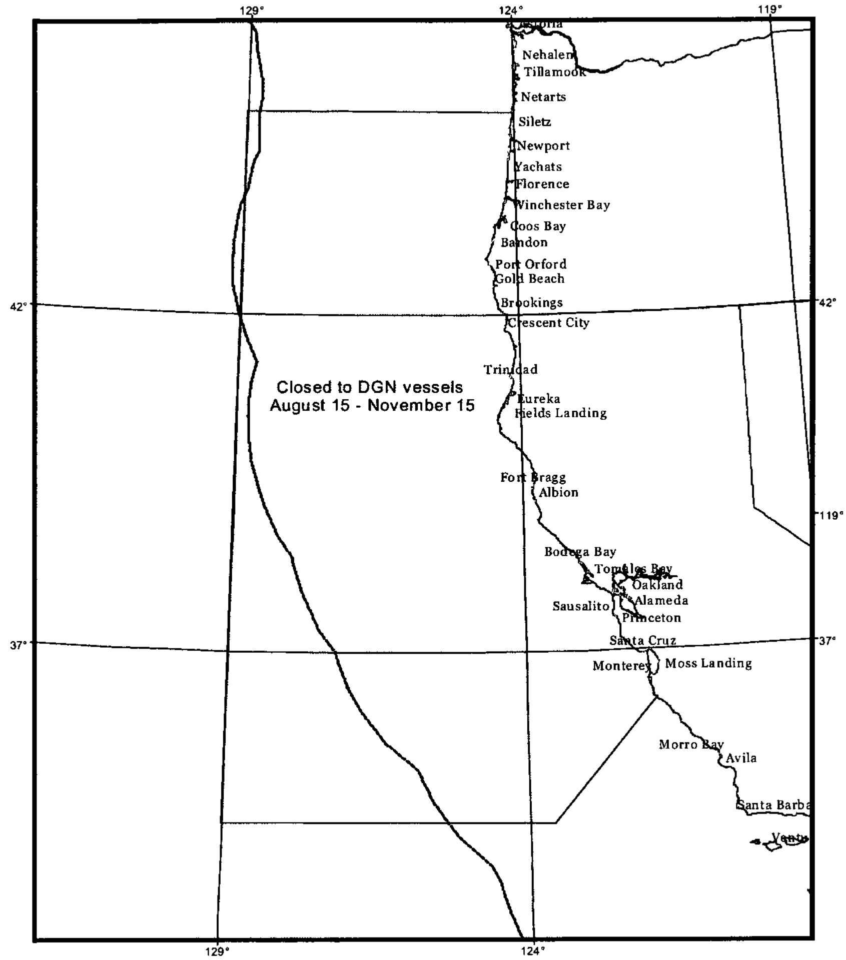
Modified from NMFS (2006).

Figure 2. Drift gillnet diagram



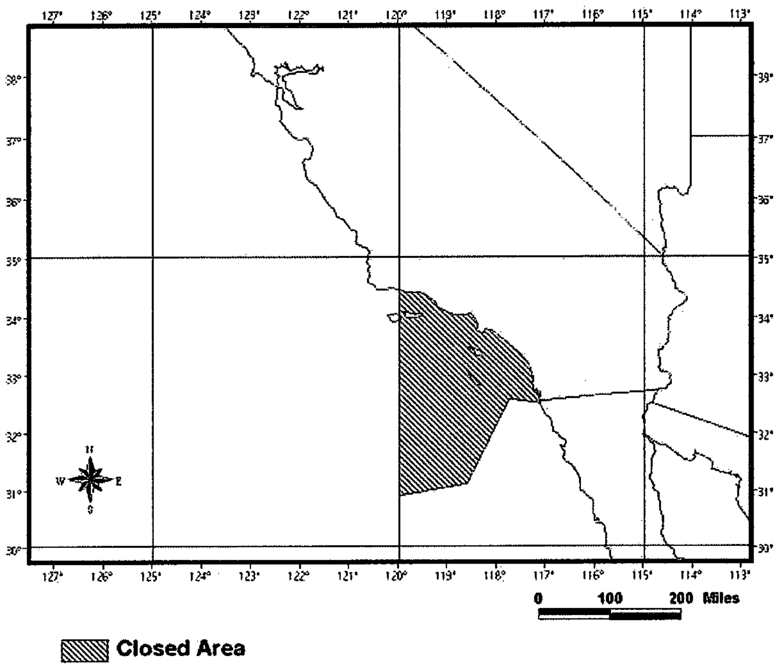
California Seafood Council 1/8/2008

Figure 3. Map of Leatherback Conservation Closure Area.



NMFS SWR 2009

Figure 4. Map of Southern Closure Area for Loggerhead Conservation during El Nino Years



NMFS SWR 7/11/01

SECTION III: METHODOLOGY

This section presents the methodology used to assess the efficiency, productivity, and shadow price estimates of undesirable harvest for the CA/OR DGNF for the period 1996-2008. The methods considered the joint production of both desirable and undesirable outputs. The methodology is based on production theory from economics. A characterization of the production technology is presented in order to represent the relationship between input and output measures. The traditional axioms of production theory are introduced. An optimization model is used to estimate the parameters of technology using a directional distance function. It is a parametric application for modeling the production system that provides a measure of performance based on multiple inputs and outputs. This method also does not restrict one to using prices for aggregation of undesirable outputs.

The Luenberger productivity indicator was used to calculate productivity, which was then decomposed into measures of technical change and efficiency change. Shadow prices were estimated by using the directional distance function approach adapted from the work of Färe *et al.* (2005) and Vardanyan and Noh (2006) for all of the undesirable outputs in the production process.

a. Theoretical background

Production functions are typically used to describe the relationship between the inputs and product of a single-output firm, expressed using a single output (y) as a function (f) of a vector of a vector of inputs (x), written in equation form as:

$$y = f(x). \quad (3)$$

However, when a firm such as a multi-species fishery produces more than one output, most simply aggregate or use a dual representation of the production technology, such as revenue function that accounts for the multi-output nature of the production (Coelli *et al.,* 1998; Coelli and Perelman 2000; Färe and Primont, 1995).

Combining multiple outputs into a single-output index can lead to problems with aggregation. By using the primal distance function representation of the production technology, first introduced by Shephard (1970), the need for aggregation or price information is avoided. Färe and Grosskopf (2004) furthered the use of distance functions by specifying a directional distance function that is a variation of the Luenberger shortage function developed in Luenberger (1992).

Directional distance functions provide a good representation of a multi-input, multi-output production technology, which is useful in this production context because it allows for the radial and non-radial expansion of the outputs: The amount by which different outputs expand or contract is determined by the chosen direction vector. This is not possible when an aggregated ratio of total outputs to inputs is used to measure the production technology.

Directional distance functions can be specified using inputs or outputs. For the purpose of this study, a directional output distance function was specified. Directional output distance functions are also dual to the revenue function and allow for the calculation of revenue-based shadow prices of the undesirable outputs (Färe and Grosskopf, 2004).

i. Production possibility set

In environmental economics one often wishes to distinguish between desirable and undesirable outputs. In the production context, marketable goods typically comprise the former while the latter often include non-marketed byproducts that may have deleterious effects on the environment. The disposal or reduction of undesirable outputs hence is often subject to regulations. As a result, it is useful to explicitly model the effects of producing both types of outputs, taking into account their characteristics and interactions (Färe and Grosskopf, 2004).

Consider a production process where desirable and undesirable outputs may be jointly produced, i.e. undesirable outputs b are a byproduct of the production of desirable outputs y, where both b and y are vectors of outputs. Here, the application is the drift gillnet fishery that harvests marketable and non-marketed species. In this case, the desirable or marketable output vector y includes quantities of swordfish, thresher shark, tuna, and other marketable species. There is also the harvest of undesirable outputs, such as the incidental capture or mortality of marine mammals, sea birds, sea turtles, and other non-marketable species quantified as components of b.

The basic problem is that given technology, harvesting swordfish and thresher sharks means simultaneously harvesting juvenile marketable species or other undesirable catch. The capture of undesirable species like leatherback sea turtles and blue shark is not only detrimental to the affected populations but also requires intense and costly labor to disentangle the catch from the gear or perhaps even to repair damaged gear or to replace damaged gear.

The production technology is described by a production possibility set P(x), defined as a set of desirable and undesirable outputs that can be produced from a given level of inputs, x. Chambers (1988), Coelli *et al.* (1998), Coelli *et al.* (2005), and Färe *et al.* (2006) define the production function by four basic properties: (1) the value of the set P(x) is a finite, non negative real number; (2) the production function of positive output is infeasible without one input; (3) additional units of inputs will not decrease outputs, often referred to in the literature as monotonicity; and (4) concavity in inputs. For more information and equations for the production function properties and the output possibility sets, refer to Coelli *et al.* (1998) and Färe *et al.* (2006).

The production possibility set describes the possible transformation of inputs into desirable and undesirable outputs:

$$P(x) \ = \ \{(y,b): x \ can \ produce \ (y,b)\} \qquad (3)$$

where,

$P(x)$ = the production possibility set

x = inputs

y = desirable outputs

b = undesirable outputs

ii. Output distance function

There are three basic distance measures described in the productivity measurement literature; input, output, and directional. The output distance function is first explained below, followed by the directional distance function. An input distance function characterizes the production technology by looking at the minimum proportional contraction of inputs with a given level of outputs for which the input vector would remain in the input set. For more information on the input distance functions refer to Coelli *et al.* (1998).

Shephard's output distance function (Shephard, 1970) can be used to determine how far the production or output level is from the frontier given existing input levels. It is defined as the ratio of actual output to maximum potential output and equals the reciprocal of Farrell's (1957) output efficiency measure. For any trip by a vessel, the equation for Shephard's output distance function is:

$$\vec{D}_o(x,y) = \inf\left\{\Phi: \left(\frac{y}{\Phi}\right) \in P(x)\right\} = \left[\sup\{\Phi: (\tfrac{y}{\Phi}) \in P(x)\}\right]^{-1} \quad (4)$$

In order to illustrate the concept of Shephard's output distance function, assume that a drift gillnet vessel trip harvests only two outputs, y_1 and y_2, from a given input vector. Figure 5 shows a hypothetical output possibility set, represented by $P(x)$. The set is bounded by the production possibility frontier, labeled $PPC - P(x)$, and the y_1 and y_2 axes. The frontier of the set is defined as the output vector that cannot be increased by a scalar multiple without leaving the set. In the figure, the frontier represents all efficient combinations of outputs y_1 and y_2.

For a trip by a vessel using some levels of inputs *x* to harvest outputs *y1* and *y2*, the value of the distance function is defined by point A in Figure 5 and is equal to the ratio, $\vec{D}_o(x,y) = \frac{OA}{OB}$. This is a measure of how far the vessel trip A is from the frontier. The function is equal to one for all efficient vessel trips such as vessel trip B in the figure, and less than one for inefficient vessel trips.

The reciprocal of the distance function measure is the technical efficiency score, which is the factor by which the production of all output quantities could be increased while holding input levels constant (Coelli *et al.* 1998). Drift gillnet vessels do not always operate trips efficiently; therefore, inefficient vessel trips lie below the efficient frontier with an distance function and efficiency score greater than zero, represented in the figure by point A.

The reciprocal of the output distance function $\frac{OB}{OA}$ or the Farrell measure gives the maximum proportional expansion in all outputs that is feasible for a given set. A completely efficient vessel trip would have a technical efficiency score equal to one and a distance function of one. The distance function completely characterizes the production technology T, because a production vector is in the output set if and only if the distance function takes a value of one or less: $y \in P(x) \Leftrightarrow D_o(x,y) \leq 1$ (Färe *et al.,* 1994; Färe and Primont, 1995).

By redefining the equation 4, the undesirable outputs can be included, however, this is not appropriate for this research as it would result in a proportional expansion of desirable and undesirable outputs and would not credit the reduction of undesirable outputs. In the case of fisheries that jointly produce desirable and undesirable outputs, this approach would not be useful as managers wish to minimize undesirable output.

iii. Directional output distance function

Unlike the output distance function, the directional distance function permits outputs (inputs) to be expanded (reduced) by the same proportion or by the same level. Recently, a new directional distance function was introduced by Färe *et al.* (2010), which allowed each desirable output to be expanded by a different level and each undesirable output to be contracted by a different level; however, this approach does not permit estimation of shadow prices. The joint production of desirable and undesirable outputs in the production possibility set requires that Shephard's output distance function to be modified so that the efficiency measure will credit the expansion of desirable outputs and the reduction of undesirable outputs.

Following the work and notation of Färe *et al.* (2004), suppose a vessel employs a vector of inputs $x \in \Re_+^K$ to produce a vector of desirable outputs $y \in \Re_+^M$, and undesirable outputs $b \in \Re_+^N$, then let $P(x)$ represent the output set of desirable and undesirable outputs (y, b) that can be jointly produced from the input vector x,

$P(x) = \{(y, b) : x \; can \; produce \; (y, b)\}.$

In a fishing context, K vessel trips each characterized by inputs, desirable, and undesirable outputs (x_k, y_k, b_k) are examined.

The following assumptions need to be specified to model the production technology when desirable and undesirable outputs are jointly produced. The assumption will allow the researcher to impose structure on the parameters of the function which will be used to empirically estimate trip-specific efficiency and productivity of the fishing entity, along with the shadow prices of the undesirable outputs. Following Färe *et al.* (1997; 2004; 2007a) I will use axioms laid out by Shephard (1970) to specify the assumptions.

The first assumption $P(0) = \{0,0\}$ states that zero inputs yield zero outputs and any non-negative input yields at least zero output. This assumption is often referred to as a condition of 'no free lunch'.

Second, the output set is compact for each input vector (e.g. a finite amount of inputs can only produce finite amounts of output) or as Färe and Primont (1995) note

'...scarcity of inputs must imply scarcity of outputs.' The assumption implies that the output set is closed and bounded.

Third, the input is strongly or freely disposable; that is, we assume if

$$x' \geqq x \text{ then } P(x') \supseteq P(x).$$

This means inputs are allowed to be costlessly disposed. It also implies that an increase in any one input does not reduce the size of the output possibility set $P(x)$.

Fourth, desirable outputs will be strongly and freely disposable.

$$\textit{If } (y, b)\ P(x) \textit{ and } (y', b) \leq (y, b) \textit{ then } (y', b) \in P(x).$$

According to Färe (2004), free or strong disposability implies that if any observed desirable or undesirable output vector is feasible, then any output vector where desirable output was reduced is also feasible. This suggests that a firm (fishing entity) is free to dispose of desirable output without cost.

Due to regulations designed to mitigate bycatch and incidental takes, fishing entities are forced to reduce their undesirable output. Desirable and undesirable outputs should be treated asymmetrically in terms of the disposability characteristics (Ball *et al.*, 2005). Even in the absence of regulation, increased environmental consciousness from stakeholders still requires careful treatment of undesirable outputs as weakly disposable. Weak disposability is the notion that some cost is associated with disposing of undesirable outputs or inputs. When desirable and undesirable outputs are jointly produced then, undesirable outputs must be disposed at some cost in terms of the opportunity cost of foregone desirable outputs. For example, a reduction in one sea turtle captured would equate to some amount of forgone swordfish harvest that would have been captured in the absence of regulations.

To model the assumption that there is a cost to reducing undesirable outputs, the following requirement is imposed:

$$If\,(y, b) \in P(x)\ and\ 0 \leqq \Theta \leqq 1\ then\ (\Theta y, \Theta b) \in P(x).$$

This assumption can be interpreted as a proportional contraction of desirable and undesirable outputs together, and is feasible if, for a given input x, reductions in bad outputs are always possible if good outputs are reduced in proportion. Therefore, desirable and undesirable inputs are jointly produced, which means that reduction of undesirable outputs will have a private cost.[3] The cost to the fishing entity could be reduced desirable catch and variable profits

Finally, in order to integrate the undesirable harvest (e.g. sea turtle, marine mammal and all other non-marketable harvest), they (undesirable outputs) must first be specified as outputs. In order to explicitly model the joint production, I make the assumption of null-jointness:

$$If\,(y, b) \in P(x)\ and\ b = 0\ then\ y = 0.$$

This assumption states that if an output vector (y, b) is feasible and there are no undesirable outputs, under null-jointness only zero desirable outputs can be produced. In other words, if some positive amount of desirable output is produced then undesirable output must also be produced. In context of drift gillnet vessels, null-jointness simply implies that where there is harvest of swordfish, shark, or tuna, there must also be some harvest of bycatch (i.e., juvenile marketable species, sea turtles, marine mammals, or other unintended catch). The recent approach of Färe *et al.* (2010) eliminates this restriction. For the purpose of estimating the production frontier, all equations are

[3] A private cost of an action is the cost experienced by the party making the decision leading to some action. In the case a operating a vessel the private cost would be fuel, oil, maintenance, depreciation, fishing gear, and even the boat time experienced by the captain and crew.

represented in functional form. Let $g = (g_y, g_b)$ be a directional vector with $g \in \Re^M x \Re^J$ and $\beta \in \Re^1$ (g is an $M+J$-dimensional real vector and β is a real scalar). The directional output function is defined as,

$$\vec{D}o\ (x, y, b: g_y, -g_b) = max\{\beta : (y + \beta g_y, b - \beta g_b) \in P(x)\}.$$

The function will simultaneously maximize the reduction of undesirable outputs and the expansion of desirable inputs while keeping outputs feasible. The directional distance function is bounded between zero and infinity and will be non-negative for feasible output vectors. It provides an equivalent characterization of the technology to that implied by the output possibility set $P(x)$.

An illustration of the directional distance function is provided in Figure 6. Point A is the output mix of a vessel that jointly produces two outputs, one desirable (e.g., swordfish) and one undesirable (e.g., sea turtles). The output mix for the vessel at point A is inefficient, as it is not on the frontier. Unlike the earlier output distance measure of technical efficiency, which would have considered a movement along the ray 0A, the directional distance function measure considers the movement along either a positive or negative direction. Under the definition of a vector, it comes with the characteristics of magnitude β and direction g. In Figure 6, the directional vector considers the movement along ADE or the vertical line AC. There is an expansion in desirable outputs and a reduction in undesirable outputs. The point G is the coordinate point (g_y, g_b); $g(y)$ and $g(b)$ represent directions in the observed values of one good output y and one bad output b. The distance from point A to point E on the frontier measured in the direction of line segment ADE is referred to as β and is less than or equal to one. If the ratio of the directional vector is $\frac{0G}{OF} = 0$, then it is efficient. In the example, desirable outputs are expanded while bad or undesirable outputs are compressed. Therefore the vector $0F$ is in the negative direction on the axis $-g(y)$.

iv. Shadow price

Following the work of Färe *et al.* (2006), Weber and Domazlicky (2001), and Vardanyan and Noh (2006), the generalized quadratic directional output distance function was used to calculate the shadow price for undesirable species harvested in the drift gillnet fishery. Unlike Weber and Domazlicky (2001), which used the translog flexible functional form, Färe *et al.* (2004), and Vardanyan and Noh (2006) used the quadratic functional form, which allows for the zero values for outputs in some of the observations.

In order to obtain shadow prices for undesirable outputs it is first necessary to examine the relationship between the maximum revenue function and the directional output distance function (Färe *et al*, 2004). The following the model was adapted from the work of Färe *et al.* (2006).

Let $p = (p_1, \ldots, p_M) \in R_+^M$ represent desirable output prices (e.g. composite swordfish and thresher shark prices) and let $q = (q_1, \ldots, q_J) \in R_+^J$ represent undesirable output prices (e.g. unknown price of a sea turtle). The revenue function, which accounts for the negative revenue generated by the undesirable outputs, and can be defined as:

$$R(x,p,q) = max_{y,b} \{py - qb : (y,b) \in P(x)\}. \quad (5)$$

$R(x,p,q)$ gives the maximum revenue that can be obtained from the productions inputs, x, when the firm (trip) has desirable output prices, p, and undesirable $\vec{D}$ output prices, q. The multiplication operation in the revenue calculation is the dot product.

The maximum revenue function can be written as:

$$R(x,p,q) = max_{y,b} \{py - qb : \vec{D}_o(x,y,b;\, g) \geq 0\}. \quad (6)$$

$If (y,b) \in P(x)\ then\ (y+\ \beta g_y, b\ -\ \beta g_b)\ =\ \{(y\ +\vec{D}_o(x,y,b;g)\ \cdot\ g_y, b\ -$ $\vec{D}_o(x,y,b;g)\ \cdot\ g_b) \in$ P(x)}. This means that if an output vector (y, b) is feasible, then the reduction of any inefficiency associated with that output vector by moving in the direction g is also feasible. This can be re-written as:

$$R(x,p,q)\ \geq (p, -q(y\ +\ \vec{D}_o(x,y,b;g)\ \cdot\ g_y, b\ -\ \vec{D}_o(x,y,b;g)\ \cdot\ g_b\ or$$

$$R(x,p,q) \geq \left(py - qb\right) +\ p\vec{D}_o(x,y,b;\ g) \cdot\ g_y\ +\ q\vec{D}_o(x,y,b;\ g) \cdot\ g_b. \qquad (7)$$

Maximum revenue is on the left-hand side of the inequality in (7) while the right hand side represents actual revenue $(py - qb)$ plus the revenue gained by the removal of technical inefficiency on the right side. The gain in revenue from the removal of technical inefficiency has two components: the gain due to an expansion in desirable outputs $(p\vec{D}_o(x,y,b;\ g)\ \cdot\ g_y)$, and the gain due to a contraction in undesirable outputs $(p\vec{D}_o(x,y,b;\ g)\ \cdot\ g_b)$, since the cost of undesirable outputs is subtracted from desirable revenues.

If the firm has a one unit movement in a direction that takes it to the allocatively efficient output mix on the frontier of $P(x)$ then the inequality associated with the maximum revenue function in equation 7 becomes an equality. By rearranging the maximum revenue equation, the directional output distance function and the maximal revenue function can be related using the following inequality:

$$\vec{D}_o(x,y,b;\ g) \leq \{R(x,p,q)\ -\ (py\ -\ qb)\}/(pg_y\ + qg_b). \qquad (8)$$

The directional output distance function given can also be recovered from the revenue function as:

$$\vec{D}_o(x,y,b;\ g) = min_{p,q}\ \{R(x,p,q)\ -\ (py\ -\ qb)\}/(pg_y\ + qg_b). \qquad (9)$$

Applying the envelope theorem twice to the previous equation yields our shadow price model:

$$\nabla_b \vec{D}_o(x, y, b;\ g) = \frac{q}{pg_y + qg_b} \geq 0 \text{ and} \tag{10}$$

$$\nabla_y \vec{D}_o(x, y, b;\ g) = \frac{-p}{pg_y + qg_b} \leq 0. \tag{11}$$

where ∇_{b} and ∇_{y} are changes in the desirable and undesirable outputs.

Given the output price of one desirable output, the m^{th}, the $j = 1, \ldots, J$ nominal undesirable output prices can be calculated as:

$$q_j = -p_m\left(\frac{\partial \vec{D}_o(x,y,b;\ g)}{\partial b j \ /\partial \vec{D}_o(x,y,b;\ g)/\ \partial y_m}\right),\ j = 1, \ldots, J. \tag{12}$$

b. Empirical estimation of directional output distance function and productivity change

Following Färe *et al.* (2005), the quadratic directional distance output function, which can serve as the second order approximation to a true, but unknown, function for the estimation of productivity and the shadow price of undesirable harvest, was estimated using trip-level data from the NOAA DGN fishery observer logbooks and PacFIN database. The function must satisfy the translation property, which requires that moving an output point closer to the frontier by a scalar multiple α times the directional vector will reduce the measured distance from the frontier by α. The function is specified parametrically as a generalized quadratic functional form. The advantage of this approach is that it is differentiable, unlike the frontier for non-parametric data envelopment analysis (DEA). The specification of the generalized quadratic directional distance function is deterministic, which implies all deviations from the frontier are due to inefficiency.

The quadratic form of the directional distance function that is twice differentiable and flexible is employed in this study and can be written as follows:

$$\vec{D}_o(x_k, y_k, b_k) = \alpha_o + \sum_{n=1}^{N} \alpha_n x_{nk} + \sum_{m=1}^{M} \beta_m y_{mk}$$
$$+ \sum_{i=1}^{I} \gamma_i b_{ik} + \frac{1}{2}\sum_{n=1}^{N} \sum_{n'=1}^{N} \alpha_{nn'} x_{nk} x_{n'k} + \frac{1}{2}\sum_{m=1}^{M} \sum_{m'=1}^{M} \beta_{mm'} y_{mk} y_{m'k}$$
$$+ \frac{1}{2}\sum_{i=1}^{I} \sum_{i'=1}^{I} \gamma_{ii'} b_{ik} b_{i'k} + \sum_{n=1}^{N} \sum_{m=1}^{M} \delta_{nm} x_{nk} y_{mk}$$
$$+ \sum_{n=1}^{N} \sum_{i=1}^{I} \eta_{ni'} x_{nk} b_{ik} + \sum_{m=1}^{M} \sum_{i=1}^{I} \mu_{mi'} y_{mk} b_{ik}$$

(13)

$\vec{D}_o$ is the directional output distance; x_k is a vector of N factors of production (inputs) (i.e., number of sets, net depth in feet, net length in fathoms, soak time in hours, vessel length in feet, and vessel horsepower); y_k is a vector of M desirable outputs (composite weight in pounds of swordfish and thresher shark and composite of all other marketable species); and b_k is a vector of I undesirable outputs (total number of market species discards, unmarketable discards, sea turtles, and marine mammals).

Dummy variables were used to account for the effect on the technological frontier of time periods and for whether effort occurred inside or outside of the closure. The parameters (all of the remaining variable in the equation (e.g. α_o) of the directional distance function were estimated using linear programming methods developed by Aigner and Chu (1968), which minimizes the total distance between the observations and the predicted frontier. The minimization problem following the work of Vardanyan and Noh (2006) is derived below.

$$Min \sum_{k=1}^{K} (\vec{D}_o(x_k, y_k, b_k; \sigma, -v) - 0)$$

s.t. (i) $\vec{D}o\ (x_k, y_k, b_k; \sigma, v) \geq 0),\ k = 1, \dots K,$

(ii) $\frac{\partial \vec{D}o\ (x_k, y_k, b_k; \sigma, v)}{\partial y_m} \leq 0),\ m = 1, \dots M, k = 1, \dots K,$

(iii) $\frac{\partial \vec{D}o\ (x_k, y_k, b_k; \sigma, v)}{\partial b_{ik}} \geq 0),\ i = 1, \dots I, k = 1, \dots K,$

(iv) $\frac{\partial \vec{D}o\ (x_k, y_k, b_k; \sigma, v)}{\partial x_{nk}} \geq 0),\ n = 1, \dots N, k = 1. \dots K$

(v) $\sigma \sum_{m=1}^{M} \beta_m - v \sum_{i=1}^{I} \gamma_i = -1,$

$\sigma \sum_{m'=1}^{M} \beta_{mm'} - v \sum_{i=1}^{I} \mu_{mi} = 0;\ m = 1, \dots, M,$

$\sigma \sum_{m=1}^{M} \mu_{mi} - v \sum_{i=1}^{I} \gamma_{ii'} = 0;\ i' = 1, \dots, I,$

$\sigma \sum_{m=1}^{M} \beta\delta_{mm} - v \sum_{i=1}^{I} \eta_{ni} = 0;\ n = 1, \dots, N,$

$\sigma^2 \sum_{m=1}^{M} \quad \sum_{m'=1}^{M} \beta_{mm'} + v^2 \sum_{i=1}^{I} \quad \sum_{i'=1}^{I} \gamma_{ii'} - \sigma v \sum_{m=1}^{M} \quad \sum_{i=1}^{I} \mu_{mi} = 0,$

(vi) $\alpha_{nn'} = \alpha_{n'n};\ n \neq n',\ \beta_{mm'} = \beta_{m'm};\ m \neq m', \gamma_{ii'} = \gamma_{i'i}; i \neq i'.$

(14)

The sum of deviations of the estimated directional distance function (13) from the frontier is minimized. A value of zero indicates an efficient observation. A value greater than zero represents the amount by which the vessel's production could have been maximized, if it had been efficient. As Färe *et al.* (2005) states, "the linear programming objective …, chooses the parameters that make firms appear as efficient as possible." The feasibility of each observation is ensured through the representation property in the first set of constraints (i), the second through the fourth (ii) (iii), and (iv) model monotonicity in the above linear programming problem. Constraint (v) is the translation property. The remaining constraint (vi) imposes symmetry. The last two constraints, the translation property and symmetry, are required for the shadow price estimates to be positive (Färe *et al.*, 2005).

The constraints can be explained as:

(i) Representation: require the output-input vector to be feasible for the trips in each of the years. The representation property requires that the directional distance function is non-negative for all feasible input-output combinations. It also implies the directional distance function take the value zero if and only if the firm lies on the boundary of the production possibility set.

(ii) - (iv) Monotonicity: imposes positive monotonicity on the inputs for the mean level of input usage. That is, at the mean level of inputs, $\bar{x}$, an increase in input usage, holding good and bad outputs constant, causes the directional output distance function to increase, implying greater inefficiency.

(v) Translation: The translation property indicates that expanding the output vector by some amount has the effect of reducing the directional distance by that amount. If a different g-vector is chosen, the restriction $\Sigma_m \beta_m - \Sigma_j \gamma_j = -1$, changes to $\Sigma_m \beta_m g_y - \Sigma_j \gamma_j g_b = -1$.

(vi) Symmetry: $\beta_{ij} = \beta_{ji}$

i. Luenberger productivity indicator

This study used the Luenberger productivity indicator, which is dual to the profit function and does not require the choice of input-output orientation (Chambers *et al.*, 1996). Another advantage is the ability of the indicator to handle multiple inputs and outputs that exist in fisheries.

The directional distance function was modified to be time dependent in order to compare the economic performance between two periods, t and t+1. The productivity indicator was constructed as the arithmetic mean of the difference in productivity measured by the technology at time T_{t-1} and T_t. Following Chambers (1998) and Chambers *et al.* (1996), the Luenberger productivity indicator of *k*-th firm in measuring productivity changes based on the directional distance function was defined as follows:

$$\mathcal{L}\ {}^{t+1}_{t} = \frac{1}{2}\big(\vec{D}_o^{t+1}(x^t, y^y, b^t; g_y, g_b) - \vec{D}_o^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; g_y, g_b) +$$

$$\vec{D}_o^{t}(x^t, y^y, b^t; g_y, g_b) - \vec{D}_o^{t}(x^{t+1}, y^{y+1}, b^{t+1}; g_y, g_b)\big). \qquad (15)$$

$\vec{D}_o^t$ and $\vec{D}_o^{t+1}$ represent the directional distance functions for the period t and t+1, respectively. The indicator averages the productivity change from period t to t+1 measured using the distance function estimated for period t+1 with the productivity change measured by the distance function estimated for period t. A positive value for the indicator represents productivity improvements, while a negative value indicates productivity decline. The value of the productivity indicator provides a measure of unit change and not a percentage. The additive structure of the Luenberger productivity indicator allows for the decomposition of the indicator into two components; efficiency change (LECH) and technical change (LTCH)[4] (Färe *et al.*, 2005). Technological

[4] Grosskopf (2003) provides more information on the decomposition of the indicator.

change represents the shift in the technology over the two time periods. The respective equations can be written as follows:

$$LECH_t^{t+1} = \vec{D}_o^t(x^t, y^y, b^t; g_y, g_b) - \vec{D}_o^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; g_y, g_b)$$

$$LTCH_t^{t+1} = \frac{1}{2}[\vec{D}_o^{t+1}\left(x^{t+1}, y^{t+1}, b^{t+1}; g_y, g_b - \vec{D}_o^t(x^{t+1}, y^{t+1}, b^{t+1}; g_y, g_b)\right) +$$

$$\vec{D}_o^{t+1}(x^t, y^y, b^t; g_y, g_b) - \vec{D}_o^{t+1} - \vec{D}_o^t(x^t, y^y, b^t; g_y, g_b) - \vec{D}_o^{t+1} \quad (16)$$

The sign of the value of LECH or LTCH determines if the productivity level has increased in either technical efficiency, or technical change from the period t to period t+1. The decomposition of the indicator provides an empirical framework to investigate the nature of the productivity changes occurring in the fishery over time.

Figure 7 demonstrates the construction of the Luenberger productivity indicator. Because of the output orientation, inputs are held constant in the two periods and are presented as $x = x^t$ and x^{t+1}. The directional vector g is chosen by the researcher, and in this figure is equal to g=(1,1) which allowed an expansion in both desirable and undesirable outputs, and illustrates the case for technological progress and increased productivity from period t to t+1. A fishing entity is observed to harvest at point D in the period t and D' in the period t+1. If the same fishing entity increased its efficiency it could operate at point H in period t and M in period t +1. The change in efficiency LECH = $\frac{DH}{0g} - \frac{D'-M}{0g}$ and LTCH = $\frac{1}{2}[\frac{DL}{0g} - \frac{DH}{0g} + \frac{D'M}{0g} - \frac{D'N}{0g}]$. In words, efficiency change measures how close observations H and M are to technologies T_t and T_{t+1}, whereas, technology change is the average distance between the two technologies. If the productivity value is greater than zero at time t and is less than zero at period t+1, it would indicate technical progress and a possible increase in productivity.

The indicator was calculated by estimating each directional distance function that makes up the indicator using the linear programming approach previous stated in equation (14). The direction of the vector can affect the distance of the vector from the frontier, and therefore, several directional vectors were used to estimate productivity change and compared to elucidate the effects of the different vectors.

Directional vectors contain two pieces of information, the direction of the vector and the value. The sign in front of the reference vector values show whether outputs increase or decrease. For ease in interpretation and computation, a direction vector g = (1,0) was used as the standard for comparison, as it implies a maximum expansion in desirable outputs and no change in undesirable output. This represented the conventional measure of production process that ignored undesirable outputs. The direction best suited for fisheries management is one where the goal is to minimize the harvest of undesirable species such as sea turtles while maximizing the desirable species. For this reason the direction vector g = (1,-1) was chosen as the green-based approach.

c. Pseudo-panel Data

In fisheries it is rare to find long-running panels of data that consistently measure the same fishermen or vessels over time. However, observer logbooks can serve as independent cross-sectional surveys. Samples which include similar but generally different cross-sections of individuals in each time period are often referred to as pseudo-panel data. Such data are typically constructed from a time series of an independent survey that has been conducted under the same methodology and for the same reference population over different periods (Baltagi, 2005). Since the data used for this research includes observations and landings from generally different groups of participants in the CA/OR DGNF for each year of the study period, it constitutes a pseudo-panel data set.

Deaton (1985) was one of the first to use pseudo-panel data and suggested using a grouping approach. The individuals in the population are grouped into "cohorts" according to the researcher's criteria that are unchanged throughout the survey. The cross-sections of the observed individuals are averaged over time for a desired "cohort". One example would be group averages by gear type or by vessel engine size.

Deaton (1985) assumed that independent cross-sections in successive years could be grouped into comparable demographic categories and then differenced. One advantage to this approach was the homogenization of the individual effects among the individual in the "cohort" or group and averaging out the specific effects between the periods. Grafton *et al.* (2000) used pseudo-panel data to evaluate efficiency in the British Columbia halibut longline fishery, combining three independent cross-sectional cost and earnings surveys.

Measurement error can occur in the pseudo-panel data when corresponding "cohorts" do not contain the same individuals in the different time periods. Additionally, the data do not allow analysis within the cohorts. However, each survey can provide information about the cohort's distribution (Deaton, 1997). Deaton (1985) treated this problem as a measurement error, where the "cohort" averages are error-corrected measures of the true "cohort" averages.

There are several advantages to using pseudo-panel data compared to true panel data. Deaton (1997) claimed pseudo-panels remove the issue of attrition because the cohort dare are from annual "fresh samples". Also, the analysis of the cohort is less affected by measurement error. Since the mean cohort over time is sensitive to the presence of outliers, the median percentile is often more useful to correct for possible outliers, reducing measurement error (Baltagi, 2005).

d. Data used in the analysis

Data on the inputs and outputs used in the analysis came from two main sources, the CA/OR DGNF observer logbook database and the PacFin database. All input data were extracted from trip level data collected by NMFS on-board observers during the research period 1996-2008. Data on undesirable outputs were also collected from the observer logbook database and aggregated into four categories based on species type and regulatory restrictions. Desirable output landings and price information were extracted from fish ticket data in the PacFin database.

There currently is no existing database that combines economic and biological data for the observed drift gillnet fishery. Therefore, the data contained in the CA/OR DGNF logbook was merged to the PacFin database to enable comparison of desirable and undesirable biological outputs to economic inputs on individual trips to create a pseudo-panel dataset for the research period. Observer trip data can be linked to sales records using either a vessel's US Coast Guard number or state issued vessel plate number, fish ticket identification number, and observer logbook trip identification number. Observer data was then linked to PacFin landings records by comparing the start and return dates recorded by the observer with the dates of fish tickets from each of the observed vessels. There were several complicating factors that made this task difficult. Not every trip could be matched based by matching the offloading date in PacFin to the date of the last recorded set in the observer database for the following reasons.

1. Some observed vessels had multiple fish tickets from the same trip.
2. Some vessels offloaded during the middle of their observed trip, then fished additional sets before the end of their trip.
3. Observed vessels offloaded up to 7 days after last date set.
4. Some observed vessels did not offload any marketable catch.

810 economic trips were successfully matched that provided information on factors of production and desirable and undesirable outputs. Outputs were aggregated into six categories to compare the performance of the vessels over time. Because catch was reported by summing all the landings by species for the economic trip, the output value of species was calculated using a Divisia quantity index[5] to form two composite desirable outputs. The primary target species, swordfish and thresher shark, were aggregated into one output variable and the secondary targets, defined as all other marketable species, were also aggregated into a second output variable. The catch was measured in current prices; in order to compare over time, these were converted to constant prices[6]. Undesirable outputs that do not have a market price were reported as total count, since weight information was not available for all trips.

Each observed trip was separated into economic trips based on matching landings records from PacFin with the dates of observer trips. Each trip resulted in a harvest of desirable outputs, swordfish and thresher shark (y1) and secondary, all other desirable

[5] Adapted from Hulten (1973).
[6] Constant dollar refers to a metric for valuing the price of a good or service over time, without that metric changing due to inflation or deflation. Specifically, it is the present value of the dollar in a given year.

marketable species (y2) concomitantly with undesirable species. Undesirable species were broken down into four categories: marketable discards (b1), unmarketable discards (b2), sea turtles (b3), and marine mammals (b4). Mean values of the factors of production (inputs) used by the vessels over each trip from the observed database were also used to provide valuable information needed for measuring technical and efficiency changes, as well as measuring productivity change. Inputs used for each trip were the number of sets (x1), net depth (x2), net length (x3), net soak time (x4), vessel length (x5), and vessel horsepower (x6).

Figure 5. Illustration of distance function for two desirable outputs.

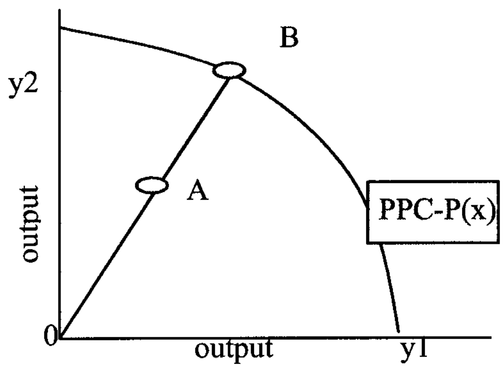


Figure 6. Illustration of a directional and radial distance function for one desirable and one undesirable output.

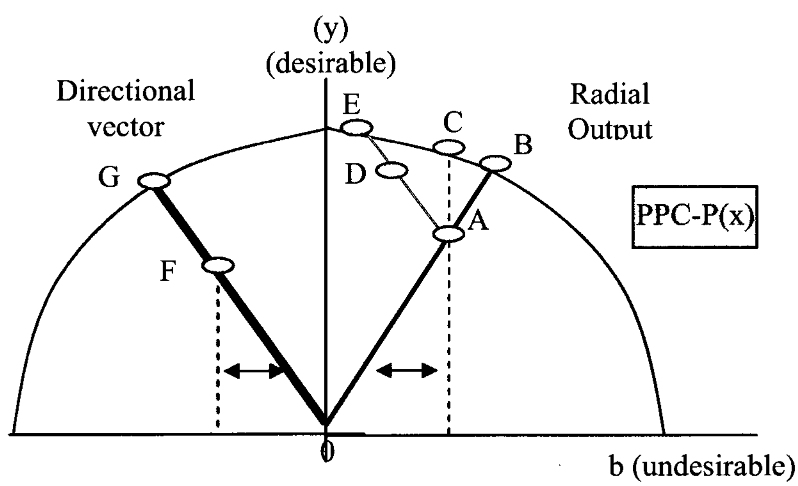
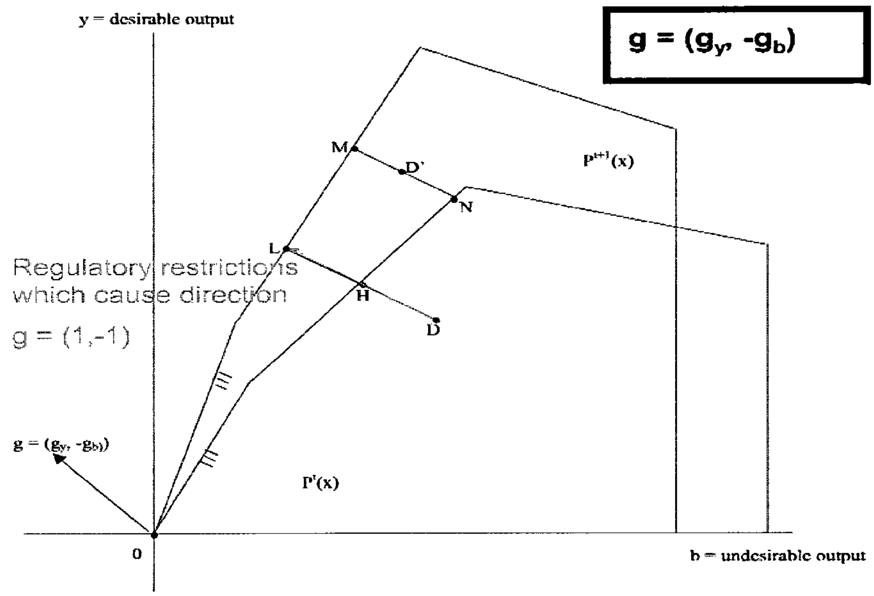


Figure 7. Illustration of Luenberger Productivity Indicator



SECTION IV: RESULTS AND DISCUSSION

Several models were specified and estimated to compare the results of productivity measures if undesirable outputs are reflected in the measure to the results if undesirable outputs are ignored.

a. Model Specification and Estimation

Using the inputs and outputs described in SECTION III, the output directional distance function was estimated using the assumptions as follows: (1) maximum expansion of desirable outputs and no change in undesirable outputs, (2) maximum expansion of both desirable and undesirable outputs, and (3) maximum expansion of desirable outputs with maximum contraction of undesirable outputs. The directional distance function was estimated using mean normalized inputs and outputs due to convergence problems in the model due to the numerical size of the outputs reported in Table 4 (Färe *et al.*, 2004). This means that a trip using mean inputs and harvesting mean outputs has $(y, b, x) = (1,1,1)$. Each trip's level of efficiency score was summarized to the mean annual level. Three different variations of directional vectors $g = (y, b)$ were chosen to compare the effects of increased regulations on the fishery, denoted Models 1, 2, and 3.

Model 1 ignores undesirable outputs and serves as the baseline or conventional measure of economic performance using the directional vector, $g = (1,0)$. The use of this directional vector results in the maximum expansion of desirable outputs with no change in undesirable outputs.

Model 2 represents the case of no regulatory constraints being imposed. The directional vector (1,1) is employed to maximize the simultaneous expansion of desirable and undesirable outputs.

Model 3 represents the green-based approach which incorporates undesirable harvest and maximizes its reduction while simultaneously expanding desirable outputs. This represents the current goals of fisheries managers to reduce discards, bycatch, interaction with sea turtles and marine mammals, while still utilizing the resource.

i. Parameter Estimates

All models were estimated using Lingo 11.0, which is a mathematical programming package. Code was written to estimate the generalized quadratic directional distance function specification using the Aigner and Chu (1968) linear programming (LP) approach. Running Lingo 11.0 code specially designed for the estimation of the directional output distance function in the quadratic form resulted in the parameter estimates for the three models, presented for comparison in Table 5. The parameter values show the effects of the desirable and undesirable outputs have on the directional distance function and, therefore, the efficiency scores.

ii. Summary of Inputs and Outputs

Average composite weight of swordfish and thresher shark was 1721.75 pounds per economic trip (Table 3). The average price per pound of $4.31[7], equates to approximately $7420.74 in swordfish and thresher shark revenue generated on average over the thirteen year period. The largest amount of undesirable outputs taken on an economic trip occurred in 1999.

[7] Price information obtained from PacFin was deflated by the producer price industry index for the fresh and frozen seafood processing to obtain real revenue that could be compared annually to 2008 values.

When the output values were summarized at the pre- and post-closure levels in Table 6 it was revealed that the average revenue generated pre-closure per trip was \$7738.92 while post-closure it fell to \$7148.70. Every input and output was greater when trips were operated inside the closure with the exception of marine mammals. Marine mammal captures were greater in the area outside of the closure by a difference of 0.02 (Table 7). Trips that captured sea turtles had higher mean efficiency values compared to those trips that experienced no turtle takes. The only input that was not higher when there were turtle takes was soak time, with a greater soak time of 12.04 compared to 11.80 with sea turtle takes. Marine mammal capture was greater when no sea turtle take occurred, with a value of 0.44 when compared to the mean of 0.40 for trip that had sea turtle takes (Table 8). Overall the results revealed that trips that operated inside the closed area and had sea turtle captures also had reduced swordfish and thresher shark harvest levels.

iii. Estimates of Efficiency Using Different Vectors

Efficiency scores represent the value of the distance from the estimated production frontier. The efficiency score represents the amount of output that could have been expanded if the trip were completely efficient. Efficiency scores based on the additive directional distance function, can range from 0 to infinity. Higher scores indicate reduced efficiency. Efficiency scores can be interpreted as radial expansions (contractions) due to mean scaling of the data (Färe *et al.*, 2001). The average annual efficiency scores are presented for each model (Table 9, 10, and 11). All three models indicate that the greatest inefficiency occurred in 1999.

As previously stated, the 2001 closure represented a natural experiment, offering the chance to compare productivity and efficiency for the portion of the economic trips that occurred inside and outside the area prior to the closure, and for all trips that occurred outside the area after the closure. There were 480 trips prior to the effective date of the closure; of those, 116 took place inside the area that is now closed. Efficiency scores were averaged, and the pre-and post-post closure scores were compared. Then the scores from trips inside and outside the closed area were compared to elucidate the effects of this experiment for each model.

Model 1: Expansion of desirable outputs while ignoring undesirable outputs (conventional measure, status quo)

Of the 810 economic trips, only 25 trips operated efficiently with the model specified using the direction vector g = (1,0). This suggested that 785 trips fell below the frontier and were inefficient. The average inefficient trip used more net and soaked the gear longer compared to efficient trips. Inefficient trips were operated on larger vessels with greater engine horsepower. However, the increased inputs did not produce increased harvest. On average, inefficient trips had lower harvest of desirable and undesirable species. The exception was marketable discards that were almost three times higher in the inefficient trips (Table 12).

The distance value or efficiency score of the output directional distance function ranged from 0 to 10.69 over the research period, with an average of 2.63. Since the data were normalized by the means to estimate the directional distance function, the scores can be translated into proportional expansions rather than unit expansions (Färe *et al.*, 2001). This suggests that a maximum expansion of 263% of desirable output with no change in undesirable output. On average, an economic trip, if operated efficiently, could have harvested a maximum of 6249.95 composite pounds of swordfish and thresher shark and 1240.26 composite pounds of other marketable species, 13 marketable discards, 11 non-marketable bycatch, 1 sea turtle, and 1 marine mammal[8]. Maximum output was calculated by multiplying the observed value by the efficiency score and then adding it back to the observed amount. Annual means for Model 1 ranged from 1.36 in 2003 to 5.79 in 1999 (Table 9). The number of sets, net length, landings of swordfish and thresher shark, and all other marketable species were greater in trips that were efficient than for inefficient trips. Inefficient trips calculated using Model 1 had higher values of marketable discards but lower values of unmarketable discards and turtles (Table 9).

Mean efficiency scores were calculated for the pre- and post closure levels. This revealed that on average in the years prior to the closure (1996-2000) the annual efficiency score was 3.18, with a range from 0 to 10.70 (Table 12). Of the 480 trips that took place before the closure only 11 operated on the frontier with an efficiency score of zero. Only three of those 11 trips occurred within the area that is now closed. After the closure the trips operated more efficiently with 15 of the 330 trips operating on the frontier. Trips that fished after the closure had average efficiency score of 1.82. The decline in the inefficiency score was due to the greater percentage of trips operating at the efficient level. The range of annual mean efficiency scores for the post-closure years (2001-2008) was 0 to 6.15. When the efficient models were taken out of the average we find the efficiency score was 2.71 (Table 13). It could be speculated that the vessels that operated inefficiently left the fishery after the closure occurred in 2001; or that in response to the decrease in fishing ground, fisherman quickly adapted and were able to operate using fewer inputs but having higher yields than before the closure.

[8] Undesirable outputs are a total count of captured species and are rounded a whole number.

Efficiency scores and the input-output mix were compared for trips that had incidental takes of sea turtles. It was revealed that 14 of the 810 trips that took sea turtles had a higher average efficiency score of 3.97 (Table 14) than those with no takes. The range of efficiency scores for trips that had no sea turtle takes ranged from 0 to 10.70. While this is a large range, the average was 2.60. Of the 795 trips, only one occurred inside the closed area prior to the closure. There was a greater amount of input usage for those trips that had turtle takes. Larger levels of outputs would be expected with this increased use of inputs, which was the case for those trips that had turtle takes.

Model 2: Expansion of desirable and undesirable outputs (unregulated)

In an unregulated world, fishermen would be able to freely dispose of the undesirable outputs. In order to model this scenario, the undesirable outputs were allowed to expand. Similar to Model 1, 25 trips were efficient when the direction vector $g = (1,1)$. The efficiency score of the output directional distance function ranged from 0 to 9.78 over the research period, with an average of 2.47 (Table 10). This was slightly lower when compared to Model 1. When all outputs were allowed to expand, the average maximum expansion was 248% of desirable and undesirable output. On average, if an inefficient trip had operated efficiently, then it could have harvested a maximum of 5991.69 composite pounds of swordfish and thresher shark and 1189.02 composite pounds of other marketable species. Model 2 allowed the expansion of undesirable outputs and a total of 42 marketable discards, 38 non-marketable bycatch, 1 sea turtle, and 2 marine mammals could have been taken if the average inefficient trip had operated efficiently. As in Model 1, 2003 was the most efficient year with an average efficiency score of 1.23 (Table 10). The least efficient year was 1999, the same as Model 1, with an average score of 5.85. This value was slightly higher than Model 1 due to the allowed expansion of undesirable outputs.

When efficiency scores were summarized to the mean pre- and post-closure levels, it was found that, on average, in the years prior to the closure the average annual efficiency was 3.00, with a range from 0 to 9.78 (Table 6). Of the 480 trips that took place before the closure, only 10 operated on the frontier with an efficiency score of zero.

When undesirable outputs were allowed to expand, efficient trips used fewer inputs and produced greater outputs than in Model 1. The exceptions were the number of sets, which was slightly higher with five sets on average being deployed compared to Model 1, and a 30 percent lower harvest of other marketable species (Table 15). Three of the 10 trips occurred within the area that is now closed. Trips which operated after the closure were more efficient with 15 efficiently operating on the frontier. Trips that fished after the closure had an average efficiency score of 1.73 (Table 6). The range for the post-closure years (2001-2008) was 0 to 4.50. This decline in estimated inefficiency was directly related to the chosen direction vector which allowed both desirable and undesirable outputs to expand.

Efficiency scores and the input-output mix were compared for trips that had incidental takes of sea turtles. When trips that had incidental takes of sea turtle were compared to trips with no takes, 15 of the 810 trips that took sea turtles had a higher average efficiency score of 3.42 (Table 14). The range of efficiency scores for the trip that had no sea turtle takes ranged from 0 to 9.78, with an average of 2.47. Of the 15 trips that had turtle takes, four occurred inside the area that is now closed and 13 took place before 2001. This indicates that the closed area was effective and levels of takes substantially declined after 2001. Again, there were a greater number of inputs used for those trips that had turtle takes compared to those that had no turtle takes.

Model 3: Expansion of desirable and simultaneous reduction of undesirable outputs (green-based measure, adjusting for undesirable outputs)

Fisheries management seeks to influence the behavior of fishermen through implementation of regulations to achieve specific goals. Within MSFMCA, 10 National Standards are presented that represent the national objectives of fishery conservation and management. National Standard Five and National Standard Nine have potentially competing objectives: National standard five has a goal of management to consider efficiency and utilization of the resource while National Standard Nine is concerned with the reduction of bycatch. These goals are modeled in the green-based approach using a direction vector ($g = (1, -1)$) that forces the undesirable output to contract while simultaneously allowing the desirable outputs to expand. Values of efficiency, when summarized, were restricted between 0 and 1.00[9]. The upper bound was set to one so that the level of contractions of undesirable outputs would not exceed the observed value. Annual efficiency scores for each year during the research period are presented in Table 11. Of the 810 economic trips, 26 operated efficiently. Trips that operated efficiently had greater desirable outputs and fewer undesirable outputs (Table 16.) Inputs were also greater for inefficient trips, with the exception of soak time. The efficiency scores ranged from 0 to 1, with 15 trips having the maximum allowed score of 1. Over the research period, efficiency scores, on average, revealed that the inefficient trips could have maximized their desirable outputs by as much as 6.9 percent. This translated into the

[9] Results indicate that 15 out of 810 observations indicated reductions greater than observed undesirable output levels. This was a result of failing to globally satisfy the regularity conditions and is why the summaries were restricted to those observations with contractions less than 100 percent).

maximum expansion of 1840.55 composite pounds of swordfish and thresher shark and 365.24 composite pounds of other marketable species, 12 marketable discards, 10 non-marketable bycatch, 1 sea turtle, and 1 marine mammal. Maximum reduction in undesirable outputs was calculated by multiplying the observed value by the efficiency score and then subtracting the value from the observed amount. Unlike Models 1 and 2, the most efficient year was 2002 with an average efficiency score of 0.032 (Table 11). The least efficient year was still 1999, with an average score of 0.10. This means that in the least efficient year the average trip that operated below the frontier could have maximized their desirable outputs by as much as 10 percent.

Efficiency scores at the mean pre- and post-closure levels revealed, on average, in the years prior to the closure the efficiency was 0.08 with a range from 0 to 1.00. Of the 480 trips that took place before the closure, only 12 operated on the frontier with an efficiency score of zero. Seven of the 26 efficient trips occurred within the area that is now closed. After the closure the trips operated more efficiently, with 14 of 330 trips operating on the frontier. Trips that fished after the closure had an average score of 0.050, translating into a maximum expansion and contraction of five percent (Table 16).

Efficiency scores and the input-output mix were again compared for trips that had incidental takes of sea turtles. On average, all 15 trips that had incidental take of sea turtles had a maximum efficiency score of 1.00 (Table 16). This suggests that if trips with sea turtle take operated at the efficient level, then they could have reduced their undesirable outputs to zero and doubled their desirable outputs.

b. Model comparison and hypothesis testing

The results of the three models told a similar story, with each model estimating higher efficiency scores in the pre-closure averages. Over the research period all three models estimated in 1999 to be the most inefficient year over the research period.

One of the objectives of this research was to test if there was a difference in efficiency scores when different direction vectors, reflecting differing incorporation of bycatch, were assumed in the calculation of the directional distance function. In order to test whether there is a significant difference between efficiency scores of the three models, parametric ANOVA and a non-parametric Kruskal-Wallis test were conducted. Results of the ANOVA revealed that the efficiency scores of Models 1 and 2 were significantly different higher when compared to Model 3 efficiency scores, with a p value less than 0.05. A Kruskal-Wallis test was employed because of truncation or censoring of the directional distance values at zero and results demonstrate the efficiency scores from the three models are significantly different (Table 17).

Using the ANOVA post-hoc test results, efficiency scores for Model 1 and 2 are significantly higher than Model 3, while the scores between Models 1 and 2 are not significantly different. Therefore, the null hypothesis is rejected, as efficiency scores are significantly lower when undesirable outputs are accounted for in the production process. Therefore, the models of efficiency that ignored the capture of undesirable outputs gave a biased estimate of efficiency.

c. Natural experiment

Another objective of the research was to test the hypotheses that trips inside the area closure would have greater efficiency than trips outside of the area closure. As previously mentioned, the 2001 closure acted as a natural experiment and provided evidence to the impact of the closure. Average pre- and post-closure, as well as inside and outside of the closure area efficiency scores were compared to test for significant differences using a paired t-test and a Kruskal-Wallis H test. Only Model 3 efficiency scores were tested because this was the only model that assumed a regulated environment. The test revealed that efficiency scores were significantly higher in trips that occurred before and the 2001 closure with p-values >0.05 (Table 18). Therefore, the null hypothesis was rejected as a significant difference existed between pre- and post-closure efficiency scores.

Mann-Whitney and Wilcoxon tests were used to test whether the difference between annual mean efficiency values for trips that occurred inside and outside the area prior to the closure were significantly different. The test revealed a significant difference with a p value <0.05 (Table 19). Therefore, the null hypothesis was rejected. Trips that took place inside the area now closed before the closure was implemented were less efficient than after the closure was implemented in 2001.

d. Estimates of productivity, efficiency change, and technical change

i. Changes relative to the base year 1996

Table 20, presents estimates of the average annual Luenberger productivity indicator compared to the base year 1996 levels for the three models. Comparison of productivity change for the three models was depicted graphically in Figure 9. Models 1 and 2 ignored or allowed for the expansion of undesirable outputs, respectively, and showed positive values of productivity. This suggests continual growth over the research period. While the values varied over the years, the continual trend of increased productivity was clearly evident in Models 1 and 2 while Model 3 showed productivity declines, made evident by the negative values that were present in productivity estimates for the years 1997 and 1999. Both of these years had large amounts of undesirable outputs. Similar to the results of Models 1 and 2, there was a positive trend in productivity growth over the research period in Model 3. When productivity change results were averaged over the pre- and post-closure levels, all three models showed increased levels of productivity growth after the closure.

Comparison of productivity change and hypothesis testing

An ANOVA was calculated to test the hypothesis that no statistically significant differences existed between the mean productivity change estimates from Model 1, 2, and 3. Similar to the results of the efficiency hypothesis tests, a significant difference in annual mean productivity change was found among the three models (Table 21).

Decomposition of productivity change

The Luenberger productivity indicator was decomposed into efficiency and technical change. Efficiency change results are presented in Table 22 and graphically depicted in Figure 10. For Model 1, the average efficiency change over the research period was -0.14. This suggested that trips, on average, were became more inefficient, instead contributed to the decline or slow down in productivity. For Model 2, when undesirable outputs were allowed to expand the picture was quite different with efficiency change having a positive average value of 0.24. Model 3, similar to Model 2 revealed a positive value which indicated an increase in efficiency that contributed to productivity growth. Of the three models, it was clear that efficiency change on average has the highest value in Model 3 with a value of 0.72, and contributed the most to productivity growth when compared to the base year. As with productivity change, pre- and post-closure impacts were evident. Greater efficiency change occurred in the post-closure years.

While efficiency change measures the 'catching up' or ability to improve efficiency of the trip to those trip operating on the frontier, technical change represents a shift in the production function through technological progress or innovation. Technical change results suggested that, on average, over the study period, Model 1 indicated the greatest level of improvement due to technical change, with a value of 0.70 (Table 23). Model 3 was the only model that has a negative average (-0.0005). This was an extremely small impact to the overall productivity. This would translate into less than a pound of swordfish and thresher shark being lost due to technical regress when compared to the base year 1996.

ii. Annual changes

In order to assess the annual fluctuation in productivity, efficiency and technical change were calculated on a year-to-year basis. In Table 24 estimates were presented for the annual mean value of the Luenberger productivity indicator and decomposed into its two components of efficiency and technical change. A graph demonstrating the annual mean fluctuations per trip is in presented in Figure 10. Results showed a slightly different picture with a less substantial variation in productivity change. Models 1and 2 indicated declines in annual variations with an average value of -0.28, while Model 3 had minimal growth with a value of 0.03. When annual variations are aggregated to the pre- and post-closure years, post-closure years had greater growth when assessed for annual variations. This further confirmed that post-closure years had greater productivity growth regardless if the model accounted for undesirable output.

When productivity change was decomposed into efficiency and technical change it was evident that Model 1 and 2 measured similar declines in efficiency change. Model 3 had minimal impact on annual productivity change with a value of 0.05 (Table 25). Technical change also had a minimal impact on productivity with a value of 0.0007 (Table 26). Once again, when values were summarized to the mean pre-and post-closure years, the average technical change value was negative which reduced productivity change. The trend was reversed in the post-closure years. Model 3 had the greatest technical change impact on productivity. The average post-closure value was 0.003 units. This suggested technical progress had a minimal contribution to productivity growth for Model 3 compared to Models 1 and 2. Model 2 had the greatest contribution to productivity with a value of 0.72.

e. Shadow price

A major objective of this research was to estimate the potential opportunity costs or change in social welfare of reducing undesirable outputs. Shadow prices were calculated based on the estimated directional distance function using the directional vector specified in Model 3 and the duality between the directional output distance function and the revenue function (Färe *et al.*, 2001). The equation required a price on just one desirable output. The primary desirable output was chosen. This allowed the shadow prices to be translated into the forgone value of a composite of swordfish and thresher shark landings. As stated previously, swordfish sales contributed the greatest amount of industry revenues. However, the composite price of swordfish and thresher shark was used due to the use of the composite weight as the desirable output (y1) in the estimation of the directional distance function. Shadow price, as defined, was the lower bound cost to society for conservation measures, therefore, the values may be lower than values that would be revealed through contingent valuation methodology. Shadow price estimates were averaged over the research period and varied for the four undesirable species (Table 27).

In order to estimate the shadow prices, the observed values were normalized by the mean value. Following the work of Färe *et al.* (2001), the normalization of the data allowed for easier interpretation of the parameters estimated for the directional distance function when undesirable outputs were contracted. For a trip that used mean levels of inputs and harvested mean levels of desirable and undesirable outputs, the shadow price represents the forgone revenue for one composite unit of swordfish and thresher shark when the undesirable output is reduced by one unit.

Mean estimates of shadow price for the four undesirable outputs averaged annually in terms of forgone revenue are presented in Table 28. Values estimated using annual means are also presented for those years having undesirable harvest. Several years following the closure had no estimate of shadow price for sea turtle as no takes occurred during those years. The average shadow price value per trip was calculated to be $26,700 for marketable discards, $59,800 for unmarketable discards, $92,000 for sea turtles, and $9,800 marine mammals (Table 28)[10]. Average trip shadow prices per animal captured represented the conservation cost for the reduction of undesirable outputs. This includes $2,500 for marketable discards, $6,600 for unmarketable discard, $28,800 for a

[10] Shadow prices measure in term of forgone swordfish and thresher shark revenue are rounded to the near hundred dollars.

sea turtle, and $9,800 for a marine mammal in forgone composite swordfish and thresher shark revenue.

Annual shadow price values of marketable discards per trip ranged from $15,000 in 2001 to a high of $42,000 in 2007. Unmarketable species had a minimum of $36,000 in 2001 and maximum value of $93,200 in 2007. Marine mammals followed the same trend with 2001 having the lowest shadow value of $4,600. However, the highest shadow price for marine mammals occurred in 2008 with a value of $16,200. Sea turtle takes did not occur in every year so shadow values were greater in the years that had higher catches of swordfish and sea turtle takes. The largest shadow price for sea turtles was $100,500 in 1998. Shadow prices were also summarized for pre-and post-closure averages. For every undesirable species the shadow value decreased post-closure. The reduction in post-closure shadow price suggested that trips captured fewer undesirable outputs and had lower composite prices compared to those trips that occurred before the regulatory closure.

Comparable shadow price estimates were not available for the three undesirable outputs (marketable discards, unmarketable discards, and marine mammals). Therefore only previous studies estimating shadow prices are discussed for sea turtles. Estimates of shadow price indicated that the average cost to society for reduction in sea turtle takes per trip is $92,000 and is approximately $28,800 in forgone swordfish revenue per trip when averaged over the entire research period.

This value is slightly lower but within the range reported in other studies when adjusted for inflation (Huang and Leung 2007[11]; Curtis and Hicks, 2000[12]; Pradhan and

[11, 12, 13 and 14] These studies focused on the Hawaiian longline fishery.

Leung 2005, 2008[13]; Chakravorty and Nemoto 2000[14]). The high values for sea turtle conservation placed a strain on the already heavily regulated fisheries. The work of Gjertsen (2009) suggested there is a point where the most cost-effective conservation measures for sea turtles to generate the greatest "conservation bang for the buck" may be more likely achieved through conservation investments in nesting sites rather than through further regulation of commercial fisheries in higher income countries.

The study by Huang and Leung (2007) estimated an average shadow price of a marginal decrease in sea turtle bycatch to be worth approximately $30,873 in constant 1991 dollars $45,636 (2008 constant dollars). Curtis and Hicks (2000) also estimated the cost of reducing sea turtle bycatch, with an average estimate of $41,262 in 2000 constant dollars or $48,190 (2008 constant dollars) per turtle during a partial temporal closure. The study also predicted that if the closure were extended to the entire season, the decrease in bycatch would be worth $52,976 or $61,870 (2008 constant dollars) per turtle. Pradhan and Leung (2005) estimated the shadow price to be $56,060 or $65,473 (2008 constant dollars) on average in terms of lost revenues. These values are within the range of the values estimated in this research. Loggerhead turtle shadow price values were estimated by Chakravorty and Nemoto (2000) to be $14,000 in 1995 constant dollars translating into $18,769 in 2008 constant dollars. This value is much lower than any of the other studies mentioned; however, their model estimated lost profits rather than revenue in terms of forgone fishing activity. Pradhan and Leung's estimates and representation of shadow values as the monetary values of forgone revenue are a much better comparison and help to validate the findings of this research. The post-closure shadow price estimate for sea turtles was $65,611 in 2008 constant dollars, which was more similar to the estimates other studies.

When annual means were used to estimate shadow values, the lost revenue dramatically increased as the total mean output and composite price for swordfish and thresher shark increased. This suggested that the greater the composite price and pound harvested, the more costly it was to avoid the capture of one more sea turtle. This was also the case in several of the previous studies. Turtles were not separated by species but it could be assumed that the value for the fragile population of leatherback sea turtles and its listing as a critically endangered species would be even higher if estimated separately.

Shadow price estimates of forgone revenue, like the ones calculated in this research, can be used by policy makers to compare the cost and benefits of conservation. If the cost of commercial fishery regulation to further reduce bycatch is too high, policy makers can investigate other conservation methods that have less of a financial impact on the fishery (Gjertsen *et al.,* 2009).

f. Recommendations for future research

The role of economics in fisheries management has evolved over the last few decades with the development of the Initial Regulatory Flexibility Act Guidelines by NMFS. The act stresses the need for adequate qualitative or quantitative assessments of a proposed fishery management regulation's impacts on a fishery. This allows mangers to assess and evaluate analyses such as the ones used in this research in the fishery management review process that occur prior to implementation of a regulation.

The major disciplines of economics, biology, and sociology still remain separate sciences in the fisheries management process. By this I mean that when an analysis of a proposed fishery management regulation is conducted, the economic, biological, and sociological assessments are conducted independently. It is up to fishery managers to integrate these separate analyses to determine if a proposed regulation has the potential to achieve its management goals and objectives. This task is difficult because these analyses are often based on different sets of assumptions and lead to gaps in the interpretation of results. There is a continued need to integrate all the physical, biological, economic, and social sciences into a single framework to address fishery management problems.

Combining the physical, biological, and social sciences in a meaningful and interpretable way will require the integration of the data collection programs that support these sciences, similar to the process of merging the observer database to the PacFin landing and revenue data. If scientists, economists, and observer program managers work together to determine the variables necessary to answer the management questions posed for a particular fishery, then they can develop the most cost effective and statistically valid approach for collecting the required data for those variables. To date, several observer programs are being conducted that collect economic data and biological data for a variety of fisheries.

An add-on economic survey was developed and administered during the CA/OR DGN 2008 fishing season. The survey however, had extremely low participation as it was not a mandatory reporting requirement for the drift gill net fishery. The survey was administered again in 2009. Data from the two years of surveys are still minimal and were not included in this research. While the data were not used, they provided a range of trip costs. The data collected demonstrated that economics is an important part of fisheries management. Multi-disciplinary analysis of a fishery can provide fishery managers with a set of results that are consistent, and unbiased, and meet the same objectives. As stated above, more research must be completed in our effort to integrate economics analyses with physical and biological processes.

Research must also be expanded in the field of economics and the use of directional distance functions. Work on efficiency and productivity estimation could be expanded to include a new framework that has come out of the recent work of Rolfe Färe and Shawna Grosskopf. Färe and Grosskopf (2010), suggests a slack-based measure (SBM) of efficiency based on directional distance functions. The measure is also additive, like the alternative measure used in this research. The framework differs from the current models by "removing the input and output slacks through the addition and subtraction from their respective inequalities (Färe and Grosskopf, 2010). It also is based on a non-parametric data envelopment analysis (DEA) framework. It would allow for different expansions and contractions for every output. The suggested model will also deal with the restriction of the maximum contraction of undesirable outputs and not require the researcher to place an upper limit on the estimated distance values as was done in the current framework. Just as the quadratic was able to do, this new framework has the ability to handle zeros in the estimation. This framework, however, is mathematically complex and would require manipulation of the model to estimate productivity when an unbalanced data set is used, as in the current research.

Another area for future work regards the weighting of undesirable output. As more data become available on cost of inputs and weight and ranking of outputs, it may improve the understanding and reliability of economic indicators such as efficiency and productivity change. The research could be expanded if average weights and social values were placed on the undesirable outputs. This would allow the researcher to move from a total count approach to differentiation of undesirable outputs within the aggregation process.

Use of different aggregations and weighting schemes for undesirable outputs could be completed and then the comparison could be made between different techniques. Three techniques are suggested. The first would be to weight each undesirable output equally with a weight as one as reported in this dissertation. The second would be to weight the species according to the ecological importance of each species. The third scheme would be to weight the undesirable outputs based on social values. The second and third weighting schemes would be based on a polling of various stakeholders in the fishery including biologists, fisheries representatives, and state and federal government officials.

Table 4. Descriptive statistics of inputs and outputs per trip over the research period 1996-2008.

Variable	Mean	Median	Std. dev	Minimum	Maximum
Inputs					
Number of Sets	4.72	5.00	2.38	1.00	15.00
Net Depth (ft.)	128.56	130.00	15.97	50.00	180.00
Net Length (fm.)	640.19	521.00	300.67	80.00	1000.00
Soak Time (hr.)	12.04	12.00	2.15	4.00	40.00
Vessel HP	47.54	48.00	8.08	75.00	750.00
Vessel Length (ft.)	279.45	255.00	103.71	33.80	80.00
Outputs					
Desirable					
Swordfish and thresher shark (lbs.)	1721.75	889.83	2324.03	0.00	18607.99
Other (lbs.)	341.67	189.41	498.59	0.00	4177.87
Undesirable					
Marketable Discards	12.07	2.00	32.25	0.00	393.00
Unmarketable Discards	10.65	4.00	19.37	0.00	184.00
Turtles	0.02	0	0.16	0.00	2.00
Marine Mammals	0.44	0	0.74	0.00	5.00

Table 5. Parameter Estimates of the directional distance function for the three models.[a]

Coefficient	Variable	Model 1	Model 2	Model 3
A0	Constant	2.78084	-0.00378	0.00973
A1	GEARN	-0.65107	-0.17060	0.00000
A2	NDEP	-0.90010	3.01122	-0.00466
A3	NETL	-0.04515	-0.17986	0.00562
A4	SOAK	-1.15276	-0.76671	-0.00381
A5	VESL	-5.46374	-2.53658	0.00000
A6	VESH	0.07491	-0.28875	-0.00100
C1	SWTH	-0.16588	-0.20338	-0.01395
C2	OTH	-0.83412	-0.88249	-0.00822
GAM1	MRDIS	-0.02647	-0.00524	0.00574
GAM2	UMDIS	0.26919	0.09111	0.03455
GAM3	TURT	-0.00510	0.00000	0.92923
GAM4	MM	0.00000	0.00000	0.00831
A11	GEARN2	0.52486	1.02257	0.00000
A12	GEARNNDEP	0.78757	0.31892	0.00000
A13	GEARNNETL	0.02100	0.04192	0.00000
A14	GEARNSOAK	-0.03915	0.00652	0.00000
A15	GEARNVLEN	-0.22606	-0.50752	0.00000
A16	GEARNVESH	0.26197	0.31739	0.00000
A21	NDEPGEARN	0.78757	0.31892	0.00000
A22	NDEP2	-1.78376	-4.14258	-0.00097
A23	NDEPNETL	0.19532	0.89931	0.00039
A24	NDEPSOAK	0.30154	-0.32128	0.00723
A25	NDEPVESL	4.05119	2.51582	0.00000
A26	NDEPVSH	-0.15771	-0.37838	0.00107
A31	NETLGEARN	0.02100	0.04192	0.00000
A32	NETLNDEP	0.19532	0.89931	0.00039
A33	NETL2	-0.09034	-0.48105	-0.00421
A34	NETLSOAK	-0.01695	-0.06629	0.00158
A35	NETLVESL	0.02086	0.14866	0.00000
A36	NETLVESH	-0.01944	-0.11281	0.00001
A41	SOAKGEARN	-0.03915	0.00652	0.00000
A42	SOAKNDEP	0.30154	-0.32128	0.00723
A43	SOAKNETL	-0.01695	-0.06629	0.00158
A44	SOAK2	-0.27806	-0.17771	-0.00034
A45	SOAKVESL	2.36361	1.87825	0.00000
A46	SOAKVESH	0.08144	0.65786	0.00064
A51	VESLGEARN	-0.22606	-0.50752	0.00000

A52	VESLNDEP	4.05119	2.51582	0.00000
A53	VESLNETL	0.02086	0.14866	0.00000
A54	VESLSOAK	2.36361	1.87825	0.00000
A55	VESL2	1.02159	-0.62208	0.00000
A56	VESLVESH	0.35771	0.64624	0.00000
A61	VESHGEARN	0.26197	0.31739	0.00000
A62	VESHNDEP	-0.15771	-0.37838	0.00107
A63	VESHNETL	-0.01944	-0.11281	0.00001
A64	VESHSOAK	0.08144	0.65786	0.00064
A65	VESHVESL	0.35771	0.64624	0.00000
A66	VESH2	-0.18842	-0.22318	-0.00027
B11	SWDTH2	0.04105	0.04296	0.00028
B12	SWDTHOTH	-0.04105	-0.04157	-0.00027
B22	OTH2	0.04105	0.04018	0.00027
B21	OTHSWDTH	-0.04105	-0.04157	-0.00027
GAM11	MRDIS2	-0.00026	-0.00027	-0.00059
GAM12	MRDISUMDIS	-0.00042	-0.00063	-0.00092
GAM13	MRDISTURT	0.00026	0.00000	0.00195
GAM14	MRDISMM	0.00000	0.00000	-0.00019
GAM21	UMDISMRDIS	-0.00042	-0.00063	-0.00092
GAM22	UMDIS2	-0.02562	0.00153	-0.00284
GAM23	UMDISTURT	-0.00111	0.00000	0.00471
GAM24	UMDISMM	0.00000	0.00000	-0.00049
GAM31	TURTMRDIS	0.00026	0.00000	0.00195
GAM32	TURTUMDIS	-0.00111	0.00000	0.00471
GAM33	TURT2	-0.00004	0.00000	-0.00975
GAM34	TURTMM	0.00000	0.00000	0.00192
GAM41	MMMRDIS	0.00000	0.00000	-0.00019
GAM42	MMUMDIS	0.00000	0.00000	-0.00049
GAM43	MMTURT	0.00000	0.00000	0.00192
GAM44	MM2	0.03679	0.00000	-0.00078
D11	GEARNSWDTH	-0.05777	0.03791	0.00000
D21	NDEPSWDTH	-0.31596	-0.17430	0.00819
D31	NETLSWDTH	-0.00981	-0.03852	-0.00012
D41	SOAKSWDTH	-0.17819	-0.17463	-0.00052
D51	VESLSWDTH	0.08884	0.00190	0.00000
D61	VESHSWDTH	0.03686	0.04079	-0.00009
D12	GEARNOTH	0.05777	0.05900	0.00000
D22	NDEPOTH	0.31596	0.21637	0.00221
D32	NETLOTH	0.00981	0.04170	0.00025
D42	SOAKOTH	0.17819	0.18111	0.00165

D52	VESLOTH	-0.08884	0.02103	0.00000
D62	VESHOTH	-0.03686	-0.04203	0.00098
E11	GEARNMRDIS	-0.00342	0.00636	0.00000
E21	NDEPMRDIS	0.02415	0.01236	0.01184
E31	NETLMRDIS	-0.00170	-0.00006	0.00010
E41	SOAKMRDIS	0.01417	-0.00127	0.00195
E51	VESLMRDIS	0.00527	-0.00391	0.00000
E61	VESHMRDIS	-0.00029	-0.00091	-0.00003
E12	GEARNUMDIS	-0.05627	-0.10327	0.00000
E22	NDEPUMDIS	-0.18019	-0.05442	-0.00090
E32	NETLUMDIS	-0.00314	-0.00311	-0.00012
E42	SOAKUMDIS	0.27234	-0.00521	-0.00037
E52	VESLUMDIS	0.02562	-0.01901	0.00000
E62	VESHUMDIS	-0.00702	0.00214	0.00005
E13	GEARNTURT	0.00646	0.00000	0.00000
E23	NDEPTURT	0.01284	0.00000	-0.00003
E33	NETLTURT	0.00014	0.00000	0.00000
E43	SOAKTURT	-0.00075	0.00000	-0.00005
E53	VESLTURT	-0.00419	0.00000	0.00000
E63	VESHTURT	-0.00141	0.00000	0.00000
E14	GEARNMM	0.00000	0.00000	0.00000
E24	NDEPMM	0.00000	0.00000	-0.00050
E34	NETLMM	0.00000	0.00000	0.00014
E44	SOAKMM	0.00000	0.00000	-0.00041
E54	VESLMM	0.00000	0.00000	0.00000
E64	VESHMM	0.00000	0.00000	0.00088
MU11	SWDTHMRDIS	0.00028	-0.00015	0.00015
MU21	OTHMRDIS	-0.00028	0.00105	0.00009
MU12	SWDTHUMDIS	0.03444	-0.00124	0.00031
MU22	OTHUMDIS	-0.03444	0.00034	0.00015
MU13	SWDTHTURT	-0.00007	0.00000	-0.00083
MU23	OTHTURT	0.00007	0.00000	-0.00034
MU14	SWDTHMM	0.00000	0.00000	0.00037
MU24	OTHMM	0.00000	0.00000	0.00010
T1	1997	1.67013	0.96588	-0.00734
T2	1998	0.26113	-0.28623	0.00160
T3	1999	4.03855	4.02719	0.00724
T4	2000	0.41259	0.11433	-0.00292
T5	2001	-0.01812	-0.04028	-0.00929
T6	2002	-0.01018	-0.49008	-0.00776
T7	2003	-0.64762	-1.09591	-0.00699

T8	2004	-0.01668	-0.16076	-0.00868
T9	2005	0.14738	-0.78008	0.00015
T10	2006	0.58559	-0.08621	0.01011
T11	2007	0.64756	0.67007	0.00296
T12	2008	1.31084	0.34055	0.01530
DUM1	IN	0.58949	0.99597	-0.01511
SIG		1.00000	1.00000	1.00000
V		0.00000	1.00000	1.00000

[a]Note that although some coefficients appear as zeros, they are not when expanded to more decimal places.

Table 6. Descriptive Statistics for trips that operated pre- and post-closure

Variable	Mean		Median		Std. dev		Minimum		Maximum	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Inputs										
Number of Sets	4.60	4.89	5.00	5.00	2.50	2.18	1.00	1.00	15.00	12.00
Net Length (fm)	127.68	129.85	795.00	494.72	16.44	15.19	57.60	50.00	164.00	180.00
Net Depth (ft)	680.98	580.85	130.00	130.00	297.86	295.24	100.00	80.00	1000.00	1000.00
Soak Time (hr)	12.08	11.99	12.00	12.11	2.49	1.55	4.00	6.00	40.00	16.67
Vessel HP	48.21	46.56	260.00	250.00	8.49	7.34	33.80	35.00	80.00	76.00
Vessel Length (ft)	284.73	271.77	48.00	45.00	111.92	90.06	75.00	110.00	750.00	650.00
Outputs										
Desirable										
Swordfish and thresher shark (lbs.)	1743.44	1690.20	823.50	968.07	2355.23	2281.06	0.00	0.00	15019.00	18607.99
Other (lbs.)	383.65	280.62	194.64	170.61	562.28	380.34	0.00	0.00	4177.87	3387.72
Undesirable										
Marketable Discards	12.66	11.21	2.00	2.00	32.37	32.09	0.00	0.00	358.00	393.00
Unmarketable Discards	13.19	6.96	5.00	2.00	21.23	15.61	0.00	0.00	184.00	146.00
Turtles	0.03	0.01	0	0	0.20	0.08	0.00	0.00	2.00	1.00
Marine Mammals	0.46	0.40	0	0	0.76	0.72	0.00	0.00	5.00	5.00

Table 7. Descriptive Statistic for trips that operated inside and outside the closure.

Variable	Mean		Median		Std. dev		Minimum		Maximum	
	Inside	**Outside**	**Inside**	**Outside**	**Inside**	**Outside**	**Inside**	**Outside**	**Inside**	**Outside**
Inputs										
Number of Sets	5.44	4.60	5.00	5.00	2.90	2.26	1.00	1.00	15.00	14.00
Net Depth (ft)	132.43	127.91	130.00	130.00	13.90	16.21	103.00	50.00	164.00	180.00
Net Length (fm)	730.71	625.06	942.50	500.00	300.52	298.24	100.00	80.00	1000.00	1000.00
Soak Time (hr)	12.37	11.98	12.00	12.00	3.45	1.85	4.00	5.00	40.00	27.00
Vessel HP	50.34	47.07	200.00	250.00	8.09	7.99	37.00	33.80	74.00	80.00
Vessel Length (ft)	288.69	277.91	49.50	45.00	94.45	105.16	110.00	75.00	700.00	750.00
Outputs										
Desirable										
Swordfish and thresher shark (lbs.)	2569.18	1580.10	1802.53	778.96	2342.53	2292.22	0.00	0.00	11110.7 6	18607.99
Other (lbs.)	466.74	320.77	225.27	178.28	639.93	468.18	0.00	0.00	4003.86	4177.87
Undesirable										
Marketable Discards	13.65	11.80	4.00	2.00	26.67	33.10	0.00	0.00	171.00	393.00
Unmarketable Discards	28.05	7.74	18.00	3.00	33.21	14.00	0.00	0.00	184.00	146.00
Turtles	0.04	0.02	0	0	0.24	0.14	0.00	0.00	2.00	2.00
Marine Mammals	0.42	0.44	0	0	0.76	0.74	0.00	0.00	5.00	5.00

Table 8. Descriptive Statistic comparing trips with and without sea turtle takes.

Variable	Mean		Median		Std. dev		Minimum		Maximum	
	No take	Take	No take	Take	No take	Take	No take	Take	No take	Take
Inputs										
Number of Sets	4.69	6.07	5.00	6.00	2.37	2.63	1.00	1.00	15.00	10.00
Net Length (ft.)	128.42	136.00	500.00	900.00	15.93	16.92	50.00	100.00	180.00	150.00
Net Depth (fm)	638.36	737.13	130.00	140.00	300.47	305.56	80.00	125.00	1000.00	1000.00
Soak Time (hr.)	12.04	11.80	12.00	11.67	2.17	1.26	4.00	9.80	40.00	13.67
Vessel HP	47.52	48.80	255.00	318.00	8.06	9.06	33.80	38.00	80.00	72.00
Vessel Length (ft.)	278.45	332.53	48.00	45.00	103.34	112.85	75.00	190.00	750.00	500.00
Outputs										
Desirable										
Swordfish and thresher shark (lbs.)	1701.88	2774.90	882.00	1317.10	2296.49	3433.93	0.00	0.00	18607.99	11110.76
Other (lbs.)	337.81	546.57	187.8	257.02	493.36	717.34	0.00	0.00	4177.87	2614.65
Undesirable										
Marketable Discards	12.04	13.73	2	5	32.30	30.12	0.00	0.00	393.00	119.00
Unmarketable Discards	10.52	17.73	4	10	19.33	20.80	0.00	0.00	184.00	63.00
Turtles	0.00	1.13	0	1	0.00	0.35	0.00	1.00	0.00	2.00
Marine Mammals	0.44	0.40	0	0	0.74	0.74	0.00	0.00	5.00	2.00

Table 9. Average Annual Efficiency Scores for Model 1.

Year	Efficiency Score
1996	2.25
1997	3.57
1998	2.22
1999	5.79
2000	2.08
2001	1.66
2002	1.65
2003	1.36
2004	1.89
2005	1.83
2006	2.00
2007	2.00
2008	2.51
Mean	2.22

Table 10. Average Annual Efficiency Scores for Model 2.

Year	Efficiency Score
1996	2.47
1997	3.10
1998	1.92
1999	5.85
2000	1.91
2001	1.93
2002	1.60
2003	1.23
2004	1.97
2005	1.31
2006	1.72
2007	2.24
2008	1.89
Mean	2.48

Table 11. Average Annual Efficiency Scores for Model 3.

Year	Efficiency Score
1996	0.082
1997	0.099
1998	0.075
1999	0.099
2000	0.048
2001	0.048
2002	0.032
2003	0.053
2004	0.043
2005	0.040
2006	0.082
2007	0.044
2008	0.056
Mean	0.062

Table 12. Descriptive statistics of efficiency scores for trips occurring inside and outside the closed area

Variable	Mean		Median		Std. dev		Minimum		Maximum	
	In	Out	In	Out	In	Out	In	Out	In	Out
Model 1	3.36	2.51	2.87	2.21	1.73	1.61	0.00	0.00	9.68	10.70
Model 2	3.12	2.38	2.84	2.04	1.58	1.58	0.00	0.00	9.78	8.64
Model 3	0.10	0.06	0.06	0.03	0.18	0.13	0.00	0.00	1.00	1.00

Table 13. Descriptive Statistic for efficient and inefficient trips with Model 1.

Variable	Mean		Median		Std. dev		Minimum		Maximum	
	Eff.	Ineff.	Eff.	Ineff.	Eff.	Ineff.	Eff.	Ineff.	Eff.	Ineff.
Inputs										
Number of Sets	5.12	4.71	5.00	5.00	3.15	2.35	1.00	1.00	12.00	15.00
Net Length (fm.)	129.21	128.54	500.00	600.00	15.75	15.99	100.00	50.00	150.00	180.00
Net Depth (ft.)	580.61	642.08	130.00	130.0	293.36	300.89	139.29	80.00	1000.00	1000.00
Soak Time (hr.)	11.96	12.04	12.00	12.00	1.60	2.17	7.00	4.00	14.33	40.00
Vessel HP	46.16	47.58	260.00	255.00	7.68	8.09	35.00	33.80	63.00	80.00
Vessel Length (ft.)	260.52	280.05	45.00	48.00	66.87	104.64	120.00	75.00	365.00	750.00
Outputs										
Desirable										
Swordfish and thresher shark (lbs.)	6611.2 6	1566.03	5908.66	846.00	4927.45	2010.83	0.00	0.00	18607.9 9	14887.00
Other (lbs.)	1165.3 6	315.44	1081.86	181.15	953.82	454.25	0.00	0.00	4003.86	4177.87
Undesirable										
Marketable Discards	3.88	12.33	2.00	2.00	5.14	32.71	0.00	0.00	21.00	393.00
Unmarketable Discards	10.72	10.65	6.00	4.00	13.03	19.55	0.00	0.00	43.00	184.00
Turtles	0.04	0.02	0	0	0.20	0.16	0.00	0.00	1.00	2.00
Marine Mammals	0.44	0.44	0	0	1.04	0.73	0.00	0.00	5.00	5.00
Efficiency Score	0.00	2.71	0	2.37	0.00	1.61	0.00	0.11	0.00	10.70

Table 14. Descriptive statistics of efficiency scores for trips with and without sea turtle take

Variable	Mean		Median		Std. dev		Minimum		Maximum	
	No take	Take	No take	Take	No take	Take	No take	Take	No take	Take
Model 1	2.60	3.97	2.30	4.40	1.63	2.05	0.00	0.00	10.70	6.96
Model 2	2.47	3.42	2.13	3.02	1.59	1.85	0.00	1.23	9.78	6.45
Model 3	0.05	1.00	0.03	1.00	0.05	0.00	0.00	1.00	0.35	1.00

Table 15. Descriptive Statistic for efficient and inefficient trips with Model 2.

Variable	Mean		Median		Std. dev		Minimum		Maximum	
	Eff.	**Ineff.**	**Eff.**	**Ineff.**	**Eff.**	**Ineff.**	**Eff.**	**Ineff.**	**Eff.**	**Ineff.**
Inputs										
Number of Sets	5.12	4.71	5.00	5.00	2.93	2.36	1.00	1.00	12.00	15.00
Net Length (fm.)	127.05	128.61	450.00	600.00	16.73	15.95	80.00	50.00	150.00	180.00
Net Depth (ft.)	550.68	643.04	126.67	130.00	304.02	300.32	139.29	80.00	1000.00	1000.00
Soak Time (hr.)	11.46	12.06	11.40	12.00	1.35	2.17	7.00	4.00	13.75	40.00
Vessel HP	46.92	47.56	260.00	255.00	7.47	8.10	35.00	33.80	63.00	80.00
Vessel Length (ft.)	256.80	280.17	45.00	48.00	65.01	104.65	120.00	75.00	365.00	750.00
Outputs										
Desirable										
Swordfish and thresher shark (lbs.)	5841.3 2	1590.55	4252.00	846.00	4353.54	2105.88	0.00	0.00	15019.00	18607.99
Other (lbs.)	1085.4 7	317.99	902.54	180.34	956.32	458.61	0.00	0.00	4003.86	4177.87
Undesirable										
Marketable Discards	11.40	12.09	5.00	2.00	19.54	32.58	0.00	0.00	71.00	393.00
Unmarketable Discards	28.56	10.08	9.00	4.00	46.31	17.64	0.00	0.00	184.00	160.00
Turtles	0.00	0.02	0	0	0.00	0.16	0.00	0.00	0.00	2.00
Marine Mammals	0.40	0.44	0	0	1.04	0.73	0.00	0.00	5.00	5.00
Efficiency Score	0.00	2.56	0	2.19	0.00	1.56	0.00	0.12	0.00	9.78

Table 16. Descriptive Statistic for efficient and inefficient trips with Model 3.

Variable	Mean		Median		Std. dev		Minimum		Maximum	
	Eff.	Ineff.	Eff.	Ineff.	Eff.	Ineff.	Eff.	Ineff.	Eff.	Ineff.
Inputs										
Number of Sets	3.69	4.75	3.00	5.00	2.45	2.37	1.00	1.00	12.00	15.00
Net Length (fm.)	121.37	128.80	487.80	585.60	15.09	15.95	80.00	50.00	155.00	180.00
Net Depth (ft.)	598.86	641.56	120.00	130.00	293.32	300.99	187.50	80.00	1000.00	1000.00
Soak Time (hr.)	12.40	12.03	12.00	12.00	6.16	1.89	4.00	5.00	40.00	27.00
Vessel HP	45.27	47.61	227.50	260.00	9.02	8.04	35.00	33.80	69.00	80.00
Vessel Length (ft.)	237.50	280.84	43.00	48.00	80.39	104.14	120.00	75.00	450.00	750.00
Outputs										
Desirable										
Swordfish and thresher shark (lbs.)	3485.1 9	1663.27	2358.00	867.87	3849.36	2236.21	0.00	0.00	15019.00	18607.99
Other (lbs.)	533.09	335.33	208.75	188.60	752.72	487.34	0.00	0.00	2252.70	4177.87
Undesirable										
Marketable Discards	1.00	12.43	0	2.00	1.90	32.71	0.00	0.00	7.00	393.00
Unmarketable Discards	1.73	10.95	1	4.00	2.16	19.62	0.00	0.00	11.00	184.00
Turtles	0.00	0.02	0	0	0.00	0.16	0.00	0.00	0.00	2.00
Marine Mammals	0.12	0.45	0	0	0.43	0.75	0.00	0.00	0.00	5.00
Efficiency Score	0.00	0.07	0	0.04	0.00	0.14	0.00	0.00	0.00	1.00

Table 17. ANOVA and Kruskal-Wallis Test Results for Comparison of Model Mean Efficiency Scores

Test	Test Statistic Value	P-Value	Significant Difference at .05
ANOVA	946.951	.001	Yes
Post Hoc - TUKEY HSD			
Model 1 compared to Model 2		.078	No
Model 1 compared to Model 3		.000	Yes
Model 2 compared to Model 1		.078	No
Model 2 compared to Model 3		.000	Yes
Model 3 compared to Model 1		.000	Yes
Model 3 compared to Model 2		.000	Yes
Kruskal-Wallis H	1417.27	.000	Yes

Table 18. Paired T–Test and Kruskal-Wallis results for pre-and post-closure efficiency scores.

Test	Test Statistic Value	P-Value	Significant Difference at .05
Paired t-test	3.281	.001	Yes
Kruskal-Wallis H	19.261	.000	Yes

Table 19. Mann-Whitney U and Wilcoxon W Test Results for trips operated Inside and Outside of the Closure efficiency scores.

Test	Test Statistic Value	P-Value	Significant Difference at .05
Mann-Whitney U	15120.500	.000	Yes
Wilcoxon W	79381.500	.000	Yes

Table 20. Estimates of productivity change per trip, comparison to base 1996.

Year	Model 1	Model 2	Model 3
1997	0.36	0.35	-0.81
1998	0.27	0.25	0.01
1999	0.49	0.64	-0.33
2000	0.56	0.66	0.89
2001	0.54	0.47	0.28
2002	0.58	0.39	0.90
2003	0.25	0.16	0.88
2004	0.32	0.31	0.89
2005	0.55	0.36	0.90
2006	0.83	0.66	0.10
2007	0.90	0.91	0.90
2008	1.04	0.91	0.90
Mean	0.56	0.51	0.46

Table 21. ANOVA Results for Comparison of Model Mean Productivity Change

Test	Test Statistic Value	P-Value	Significant Difference at .05
ANOVA	.186	.831	No
Post Hoc - TUKEY HSD			
Model 1 compared to Model 2		.950	No
Model 1 compared to Model 3		.816	No
Model 2 compared to Model 1		.950	No
Model 2 compared to Model 3		.951	No
Model 3 compared to Model 1		.816	No
Model 3 compared to Model 2		.951	No

Table 22. Estimates of efficiency change per trip, comparison to base 1996.

Year	Model 1	Model 2	Model 3
1997	-1.31	-0.61	-0.81
1998	0.01	0.54	0.19
1999	-3.55	-3.39	-0.34
2000	0.14	0.55	0.89
2001	0.56	0.51	0.29
2002	0.59	0.88	0.91
2003	0.90	1.25	0.89
2004	0.34	0.47	0.90
2005	0.40	1.14	0.90
2006	0.25	0.75	0.09
2007	0.26	0.24	0.89
2008	-0.27	0.57	0.88
Mean	-0.14	0.27	0.47

Table 23. Estimates of technical change per trip, comparison to base 1996.

Year	Model 1	Model 2	Model 3
1997	1.67	0.97	-0.01
1998	0.26	-0.29	0.00
1999	4.04	4.03	0.01
2000	0.41	0.11	0.00
2001	-0.02	-0.04	-0.01
2002	-0.01	-0.49	-0.01
2003	-0.65	-1.10	-0.01
2004	-0.02	-0.16	-0.01
2005	0.15	-0.78	0.00
2006	0.59	-0.09	0.01
2007	0.65	0.67	0.00
2008	1.31	0.34	0.02
Mean	0.70	0.26	0.008

Table 24. Annual mean fluctuation estimates of productivity change per trip.

Between Years	Model 1	Model 2	Model 3
1996-1997	0.36	0.35	-0.81
1997-1998	-0.09	-0.10	1.00
1998-1999	0.22	0.39	-0.53
1999-2000	0.07	0.02	1.22
2000-2001	-0.01	-0.19	-0.61
2001-2002	0.04	-0.08	0.62
2002-2003	-0.33	-0.24	-0.02
2003-2004	0.07	0.16	0.01
2004-2005	0.22	0.05	0.01
2005-2006	0.29	0.30	-0.80
2006-2007	0.22	0.39	-0.53
2007-2008	0.07	0.25	0.80
Mean	0.09	0.11	0.03

Table 25. Annual mean fluctuation estimates of efficiency change per trip.

Between Years	Model 1	Model 2	Model 3
1996-1997	-1.31	-0.61	-0.81
1997-1998	1.32	1.15	1.00
1998-1999	-3.56	-3.92	-0.53
1999-2000	3.69	3.94	1.23
2000-2001	0.42	-0.04	-0.60
2001-2002	0.03	0.37	0.61
2002-2003	0.31	0.37	-0.02
2003-2004	-0.56	-0.78	0.01
2004-2005	0.06	0.67	0.00
2005-2006	-0.15	-0.39	-0.81
2006-2007	-3.56	-3.92	-0.53
2007-2008	0.07	0.25	0.80
Mean	-0.27	-0.24	0.03

Table 26. Annual mean fluctuation estimates of technical change per trip.

Between Years	Model 1	Model 2	Model 3
1996-1997	-1.31	0.97	-0.007
1997-1998	1.32	-1.25	0.009
1998-1999	-3.56	4.31	0.006
1999-2000	3.69	-3.91	-0.010
2000-2001	0.42	-0.15	-0.006
2001-2002	0.03	-0.45	0.002
2002-2003	0.31	-0.61	0.001
2003-2004	-0.56	0.94	-0.002
2004-2005	0.06	-0.62	0.009
2005-2006	-0.15	0.69	0.010
2006-2007	-3.56	4.31	0.006
2007-2008	0.01	0.76	-0.007
Mean	-0.28	0.42	0.001

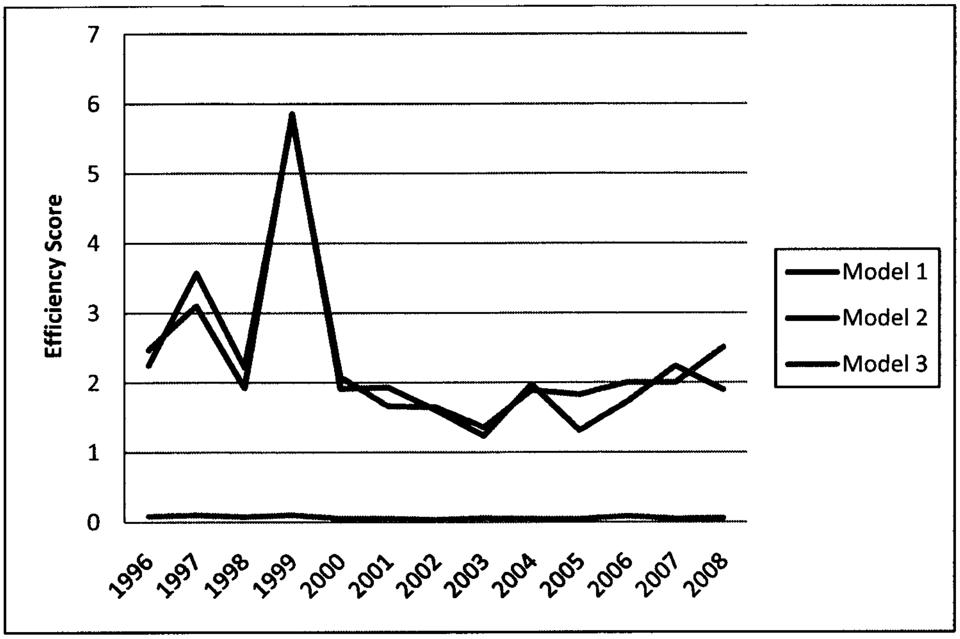
Table 27. Descriptive Statistics for shadow price estimates for undesirable outputs over the research period.

	Marketable Discards	Unmarketable Discards	Sea Turtles	Marine Mammals
Mean	$26,698.99	$59,821.22	$91,990.84	$9,777.53
Median	$23341.17	$53574.64	$99007.78	$8805.57
Standard Error	764.730	1298.024	5992.82	374.31
Standard Deviation	20915.07	35500.43	20759.74	5906.55
Minimum	$2,309.53	$5,008.81	$55,514.95	$1,114.75
Maximum	$413,305.81	$363,475.15	$122,801.65	$53,067.51
Sum	$19970841.92	$44746270.26	$1103890.06	$2434605.32

Table 28. Annual mean shadow price estimates for undesirable outputs.

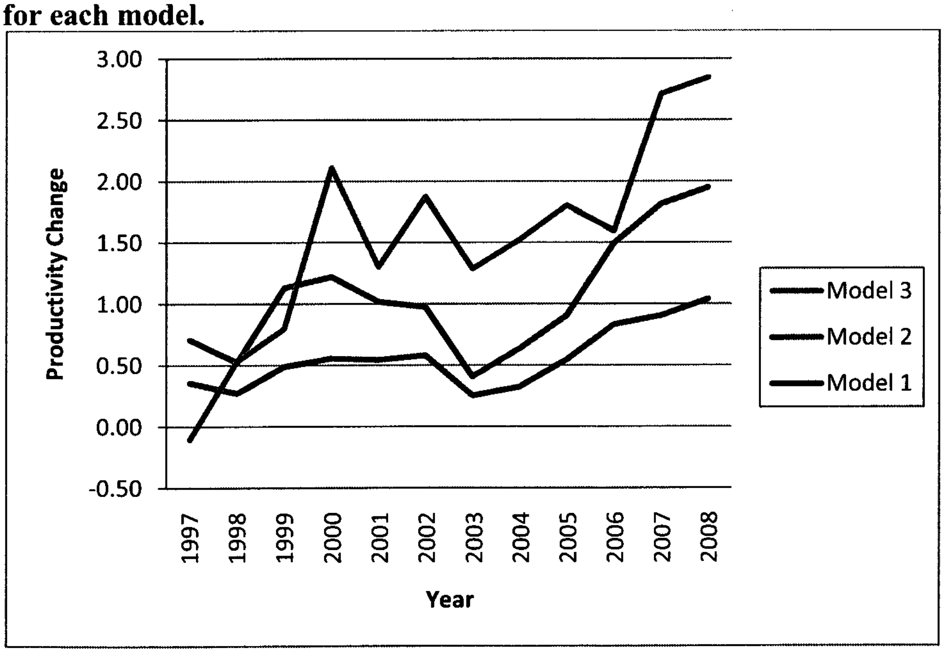
Year	Marketable Discards	Unmarketable Discards	Sea Turtles	Marine Mammals
1996	$28,969.41	$64,330.28	$97,739.11	$9,465.81
1997	$26,479.16	$59,084.40	$97,430.03	$9,474.11
1998	$28,448.82	$58,510.10	$100,486.62	$10,809.22
1999	$29,141.25	$67,919.70	$85,054.63	$12,383.75
2000	$25,265.32	$55,527.09		$7,745.47
2001	$15,603.46	$35,955.72		$4,575.09
2002	$30,141.32	$72,378.41		$9,869.52
2003	$22,183.21	$51,844.83		$9,258.45
2004	$17,780.04	$41,552.30		$6,069.07
2005	$21,992.69	$51,854.17		$7,324.62
2006	$25,698.47	$58,643.97	$65,611.16	$9,266.30
2007	$42,275.73	$93,222.33		$13,924.71
2008	$32,420.64	$73,983.10		$16,233.52
Pre-Closure	$27,600.85	$60,732.45	$94,388.99	$9,932.79
Post-Closure	$25,403.47	$58,512.24	$65,611.16	$9,517.10

Figure 8. Model comparison of mean annual efficiency calculated for three models.



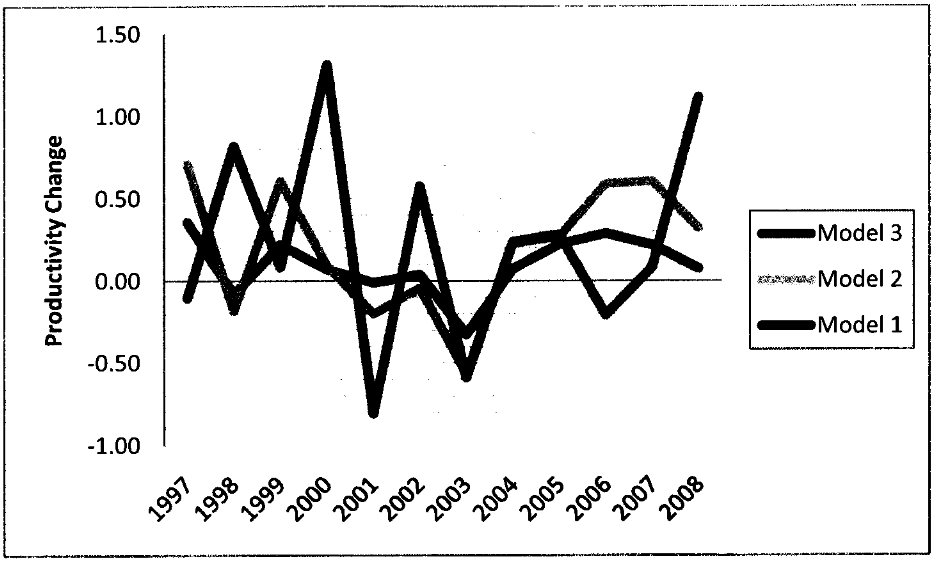
In Model 1, (status quo) undesirable outputs remained the same. Model 2, (unregulated) undesirable outputs were expanded while in Model 3, (regulated) undesirable outputs were contracted.

Figure 9. Annual mean productivity change per trip, compared to base year 1996 for each model.



In Model 1, (status quo) undesirable outputs remained the same. Model 2, (unregulated) undesirable outputs were expanded while in Model 3, (regulated) undesirable outputs were contracted.

Figure 10. Annual mean fluctuations of productivity change per trip.



In Model 1, (status quo) undesirable outputs remained the same. Model 2, (unregulated) undesirable outputs were expanded while in Model 3, (regulated) undesirable outputs were contracted.

SECTION V: CONCLUSION

Traditional economic metrics that ignore undesirable outputs in the production process often overstate or provide erroneous estimates of the efficiency and productivity of production activities by failing to account for the cost of conservation and stock sustainability. These omissions can lead to conclusions that are biased against resource conservation and protection. This research is important as it uses a "green" based approach that adjusts for undesirable harvest in the production process. These results provide policy makers with a more appropriate measure of economic performance in the California-Oregon drift gillnet fishery.

This research demonstrated that productivity and efficiency can measure regulatory impacts on fisheries such as the California-Oregon drift gillnet fishery when undesirable harvest such as discarded bycatch and take of protected species occur as undesirable outputs in the production process. For each observed economic trip, efficiency, productivity, efficiency change, and technical change were computed for the period 1996 to 2008.

This research offers an alternative methodology for estimating efficiency, productivity and shadow price using the generalized quadratic directional distance function. In this context, increased regulation may have a positive effect on productivity when undesirable outputs are recognized as part of the production process. The sources of productivity change can further more be estimated econometrically using the directional output distance function approach.

The concept of directional vectors and the quadratic directional distance function were introduced and used to demonstrate a method for estimating efficiency and productivity change when undesirable outputs were present such as the capture of sea turtles. Shadow price was used to provide a lower bound cost to society for conservation, such as the avoidance of undesirable outputs.

Seven inputs, two desirable outputs, and four undesirable outputs were used to provide an empirical example of a parametric directional distance function approach for estimating efficiency, productivity, and shadow price. The desirable outputs were a composite of the primary target species, swordfish and thresher shark, and a composite of all other marketable species which included species such as tunas, opah, louvar, Spanish mackerel, mako shark, and dolphin fish. The undesirable outputs were broken into four categories, market and regulatory discards, unmarketable discards, marine mammals, and sea turtles. Trip characteristics such as set number, net depth, net length, gear soak time, vessel length and vessel horsepower were used as inputs.

The results of the analysis indicated that productivity change has been positive when compared to the base year 1996. All three model specifications showed a positive trend, which suggested that growth occurred as the overall amount of bycatch was reduced in the fishery. The results also indicated that the post-closure means of efficiency, productivity change, efficiency change, and technical change, all increased when compared to pre-closure values. Results of statistical analyses reveal that pre-and post-closure values for both efficiency and productivity change were significantly different. One would have assumed that a loss of fishing grounds would have presented the fishermen with overcrowding and inefficiency. Attrition in the fishery, as well as reduced number of sets fished post-closure contributed to higher estimates of efficiency and productivity change.

The model that incorporated undesirables indicated that productivity grew 788 pounds of swordfish over the research period relative to the base year. Results also revealed the biases that existed when undesirable harvest were considered. Average growth of 964 pounds was calculated for Model 1, when undesirable outputs were ignored and 878 pounds for Model 2, when desirable and undesirable outputs were expanded.

The decomposition of productivity into its components, efficiency change and technical change, demonstrated a clear pattern. Post-closure productivity growth resulted in an increase of 334 pounds of swordfish harvest on average per trip when adjusted for undesirable outputs.

Post-closure productivity growth was also driven primarily by efficiency change with the greatest amount of growth occurring in the years following the closure. In 2001, the first year the closure was implemented, the least amount of growth took place due mainly to negative efficiency change. Technical change had a relatively small impact on the overall productivity measure and in some years actually contributed to slower growth. It is clear that fishermen have indeed been able to adapt to the closure area by becoming more efficient by reducing catches of bycatch species and using fewer inputs. This in turn contributed to the overall growth in productivity.

The results of the shadow price analysis provided evidence that conservation management does not exist without costs. Those costs are extensive when protected species such as sea turtles are taken in a fishery. Estimates of shadow price indicate that the average cost to society for reduction in sea turtle is $92,000 in forgone swordfish revenue. This value falls within the range of other studies for conservation cost on a per turtle basis. On the other side, however, what is the value to society of protecting sea turtles? It would be expected that the economic value to society would exceed the lost revenues from sea turtle protection.

This research can help guide fisheries managers in designing policy to reduce bycatch of protected and unmarketable discard while simultaneously maintaining productivity and commercial viability for a fishery. It should be noted that observations were based on observer data at the economic trip level and the conclusions presented in this research does not offer a clear representation of the entire fleet. Conclusions are restricted only to those vessels which were observed during the research period.

Four conclusions can be drawn from this research.

1. Performance metrics that ignore undesirable outputs may be erroneous and may lead to incorrect estimates and conclusions that are used to guide management.
2. Trips with low or no inefficiency were those with a relatively higher level of desirable harvest, lower input usage and lower levels of undesirable outputs.
3. Decomposing technical change and efficiency change from productivity growth showed that the increase in productivity change was primarily driven by efficiency change rather than technical change.
4. Productivity trends were positive over the study period and showed considerable improvement after the closure, suggesting that the remaining fishermen have adapted to the strict regulations.

This research discussed the existing gaps in the literature and suggested the use of a green-based approach to account for bycatch is just one way to assess efficiency and productivity change. Alternatives were suggested for future research which could further improve assessments of economic performance in fisheries which take undesirable species.

The "green" approach offers a useful tool in the assessment of efficiency and productivity in the presence of undesirable outputs. The major advantage of this approach is that the performance measure credits the reduction of undesirable outputs such as sea turtles while it simultaneously credits the increases in desirable outputs. This approach is in direct alignment with the goals of fishery managers and the MSFCMA.

The directional distance function is a complete representation of the technology and the marginal rate of transformation between desirable and undesirable outputs along the frontier can be used to estimate the shadow value for the undesirable species that were captured in the fishery. Shadow values are important for several reasons. They can inform managers of the opportunity cost of either reducing undesirable harvest in terms of forgone desirable harvest. Managers can use this information to find the right production mix that maximizes the desirable outcomes and obtains the level of conservation that maximizes the benefits to society.

The shadow prices can also be used in cost-benefit analyses to guide fisheries policy with respect to the optimal level of conservation. Similar to the work of Gjertsen *et al.* (2009), the estimates can be used to show which conservation practices would give you the "biggest bang for your buck." Ultimately, this information could assist fishery managers with designing and implementing regulations according to the trade-off between the number of sea turtles incidentally taken in the fishery and the cost of reducing those sea turtle interactions in the future.

APPENDIX

Glossary of Economic Terms adapted from Grafton et al., (2006) and Wooldridge (2003).

Allocative efficiency: A firm or vessel is allocatively efficient when it combines inputs or factors of production in proportions that minimize cost of producing a given level of output. In a fishery, for example, if the per unit cost of crew rises, a vessel that is allocatively efficient will substitute (to the extent possible) toward capital and technology that is labor-saving.

Base period: A period in an index number calculation to which all other periods are compared.

Biased estimate: An estimate whose expected value of the sample mean is different than the mean of the population from which the sample is drawn.

Bycatch: Fish or other species that are caught incidentally when vessels target other species.

Capital: Economic assets, such as durable goods, machines, fishing boats, and other plant and equipment that are used in combination with other inputs to produce goods and services.

Catch per unit of effort (CPUE): A measure given by the ratio of total harvest (in weight or occasionally numbers of fish) to total fishing effort, usually measured by total days fished or total trawling hours. Catch per unit of effort (or CPUE) is often used as an imperfect measure of stock abundance. CPUE, for example, may rise not because the total stock of fish has increased, but simply because boats have entered a spatial zone or part of the fishery where the concentration of fish is larger.

Coefficient of Variation (cv): The standard deviation of a variable divided by its mean, which gives a measure of its variability.

Commercial fishery: A fishery that is characterized by large scale fishing activity, using modern fishing methods, where fishing is done largely for profit.

Common-pool resource (CPR): A resource, such as a fishery, where use is rivalrous (one person's use harms other users) and the ability to exclude users is difficult.

Common property resource: A resource over which a community or group of individuals have access to and, to some extent, are able to exclude persons from outside of the group from using.

Cross-sectional data: Data that are sampled from a population at a given point in time, usually annual or seasonal.

Data envelopment analysis: A mathematical programming method used to obtain a measure of efficiency and capacity output, also referred to as DEA. DEA models are commonly used to measure capacity in a fishery, but a principal drawback is that they do not normally account for random effects.

Deterministic model: A model that assumes no uncertainty, as if all variables and relationships were not subject to random fluctuation.

Deterministic production frontier: A relationship between inputs and an output that represents the maximum possible amount of output that can be produced from any quantity or combination of inputs, assuming no uncertainty or randomness in production.

Discarding: The dumping of unwanted fish or other species, generally of low or no market value, while at sea.

Discount rate: The rate at which future income or expenditures is discounted to the present. It recognizes that a given amount of money received a year from now is worth less in terms of purchasing power today because it could be invested in the present year to yield a return.

Duality: The relationship in production economics between a primal problem, such as that of maximizing a measure of output subject to limiting constraints on input use, and its dual formulation, minimizing input use subject to a constraint on the output quantity which must be produced. The solution to the dual problem can be used to express shadow prices for the primal problem constraints.

Econometrics: The application of statistical and mathematical methods to the study of economic data, designed to give empirical content and verification to existing economic theories.

Economic efficiency: A state where all available inputs are used in the correct amounts and proportions to produce the maximum amount of output at the lowest cost of production. It is calculated as the product of allocative efficiency and technical efficiency.

Economic profit: The difference between total cost and total revenue, where total cost includes the opportunity cost or the value of any single input's next best alternative use. The opportunity cost of a skipper who owns a boat but does not receive a salary would thus be included in total costs, measured by the amount the skipper would receive as a hired-skipper on another boat. By contrast, accounting profit is simply the difference between total revenues and explicit cash outlays.

Economics: The science of choice, or a discipline that studies the allocation of scarce resources, with limited and alternative uses, for the production and distribution of goods and services.

Economies of scale: A term used to describe the fall in the long run average cost of production as a result of an increase in the amount produced.

Externality: An incidental cost or benefit imposed on others from a given action.

Factors of production: The inputs used in a production process, often aggregated into the broad categories of land, labor, capital and natural resources.

Fishing effort: An aggregate measure of the amount of inputs applied to a given fishing activity, usually measured in terms of days fished, gear units or trawling hours. Standardized fishing effort is a measure of fishing effort that attempts to adjust for differences in vessel and gear characteristics.

Fixed cost: A cost of production that does not vary with the level of output such as the cost of a fishing license or the purchase price of a statutory fishing right.

Growth rate: A measure of how a variable changes through time, usually expressed in percentage terms.

Infimum (inf): The greatest lower bound of a given set, defined as a value which is smaller than all the elements in the set (a lower bound), and for which no larger value is also a lower bound to the set. If a set contains a minimum value, it will be the infimum.

Input orientated measure of technical efficiency: The minimum amount of inputs required to produce a given level of output.

Inputs: Scarce resources, such as labor, natural resources and capital, that are used as factors of production to produce an output. In a fishery, the principal inputs or factors of production that are used to obtain a harvest of fish include crew, vessel, gear bait, ice, fuel and the stock of fish.

Isoquant: Curve or line that represents the same level of output, but that is produced with different input combinations.

Joint production: A production process that simultaneously produces more than one output. A fishing activity, for example, may result in that catch of two or more species at once, or the catch of a target species and bycatch.

Landings data: Data on catch and vessel characteristics obtained at port, or when the harvest is delivered to port.

Lower bound: A value that is smaller than all the elements in a given set.

Marginal cost: The measure of the change in the total cost of production given a marginal change in the amount of output produced.

Marginal rate of substitution: The amount of one good a person is willing to trade off for another a good.

Marginal rate of technical substitution: Also called the technical rate of substitution and is the slope of an isoquant. It represents the trade off from using marginally less of one input, while leaving output unchanged. Normally, we expect the marginal rate of technical substitution to diminish as we move down to the right along an isoquant.

Market failure: Situation where the market alone, in the absence of any intervention, fails to deliver the fullest benefit to society. In fisheries market failure frequently occurs because of the presence of negative technological externalities in harvesting.

Observer data: Data obtained by direct observation, usually for scientific purposes.

Open access resource: A resource for which no effective property rights have been established, and where it is difficult if not impossible to exclude individuals from access to the resource.

Opportunity cost: An implicit cost defined as the cost or price of the next best alternative or action. For example, if the next best employment that could be obtained by an owner-operator of a fishing vessel is $30,000/year then this amount equals the opportunity cost of the skipper's labor.

Output orientated measure of technical efficiency: A measure of actual output relative to maximum possible output of given a set of inputs.

Output set: The set of all output vectors (y,b) which can be produced using a given set of input vectors, x; $P(x) = \{(y,b) : x \text{ can produce } (y,b)\}$.

Panel data set: Data which is obtained over time from given units of observation.

Parameter: A variable that is held constant for the moment, but that can be varied in a model context to determine the effect of its change on all other variables.

Pelagic species: Fish commonly found at or near the surface, such as tuna, pilchard and herring.

Pooled cross-sectional data: Data that combines cross-sectional observations on a sample of a population over time.

Probability: The likelihood of an event occurring, typically defined as a number between zero and one. If an event occurs with certainty the probability of its occurrence is one. If the event never arises, the probability of its occurrence is zero.

Probability distribution: A mathematical formula that describes the probability of obtaining different values of a random variable.

Production frontier: A production function that shows a maximum output for any given inputs, typically used in reference to either a deterministic (without randomness) or stochastic (with random effects) production frontier.

Production function: A mathematical expression that maps or transforms inputs via a production process into a single output. Constant returns to scale production functions imply that a doubling of *all* inputs would exactly double output. A decreasing (increasing) return to scale production implies that a doubling of all inputs results in less (more) than a doubling of output.

Productivity: Typically defined as the ratio of an output (or a collection of outputs) to an input (or a collection of inputs) in a production process.

Productivity index: A measure of productivity usually indexed to a base period or a particular observation or numéraire.

Profit: The difference between total revenues and total costs.

Proxy variable: An observed variable that is related to an unobserved explanatory variable. For example, years of fishing experience may be used as a proxy for skipper skill.

Pseudo-panel data: Aggregated cross-sections of independent data obtained over time into one dataset.

Public bad: A good that generates disutility or harm to users and is both non-exclusive (it is not possible to prevent others from being harmed by the good) and non-rival (the use of the good by any one user does not diminish the harm incurred by others).

Public good: A good that generates benefits to users and is both non-exclusive (the use by any other user does not diminish any benefits from using the good by others). An example of public good is a lighthouse.

Returns to scale: The proportional change in output from a given proportional change in all inputs. Constant returns to scale implies that a doubling of *all* inputs would exactly double output. Decreasing (increasing) returns to scale implies that a doubling of all inputs result in less (more) than a doubling of output.

Sample bias: Bias or differences that arise between the mean of a sample and the population from which it is drawn because the sample is not representative of the population.

Scale efficiency: Production at a level of output, and with an amount of plant or capital equipment, that would maximize profits if the firm were economically efficient.

Shadow price: is the change in the objective value of the optimal solution of an optimization problem obtained by relaxing the constraint by one unit. It is the marginal utility or marginal rate of transformation and is often interpreted as the opportunity cost of reducing undesirable outputs (i.e. sea turtles, marine mammals, and other non-marketable catch).

Social discount rate: The discount rate at which society chooses to discount future cost and benefits. This social discount rate would normally be lower than a private or individual cost rate.

Supremum (sup): The least upper bound of a given set, defined as a value which is larger than all the elements in the set (an upper bound), and for which no other upper bound to the set is smaller. If a set contains a maximum value, it will be the infimum of the set.

Technical efficiency: A measure of how close a firm is to producing the maximum amount of output from given inputs. Unlike allocative efficiency, technical efficiency is not concerned with the proportions in which inputs are used, but at a given proportion, measures the extent to which a given amount of input results in maximum output.

Total revenue: The total receipts from fishing, or the price of fish times the quantity of fish landed.

Truncated normal distribution: A normal distribution that takes on only zero or positive values, frequently used as the distribution for the technical inefficiency term in a scholastic production frontier analysis.

Unbalanced panel: A panel data set where certain year (periods) of data are missing for some cross-sectional units.

Upper bound: A value that is larger than all the elements in a given set.

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