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An Economic Assessment of Reducing Incidental Capture of Sea Turtles in the Northwest Atlantic Pelagic Longline Fishery

Tara L. Scott
College of William and Mary - Virginia Institute of Marine Science

AN ECONOMIC ASSESSMENT OF REDUCING INCIDENTAL CAPTURE OF SEA TURTLES IN THE NORTHWEST ATLANTIC PELAGIC LONGLINE FISHERY

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Tara L. Scott

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James E. Kirkley, Ph.D.
Advisor

Dennis L. Taylor, Ph.D.

John A. Musick, Ph.D.

John M. Ward, Ph.D.
NOAA Fisheries

For my grandfathers, Lee Moorefield (Gramps) and Ben Scott (Grampa) who inspired me and reminded me to keep dreaming and to never give up. For the rest of my family, for their love and continuous support over the years.

TABLE OF CONTENTS

Page

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LIST OF TABLES

LIST OF FIGURES

ABSTRACT

NOAA Fisheries has expressed increased concern about the potential incidental take of sea turtles by the U.S. pelagic longline fishery. Under the Endangered Species Act, all sea turtles in U.S. territorial seas or Exclusive Economic Zone waters must be protected. U.S. fishing vessels in international waters must also adhere to the provisions of the ESA. In an effort to maintain the commercial fishery and reduce the incidental take of sea turtles, NOAA Fisheries initiated a series of gear experiments in 2001, which continued into 2003. The purpose of these experiments was to develop gear modifications, such as the use of the standard j-hook vs. a circle hook, and changes in fishing practices, which would reduce the take of sea turtles and maintain the economic viability of the commercial fishery. Gear modifications designed to reduce the incidental take of prohibited species, however, often have undesirable consequences, such as a reduction in the catch of the desired species. Alternatively, gear modifications may reduce technical and economic efficiency of harvesting operations. Using data from the NOAA Fisheries' experiments, this study examines the potential impacts of gear modifications on the technical and economic efficiency of the U.S. Northwest, Atlantic, pelagic longline fishery. The assessment of efficiency was done in two stages: (Stage I) technical efficiency without consideration of reducing the take of sea turtles, was estimated; and (Stage II) technical efficiency, explicitly considering the reduction in the take of sea turtles, was estimated and analyzed. The purpose of the two analyses was to ascertain the feasibility of imposing gear restrictions intended to reduce the incidental take of sea turtles. Based on the results of the analyses, it was concluded that there was no significant difference in the technical efficiency of the circle and j-hook when a regulatory induced reduction is imposed for sea turtle capture. The alternative treatments tested tended to have reduced catch compared to Treatment 1. However, when operating at an efficient level, the treatments could have higher catches. Treatment 7, a circle hook had the greatest potential for output expansion (e.g. increase catch) compared to Treatment 1. Tobit analysis revealed that set duration and gangion distance tended to increase efficiency, as well as catch, when increased. The analyses suggested that policy makers foster the development of gear that focuses on these key components. The use of the 18/0 and 16/0 circle hooks with squid or mackerel bait are by far the best hook options tested. They have higher efficiency and reduce the capture of sea turtles when compared to the industry standard.

AN ECONOMIC ASSESSMENT OF REDUCING INCIDENTAL CAPTURE OF SEA TURTLES IN THE NORTHWEST ATLANTIC PELAGIC LONGLINE FISHERY

CHAPTER 1. INTRODUCTION

1.1 Introduction

Commercial fisheries often inflict incidental mortality or harm on protected species, such as marine mammals and various sea turtles, while harvesting marketable species of fish. This has typically been the case for purse seine, trawl, and longline fisheries. In the late 1980s and early 1990s, concerns were raised about human interactions with dolphins in the eastern tropical Pacific tuna, purse seine fishery, and NOAA Fisheries and numerous Gulf of Mexico states expressed considerable concern about mortality on sea turtles in the Gulf of Mexico shrimp trawl fishery. More recently, NOAA has become increasingly concerned about human interactions with sea turtles in the Northwest Atlantic, pelagic, longline fishery.

Fisheries managers have typically addressed the incidental mortality or human interactions' problems by imposing either gear or spatial restrictions. For example, in the shrimp trawl fishery, vessel operators were required to install turtle excluded devices (TEDs). In the Northwest Atlantic, pelagic, longline fishery, both spatial and temporal restrictions were imposed to reduce interactions with sea turtles. Such restrictions, however, typically reduce the technical and economic efficiency of fishing operations by imposing costs on fishermen related to acquisition of new gear and concurrent reductions in landings.

In 2001, NOAA Fisheries became increasingly concerned about the potential increase in mortality on various sea turtles in the U.S. Northwest Atlantic, pelagic, longline fishery, and thus, initiated several experiments in an effort to determine the feasibility of alternative restrictions on fishing gear and practices. A major objective of these experiments was to determine the feasibility of reducing interactions with sea turtles, while simultaneously maintaining technical and economic efficiency.

The pelagic longline fishery is an important U.S. Northwest Atlantic fishery. The fishery primarily pursues various species of tunas and sharks, along with swordfish. If this fishery is allowed to expand or to continue operations in areas with populations of sea turtles, it is highly likely that the incidence of sea turtle captures and mortality will increase. NOAA Fisheries is responsible for the management and regulation of fisheries involving Highly Migratory Species (HMS), which includes the Northwest Atlantic, pelagic, longline Fishery. The Endangered Species Act of 1973 requires the protection of all species of sea turtles that occur in U.S. territorial waters. A major concern in the management of the Atlantic highly migratory species (HMS) fishery is the incidental harvesting and mortality of threatened and endangered species.

Presently, the Kemp's ridley (*Lepidochelys kempii*), leatherback (*Dermochelys coriacea*), and hawksbill (*Eretmochelys imbricata*) sea turtles are listed as endangered. Loggerhead (*Caretta caretta*) and green (*Chelonia mydras*) sea turtles are listed as threatened (Watson, 2003). Loggerhead and leatherback sea turtles are the most common species found in the Northwest Atlantic. In the pelagic longline fishery, sea turtles like the loggerhead are accidentally hooked in the mouth or digestive tract, or entangled in the lines. NOAA Fisheries, the Fish and Wildlife Service (FWS), under the U.S. Department of the Interior (DOI) are jointly responsible for ensuring that federal actions do not jeopardize the continued existence of the protected sea turtles. The longline fishery operates in areas with concentrations of sea turtles, and thus, the agency is required to take action to prevent incidental takings.

The experiments were designed to determine gear modifications and changes in fishing practices, which would simultaneously reduce interactions with turtles and maintain the financial viability of the fishing fleet. NOAA Fisheries contracted 13 pelagic longline fishing vessels between 2001 and 2003 to develop gear and fishing modifications to reduce the incidental mortality of sea turtles in the Northwest Atlantic, pelagic, longline, fishery.

Information on hook size and type, mainline length, soak duration, number of light sticks, etc. was collected and recorded in the Pelagic Observer Logbooks maintained by the Southeast Fisheries Science Center. Additional information included type, weight, and length of target or desirable species caught, along with the number and type of sea turtles caught. The vessel owners also provided economic information on cost and returns. A major objective of the NOAA Fisheries experiment was to determine the potential regulatory options or gear modifications that might be imposed on the fishery to reduce interactions with sea turtles.

This study presents an analysis of the potential ramifications on technical efficiency of requiring fishing operations to adopt alternative gear and fishing strategies. That is, although certain types of gear modifications or changes in fishing strategies may reduce interactions with sea turtles, they also may substantially reduce the harvest of desirable species. Alternatively, they may impose or increase technical inefficiency.

Using the experimental data provided by NOAA Fisheries, technical efficiency (TE) is estimated and assessed relative to the reduction in the capture of sea turtles and changes in landings of desirable species, such as sharks, swordfish, and various tuna. Technical efficiency may be defined from either an input or output orientation. When defined from an input orientation, TE is the minimum level of inputs (e.g., days at sea, fuel, and crew) required to produce a given level of outputs (e.g., sharks, tunas, and swordfish). From an output orientation, TE is the maximum potential output that can be produced given the existing level of inputs. There is also a non-orienting concept of TE, which is the combination of the maximum expansion of outputs and contraction of inputs.

In this study, data envelopment analysis (DEA), which is a non-parametric, mathematical programming approach, was used to estimate TE from both an output orientation and a non-orienting framework. The non-orienting framework, however, was modified to allow for the expansion of desirable outputs (e.g., swordfish, sharks, and tunas) and contraction of undesirable outputs (i.e., sea turtles). Based on DEA, TE scores were obtained for each of the potential gear modifications and changes in fishing practices, as considered in the NOAA Fisheries' experiments. Subsequently, estimates for each gear configuration were examined and compared to ascertain the potential ramifications of the gear configurations on the performance of the longline fleet.

The analysis considered three alternative frameworks: (1) an output distance function approach, which allowed estimation of technical efficiency (TE) subject to no changes in input levels (e.g., days at sea, number of hooks, etc.) but allowing for the expansion in the number of sea turtles and desirable species harvested; (2) an output distance function approach, which allowed estimation of technical efficiency (TE) subject to proportional increases in all desirable outputs (i.e., swordfish, tunas, and sharks) and no changes in input levels, but restricted the expansion of sea turtle capture to the maximum observed or existing levels; this was accomplished by imposing a restriction known as a weak subvector disposability; and (3) a directional distance vector approach, which allowed estimation of TE subject to no changes in input levels, but radial increases in desirable outputs and decreases in undesirable outputs. Additional statistical analyses were done using limited dependent variable methods, for example, Probit, Bivariate Probit, and Tobit.

The remainder of the thesis is organized as follows: *Chapter 2* provides background information on various aspects of the research including a brief overview of the history of sea turtle use and conservation, the Pelagic Longline Fishery, and Data envelopment analysis; *Chapter 3* discusses the research methodology and data used to assess the ramifications of different gear modifications designed to reduce the inadvertent capture of sea turtles; *Chapter 4* presents the results obtained in this research and an analysis of the results; and *Chapter 5* provides a summary and conclusions section.

CHAPTER 2. LITERATURE REVIEW

In this chapter, an overview of the Northwest Atlantic, pelagic, longline fishery is presented, along with a discussion on the methodology used to assess technical efficiency in the fishery. In addition, a history of sea turtle use by humans and conservation actions and legislation is provided. Special attention is given to differentiating the concepts of desirable (marketable) and undesirable (non-marketable) outputs, such as sea turtles. Data envelopment analysis (DEA) is introduced and discussed relative to how it is used to estimate and assess technical efficiency of the various potential gear configurations.

2.1 History of Sea Turtle Use

Sea turtles have been utilized by humans throughout history in a variety of ways, including sustenance, ornamentation, drugs, and talismans. This historical pattern of use has had a largely negative impact on sea turtle abundance, extirpation of some populations, and the loss of some unique sea turtle phenomena (Witherington and Frazer, 2002).[1] Sea turtle uses vary by culture and country, as well as the value associated with the species. The eggs, meat, and shell of the sea turtle are highly coveted by many cultures for their subsistence and commercial value. Some cultures base sea turtles value solely on utilitarian purposes, while others, such as the United States, place a value on their existence or indirect consumption.

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[1] For a complete list of direct human consumptive uses, see Parsons (1962), Lutcavage et al. (1997), and Thorbjarnarson et al. (2000) (Witherington and Frazer, 2002).

Incidental interactions of sea turtles and humans result in indirect consumption (Lutcavage et al., 1997; Meylan and Ehrenfeld, 2000).[2] By far, the largest indirect consumption by humans is from fishing activities, which incidentally capture or kill sea turtles. Non-consumptive uses include specimen collection for scientific studies and eco-tourism. A dollar value can be placed on eco-tourism activities, whereas the educational value cannot be assessed. The true value of non-consumption, therefore, is hard to measure. Another value associated with non-consumption of sea turtles is an option value. This value is associated with the anticipated or delayed use of the species. Because this is a future use, the value cannot be fully realized.

Sea turtles are also valued for their mere existence, which means people derive benefits from just knowing that sea turtles exist. This can be measured by assessing people's willingness to pay to preserve the species. This value can include the bequest, intrinsic, ethical, moral, social, and ecological value. For a complete explanation of these values, see Kramer and Mercer (1997) and Larson (1993).

2.2 History of Sea Turtle Conservation and Legislation

The benefits derived from the non-consumptive and non-use value stimulated the need for a law that would prohibit uses that negatively affect the species. In 1973, the United States passed the Endangered Species Act, which represented a national concern for the decline of many species. This act is one of the most comprehensive wildlife conservation laws in the world. The main purpose of the act is to conserve "the ecosystems upon which endangered and threatened species depend" and to conserve and recover listed species (United States Fish and Wildlife Service (USFWS), 2002).

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[2] Meylan and Ehrenfeld (2000) provide a compiled list of indirect consumptive uses.

Species are listed on the basis of "the best scientific and commercial data available" (USFWS, 2002). The biological status and threats to the species are the two determinants in listing a species.

Economics cannot be a factor in the listing or de-listing of a species. As part of the Endangered Species Act, all federal agencies must ensure that their actions do not jeopardize the continued existence of the species. Under the Endangered Species Act, the FWS and NOAA Fisheries are responsible for enforcing this law, but all other agencies must ensure that their actions, including authorization and funding, will not jeopardize the species. If an agency's proposed actions are seen as a threat to the existence of a species, FSW or NOAA Fisheries must issue a "biological opinion" offering "reasonable and prudent alternatives" about how the proposed action could be modified to avoid jeopardy to listed species (USFWS, 2002).

The Endangered Species Act is not the only law that protects declining populations of rare species and their habitats. The Lacey Act makes it a federal crime for any person to import, export, transport, sell, receive, acquire, possess, or purchase a species in violation of any Federal, State, foreign, or Indian tribal law, treaty, or regulation (USFWS, 2002).

There is a long history of managing the reduction of sea turtle bycatch. Under the Endangered Species Act, to take means "to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or attempt to engage in any such conduct." Fishing activities incidentally take several protected species (e.g. sea turtles), and thus, negatively affect populations. Because of this, NOAA Fisheries must issue a biological opinion, which suggests reasonable and prudent alternatives for reducing sea turtle takes. Many regulations have been passed specific to fisheries to reduce sea turtle bycatch. The U.S. shrimp fishery is most known for its sea turtle bycatch reduction management. Turtle excluder devices (TEDs) were one alternative suggested in a biological opinion. By law, all U.S. shrimp trawl-harvesting vessels are required to install and use this device. Other fisheries that have been regulated for sea turtle bycatch include the gill net, pound net, groundfish, scallop, and longline fisheries (Meylan, and Ehrenfeld, 2000; Lutcavage et al., 1997).

2.3 Overview of the Longline Fishery

Pelagic longlining became a prominent method of harvesting pelagic fish in the North Atlantic in the 1960s (Crowder and Meyers, 2001). It has expanded rapidly since the 1992 ban on pelagic drift nets (Crowder and Meyers, 2001). Pelagic longlines are free-floating gear used in open waters (Crowder and Meyers, 2001). The Northwest Atlantic, pelagic, longline fishery is a multi-species fishery that can switch gear style, and make subtle changes to the gear configuration to target the best available economic opportunity for each individual trip.

Longlines primarily target swordfish with a secondary target of tuna. The gear is composed of many different parts (Figures 1 and 2).

Figure 1. Typical longline gear configuration

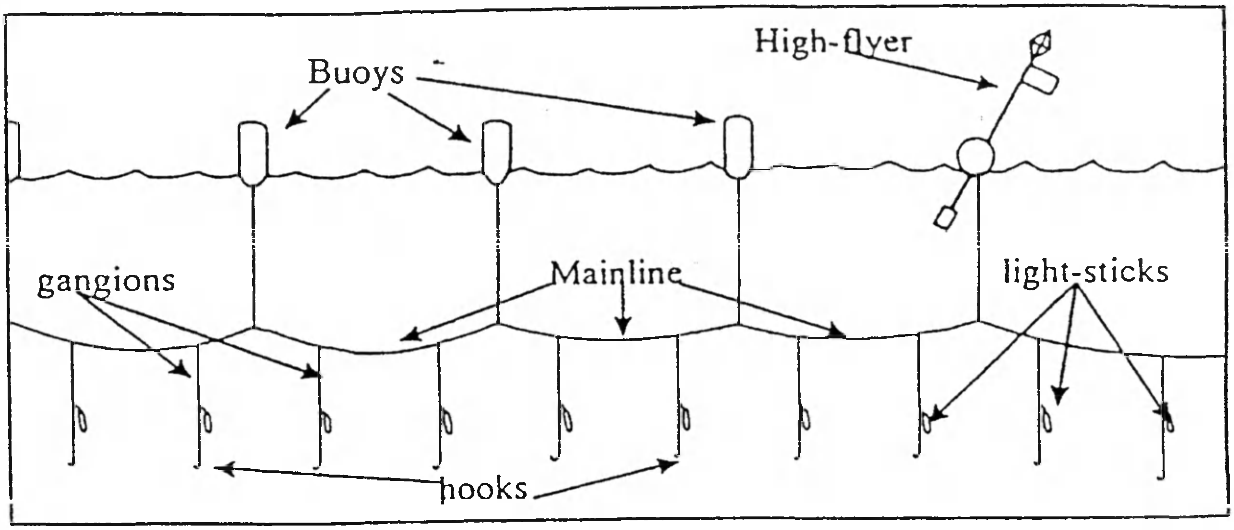
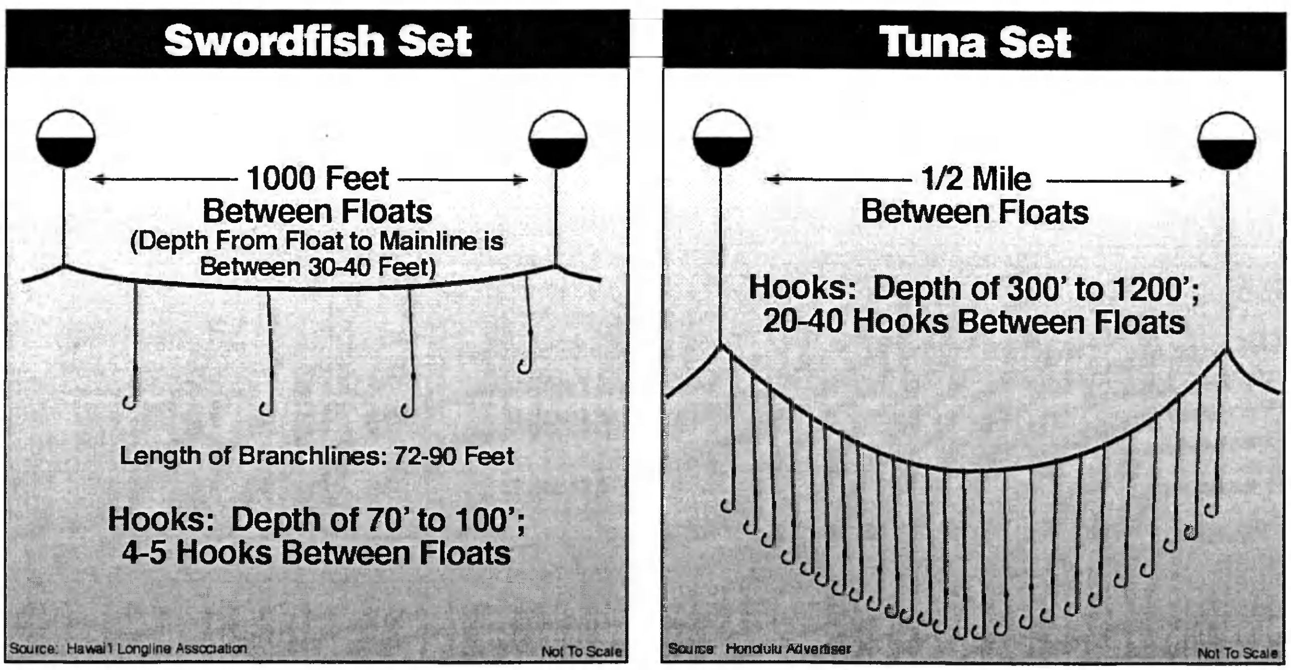


Figure 2. Set characteristics for Swordfish and Tuna directed longline gear. (Hoey and Moore, 1999)



The mainline can be 20 to 40 miles in length, and is normally set to a depth based on ocean currents and conditions and the length of the floatline. The floatline is connected to the mainline and buoys. Then, a leader to the mainline connects each hook. Some fishermen use lightsticks to attract swordfish; however, they also attract many other non-target species. Longline fishing, particularly during the full moon periods, often attracts and hooks non-target species and endangered species, such as sea turtles (NMFS, 2001a). Since the vessel operators often attempt to catch large quantities of profitable species, they may also capture non-target and endangered species, along with the profitable or marketable species. In fisheries, these non-marketable or prohibited or endangered species are termed bycatch. Economically, these non-target and endangered species are considered undesirable output.

2.4 Undesirable Output –Sea Turtles

Bycatch or the incidental harvest of non-marketable or protected species is a significant issue currently facing fisheries management. Under the Magnuson-Stevens Fishery Conservation and Management Act (MSA), bycatch is defined as fish that are harvested in a fishery, but are not sold or kept for personal use, and includes economic discards and regulatory discards. Bycatch does not include fish released alive under a recreational catch and release fishery management plan. The Magnuson-Stevens Act requires NMFS to minimize bycatch and bycatch mortality, to the extent practicable (NMFS, 2004).

Even though turtles are rarely hooked and killed, some species are considered vulnerable to local or regional extinction (e.g., Pacific and some Atlantic leatherbacks). The incidental take and mortality of sea turtles may have negative socio-economic impacts on the fishing industry (Bache et al., 2000), and therefore, is an undesirable output of the fishery. Alternatively, sea turtles, although potentially marketable, cannot be marketed under the Endangered Species Act (ESA). They are protected, and their capture is regulated. The capture of sea turtles, however, is not without cost. Fishermen lose bait and gear to turtles, and they must expend labor time to safely remove the hook or untangle the line from turtles and return them to the water. As such, sea turtles represent an undesirable output for the fishers.

Based on logbook data records from 1992 to1995, 316 leatherback and 334 loggerhead sea turtles were, on average, caught annually in the U.S. Northwest Atlantic, pelagic, longline fishery (Witzell, 1999). NMFS (2001b) estimates that between 293 and 2,439 loggerhead sea turtles and between 308 and 1,054 leatherback turtles were taken annually by the U.S. longliners who fish in the northwestern Atlantic between 1992 and 1999.

2.5 Technical Efficiency and Undesirable Outputs

A major concern of fisheries management and regulation is how regulations affect technical efficiency of fishing vessels. At the federal level, the costs and benefits of alternative regulations must be fully assessed. Does a particular regulation reduce or maintain technical efficiency? Alternatively, what might be the costs of regulations designed to prevent the capture of sea turtles or production of undesirable outputs in commercial fisheries?

Despite an extensive body of literature on assessing technical efficiency in the presence of undesirable outputs, many analyses of technical efficiency in fisheries typically ignore undesirable outputs. Alternatively, changes in desirable outputs are examined without regard to whether or not there is an increase or decrease in undesirable outputs.

There are numerous quantitative approaches for estimating technical efficiency. Most analyses of TE, however, have been done for the more traditional industries, such as banking, insurance, hospital, healthcare, logging, railroad, airlines, and electrical plants (Coelli et al. (1996), Lebel (1996), Färe (2001); for applications in fisheries, see Kirkley and DuPaul (1994), Kirkley et al. (1995, 1998), Kirkley and Squires (1999), Kirkley et al. (2001), Pascoe and Coglan (2000, 2002), Pascoe et al. (2003). In the case of fisheries management, estimates of technical efficiency have been widely used to determine modifications to fishing gear (Dupaul et al. 1989). Typically, technical efficiency for different types of gear, along with selectivity, are estimated and compared, and the estimates are used to determine appropriate gear regulations.

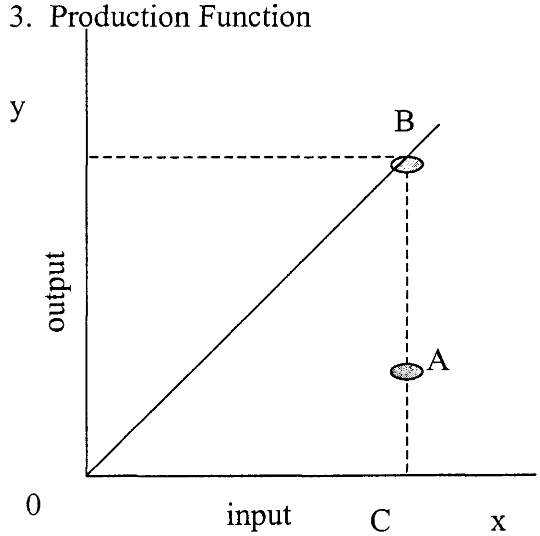
In most analyses of TE, no attempt is made to explicitly recognize or incorporate how TE might change if producers had to adjust production to reduce the level of undesirable outputs. Frameworks or methods for estimating and assessing TE in the presence of undesirable outputs are presented in Reinhart et al. (2000), Chung and Färe (1995), and Färe and Grosskopf (2004). These frameworks allow for either the contraction or maintenance of existing levels of undesirable outputs while simultaneously allowing for the expansion of desirable outputs.

2.6 Technical Efficiency

Farrell (1957) stated that efficiency was a measure that has both a practical and theoretical importance (Ali and Seiford, 1993). Technical efficiency measurement generally involves comparing a decision-making unit's (DMU's) production plan to a production plan that lies on the efficient production frontier, or isoquant (Fried et al. (1993), Färe et al. (1994), Charnes et al. (1994)). Alternatively, an existing production plan is compared to a "best-practice" production plan. As an example, the measurement of efficiency can be used to test certain hypotheses and also aid in economic policy to improve the productivity of a firm (Ali and Seiford, 1993).

To illustrate how technical efficiency is defined, consider a producer who uses a single input (x) to produce a single output (y) (Figure 3). The line in Figure 3 represents a production frontier, which characterizes the relationship between the input and the maximum possible output. The production frontier represents the maximum output attainable from each level of input. All firms that operate on this production frontier are said to be technically efficient. All firms operating underneath the frontier are inefficient. The interior point A represents an inefficient point whereas point B is efficient. Firm A is inefficient because it could increase its level of output associated with point B without requiring a higher input level (Coelli et al., 1998).

Figure 3. Production Function



Technical efficiency can be measured from several perspectives. The more common perspectives, however, are the output and input orientations (Lovell, 1993). Technical efficiency from an input orientation considers how close the minimum input bundle required to produce a given output is to the actual input bundle used to produce that output level. For example, how much could producer A in Figure 3 reduce input usage and still produce the same level of output. From an output orientation, TE indicates how close is actual output to the frontier level of output using an existing level of inputs. For example in Figure 3, how close is A to B. A third concept, and one which is being increasingly used to assess technical efficiency, is a non-orienting measure, which considers the maximum expansion in outputs and contraction in inputs.

In this study, the measure and assessment of efficiency is restricted to the Farrell (1957) output orientation and the non-orienting measure. The Farrell output-oriented efficiency measure (see Fare, Grosskopf, and Lovell, 1985, 1994) can be defined as follows. In Figure 3, the distance defined by AB represents technical inefficiency, which is the amount by which outputs can be expanded while holding the current input level constant. A measure of technical efficiency is then the inverse of the ratio CA/CB or CB/CA. Subtracting 1.0 from the ratio indicates the amount or proportion by which outputs may be expanded relative to their observed value (Fare et al. 1985, 1994; Kirkley et al., 1999).

Technical efficiency can be estimated using several methods. First, there is the parametric approach, which estimates TE from a deterministic full frontier function and assuming an error distribution for TE. An alternative approach is the stochastic production function (SPF), which introduces two error terms –a normal and an error term for TE; the error term for TE follows one of three distributions-half normal, exponential, or truncated normal. A third approach is the non-parametric linear programming approach, which yields a full frontier with multiple orientations (output, input, and directional) (Kirkley et al., 1999). Parametric methods use a well-behaved neoclassical production function to measure predicted performances (Triantis, 1990). Some of the parametric approaches have the capability of dealing with noise and outliers in the data; The SPF approach, however, is more difficult to employ when using multiple outputs. The non-parametric method will be used in the analysis due to its ability to accommodate multiple outputs. The following section will go into more detail about this approach.

2.7 Non-Parametric Method

In contrast to the parametric approach, whose goal is to optimize a single regression plane through the data, the non-parametric method optimizes on each individual observation with an objective of calculating a discrete piecewise frontier determined by a set of pareto-efficient DMUs. This method requires no functional form assumptions (Coelli et al, 1998). Non-parametric approaches are based on frontiers instead of central tendencies, as is the case for the stochastic frontier, which is also based on a frontier function. These methods can, thus, discover relationships, which could be missed by other methods (Seiford and Thrall, 1990). Measuring technical efficiency using a distance function is a non-parametric method, which can be used to obtain the TE scores for each observation, and will be discussed further in the next section.

2.8 Distance Functions

One non-parametric approach involves the use of a distance function. A distance function permits the calculation of technical efficiency and capacity with no change in fixed inputs. Shepard (1970) introduced an approach to accommodate a multiple-output technology to measure production using a distance function with either an input- or output-orientation. An input-oriented distance function describes the technology in terms of the minimal proportional contraction of the input vector to the technological frontier, given input composition and the observed output vector. On the other hand, an output-oriented approach refers to the maximal proportional expansion of the output vector, given output composition and an input vector.

In order to get an equation for the output distance function, we must first define the output set P(x):

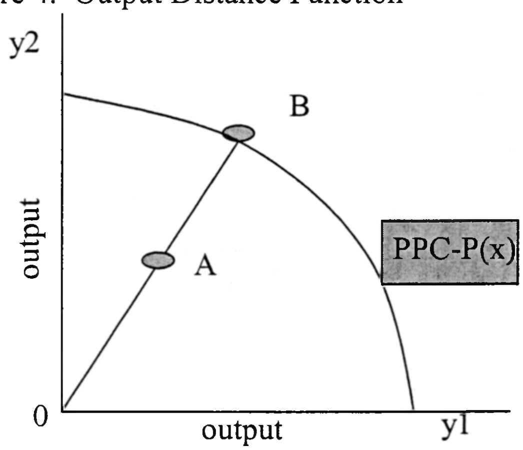
$$P(x) = \{(y_1, y_2) : x \text{ can produce } (y_1, y_2)\}. \quad (2)$$

Coelli et al. (1998) defined an output distance function on an output set P(x) as:

$$D_o(x, y,) = \min\{\delta : (y/\delta) \in P(x)\}. \quad (3)$$

The concept of an output distance function can best be represented in a two-dimensional diagram with an example having one input x and two outputs y_1 and y_2.

Figure 4. Output Distance Function



The production possibility set is represented by P(x). The set is bounded by the production possibility frontier labeled PPC-P(x) and y_1 and y_2 axes. For a firm using some level of input x to produce outputs y1 and y2, the value of the distance function is defined by the point A and is equal to the ratio δ = 0A/0B. 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). When restricted to radial,[3] all points along the PPC-P(x) will have a distance measure of 1.0. All points beneath the frontier will have a value less than one, which is an indicator of inefficiency.

2.9 Directional Distance Function

There are three basic distance measures -- input, output, and directional. In the case of the output-oriented models, the TE was determined by expanding all the outputs proportionally along a radial ray towards the origin from the point representing the firm or DMU to a projected point on the frontier.

A third concept of a distance function is the directional distance vector, which permits outputs (inputs) to be expanded (reduced) by the same proportion. In the non-radial or directional distance function measure of TE, the comparison is done between the points representing the firm or DMU, and a point of the frontier that is not on the radial ray joining the origin and the point (see Figure 5, on the right hand side of the y-axis below). In the case of an output-oriented model, the movement is in a direction so as to increase one or more of the outputs, which is not radial. Figure 5 represents the two models on the same graph. Point A is a DMU, which produces two outputs, one desirable (e.g. swordfish) and one undesirable (e.g. sea turtles). Undesirable outputs are often simultaneously produced with desirable outputs. DMU A is inefficient, as it is not on the frontier. Unlike the earlier measure of TE, 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 and direction. In Figure 5, the directional

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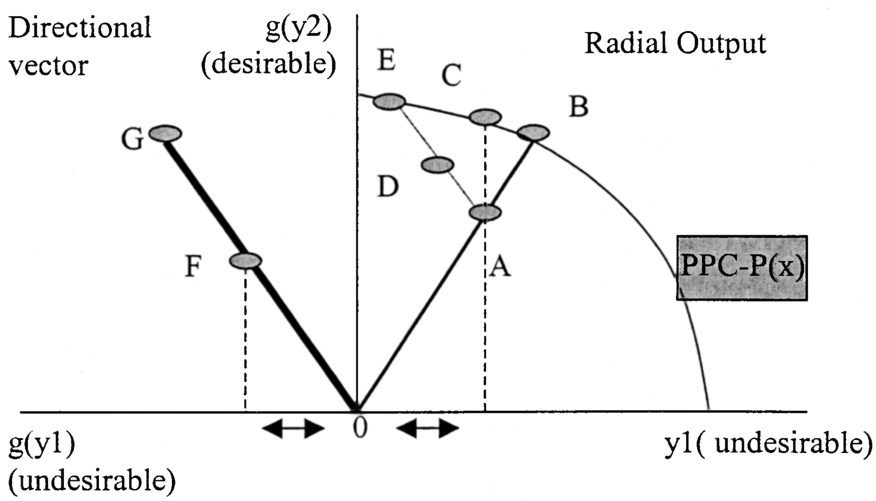
[3] Coelli, T.J. (1997). " A Multi-stage Methodology for the Solution of Orientated DEA Models", *Operational Research Letters*., 23:3-5, 143-149.

vector considers the movement along ADE or AC. There is an expansion in desirable outputs and a reduction in undesirable outputs.

Like the distance function, the directional distance vector is a functional representation of the technology. The directional distance vector differs in that it seeks to increase the desirable outputs while simultaneously decreasing the undesired output. This is incorporated in the measure of TE in such a way that both the outputs change by the same proportion but in different directions where ADE = 0F.

Figure 5. Illustration of a directional and radial distance function.



The point G is the coordinate point (gy1, gy2); g(y1) and g(y2) represented directions in the observed values of y1 and y2. The line ADE is referred to as beta and is less than or equal to one. If the ratio of the directional vector is 0G/0F = 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(y1).

Zofio and Prieto (2001) assessed the environmental performance of a set of producers by grading their ability to produce "the largest equi-proportional increase in the desirable output and decrease in the undesirable output." The authors assumed that the firms k = {1,...,K} used a set of inputs x, to produce outputs y, out of which p were desirable and q were undesirable.

$$X = (x_1, x_2, \ldots, x^m) \in R^m \quad (3)$$
$$p = (p_1, p_2, \ldots, p^n) \in R^n$$
$$q = (q1, q_2, \ldots, q^n) \in R^r$$
$$Y = (y_1, y_2) \in R^{+N}$$

The reference technology is modeled as follows:

$$R: R^m \rightarrow R\,(x)\,R^{n+R} \quad (4)$$

The equation for a directional distance function can be defined as:

$$D^H\,(p,q) = \{\theta^H : (p\theta^H, q/\theta^H) \text{ set } R(x)\}. \quad (5)$$

All three orientations of the distance function are a measure of performance and are evaluated to determine the score of the firm. The TE score is given as the inverse of the distance function. As with the input and output function a score of 1.0 means the firm is efficient.

2.10 Data Envelopment Analysis

DEA is defined by Giokas (1997) as follows:
"DEA measures relative efficiency [of DMUs] by estimating an empirical production function which represents the highest values of outputs/benefits that could be generated by inputs/resources as given by a range of observed input/output measures during a common time period."

Charnes, Cooper and Rhodes (1978), first put forward Data Envelopment Analysis (DEA), often referred to as frontier analysis. Charnes, Cooper, and Rhodes extended Farrell's (1957) work in the measurement of technical efficiency and developed Data Envelopment Analysis (DEA). The DEA methodology allows the relaxation and the enhancement of some of Farrell's (1957) assumptions for the production function and the production technology.

It is a mathematical programming technique for assessing the performance or technical efficiency of a decision making unit's (DMUs) existing technology relative to an ideal, best practice, or frontier technology (Charnes et al., Coelli et al., 1998). DEA has been applied in many fields, including banking, insurance, hospitals, logging, military, schools, and non-profit organizations. Many researchers in fisheries management, such as Kirkley et al. (2001), used DEA to assess capacity and capacity utilization.

Data Envelopment Analysis (DEA) is non-parametric and non-statistical. Farrell's (1957) original work provides the original ideas behind the use of DEA to assess technical efficiency (Kirkley et al., 1999). The DEA methodology can be used to assess a wide array of efficiency concerns (e.g., profit efficiency, revenue efficiency, cost efficiency, scale efficiency, congestion in either inputs or outputs, allocative efficiency, and of course, technical efficiency).

Data Envelopment Analysis (DEA) traces out the best production frontier. Standard radial DEA models tend to identify more representative efficient points in terms of input and output mixes. DEA need not be restricted to radial expansion. According to Coelli (1998), radial efficiency measures are unit invariant; therefore, changing the unit of measurement does not affect the value of the efficiency score. Non- radial measures, however, are not unit invariant. This does not restrict DEA to radial expansion. For further information on radial and non-radial efficiency see Coelli (1997) and Russell (1985).

One advantage of DEA is that it allows analysis of multiple-input and multiple-output production technologies without requiring price or cost data. Also, the various input and output factors need not have the same measurement units (*i.e.,* DEA is invariant to scaling of variables). This is important in public sector organizations including fisheries where financial and cost data are often unavailable for all factors.

The DEA methodology helps to identify inefficient DMUs as well as the sources and amounts of inefficiency of inputs and/or outputs. The DEA formulation can incorporate both input-reducing and output-expanding orientations, as well as constant and variable returns to scale.

2.11 Returns to scale

Returns to scale are characteristics of the surface of the graph. For observations interior to the graph, returns to scale is measured at a corresponding boundary point (Färe et al., 1994). A constant return to scale implies that the production technology is such that, an increase in all the inputs by some proportion results in an increase in the outputs by the same proportion. Variable returns to scale results in a non-proportional increase or decrease in the outputs. There are three types of returns to scale and the difference between the input-oriented and output-oriented measures, constant returns to scale (CRS), and variable returns to scale (VRS), (increase and decreasing returns to scale) are illustrated in Figures 6, 7, 8, and 9.

Figure 6. Constant Returns to Scale (CRS)

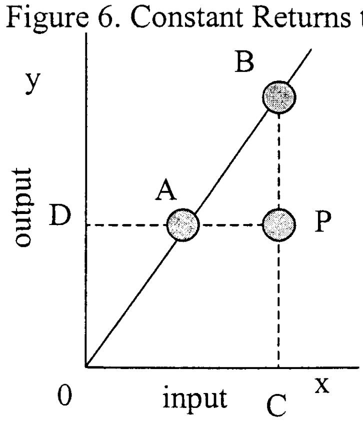


Figure 7. Decreasing Returns to Scale (DRS)

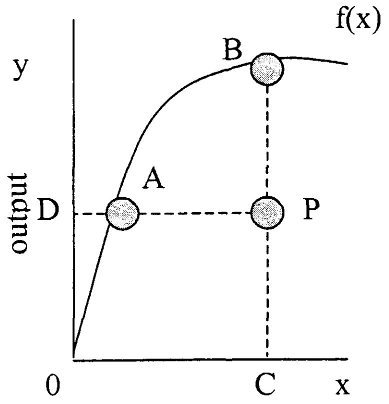


Figure 8. Increasing Returns to Scale (IRS)

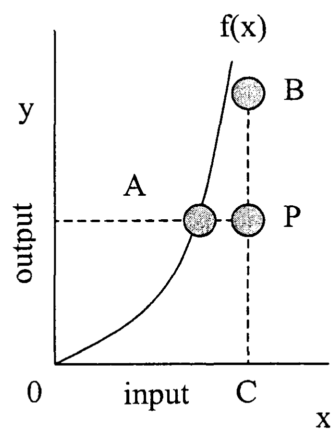
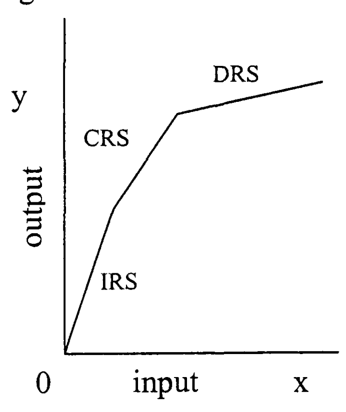


Figure 9. Variable Returns to Scale



In Figure 6, a production of a single output from a single input is illustrated graphically. The function f(x) is a straight line and has a single slope. Therefore, for every unit increase in the input that goes into the process, the output that is produced increases by a constant proportional quantity and represents constant returns to scale. In Figure 7, the function has a decreasing slope, where a decrease in input results in a non-proportional decrease in output. This is termed variable (decreasing) return to scale. In the figure 8, an increase in the input will result in an increase in the output by more than the proportional quantity represents variable (increasing) returns to scale. Figure 9, illustrated variable returns to scale (increasing, constant, and decreasing).

Constant returns to scale is viewed as the most unconstrained because variable returns require the imposition of another constraint (Kirkley et al., 1999). The assumption of CRS is only correct if all firms are operating at the optimum scale. There are various factors that affect the return to scale including imperfect competition, financial constraints, etc. The use of CRS when firms are not operating at the optimal level will lead to a measure of TE that is confounded by scale efficiencies (SE) (Coelli et al., 1998). In this study, constant and variable returns to scale are used in calculating technical efficiency scores.

2.12 Disposability of outputs

Disposability of outputs is the ability with which an output can be disposed of holding the remaining inputs constant while at the same time the resulting output set still remains part of the production possibility set. Färe et al. (1994) referred to disposability as the ability to stockpile or dispose of unwanted commodities. Thus, a private cost distinguishes two different type of disposability. Strong disposability is the ability to dispose of unwanted commodities with no private cost, and weak disposability is the ability to dispose of an unwanted commodity at a positive private cost. That is, there is a cost associated with the disposability of an output (e.g., reduction of sea turtles). Thus, weak disposability was considered for the efficiency measure for those longline sets, which captured sea turtles.

2.13 Input and output Orientation

Two ways to measure technical efficiency are an output orientation and an input orientation. Output orientation indicates the maximum potential expansion in outputs given all input levels are held constant. Input orientation indicates the maximum potential level by which all inputs may be decreased with a constant level of outputs. The output-expanding and input-reducing orientation is analogous and derived similarly. However, different results are obtained from the two orientations under the variable returns to scale assumption (Färe and Lovell (1978)). For example, a TE value of 1.5 suggests that outputs can be expanded by 50 percent with no change in the current input level. A TE score of 1.0 indicates technical efficiency with both output and input orientation.

2.14 Summary and Justification of the use of DEA

Since its original development, DEA has expanded considerably. Seiford (1996) has reported more than 800 references on the subject. Various applications of DEA to public organizations such as schools, banks, hospitals, armed services, shops, and local authority departments have been published. In this review, the foundations of the DEA framework, and the important formulations (output orientation) are presented.

DEA has two main advantages, which make it more appropriate for use in this study. The first advantage being that it does not impose any specific functional form on the underlying production function. The second advantage being that it does not impose a prior weighting scheme in order to combine inputs and outputs into aggregates. DEA is valuable in its ability to deal with inputs and outputs that do not allow for weighting, such as non-marketable inputs or outputs. Some fishing practices and components of gear are unable to be aggregated and, therefore, this method is most practical.

In this study, DEA is used to estimate an efficiency frontier of the longline sets and calculate the deviations from that frontier for inefficient sets. The results or efficiency scores are then used to projection the combinations of inputs and outputs that are efficient. From those projections, an efficient gear configuration is created. One of the main objectives of this study is to recommend a gear configuration that is efficient at reducing sea turtle capture without reducing target catch. This analysis helps to fulfill that objective. These factors combined justify the use of DEA for this project.

CHAPTER 3. METHODOLOGY

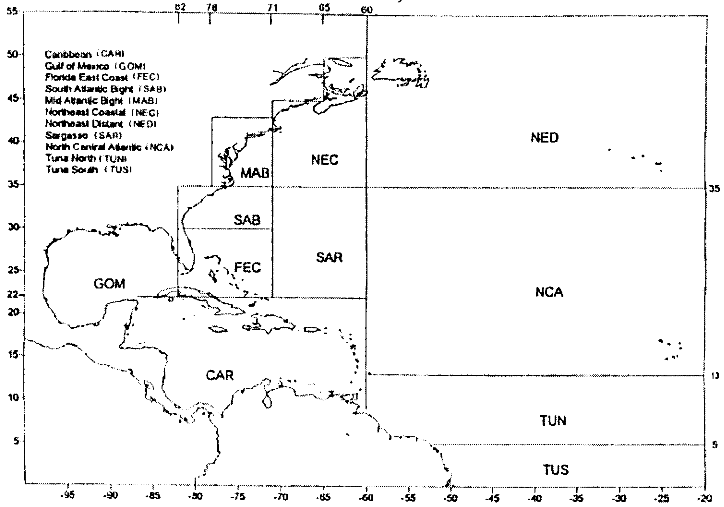
In this Chapter, the data and models used in the analysis are discussed. This chapter is divided into three sections. First the data used in the analysis is described; second, the inputs and outputs used to estimate technical efficiency are listed; third, the model used to analyze the efficiency of the observed sets is presented; and fourth, the model used to assess the probability of turtle capture and landings relative to the different gear configurations are discussed.

3.1 Data

For the purpose of this study, data were extracted from the Pelagic Longline Observer Logbook database. The data were obtained from results from a three-year study conducted by the National Marine Fisheries Service (Southeast Fisheries Science Center). The National Marine Fisheries Service conducted scientific research from 2001 through 2003 in the Northwest Atlantic under authorization of the Endangered Species Act (ESA) Section 10 Permit #1324 to develop new technologies and fishing practices to reduce the incidental take and mortality of threatened and endangered sea turtle species by the pelagic longlining gear (Watson et al., 2001).

In 2001, eight vessels were contracted by NMFS to provide platforms for research in the Northeast Distant Waters (NED) statistical reporting area (Figure 10) to provide data on all aspects of gear and gear configuration between September and November (Watson et al., 2001).

Figure 10. Pelagic Longline Fishing Areas
Source: Cramer and Adams, 2000.



The NED, a statistical reporting area in the Northwest Atlantic was closed to pelagic longlining, except for the vessels participating in the experiment. In 2002, 13 vessels participated in the experiment. In 2003, only 11 vessels participated. Each vessel was required to carry NMFS observers, and fish their gear in a specified, pre-determined manner designed to test one or more variables affecting sea turtle bycatch. Seven different treatment hooks were used throughout the experiment (Table 1).

Table 1. Description of Treatment Hooks

1	9/0 J-style hook with a 25-30 degree off set in which squid bait was used. This was referenced as the "**control hook.**" The standard for the fishery.
2	18/0 circle hook with 0 degree offset used with squid bait.
3	18/0 circle hook with 10 degree offset used with mackerel bait
4	20/0 circle hook with 10 degree offset used with mackerel bait.
5	10/0 J-style tuna hook with 0 degree offset used with mackerel bait.
6	16/0 circle hook with 10 degree offset used with squid bait.
7	18/0 circle hook with 0 degree offset used with squid bait.

Data were collected on various aspects of gear including hook type, mainline length, haul order, soak time, etc. All data were collected and entered into the Pelagic Longline Observer Logbook maintained by the Southeast Science Center (Watson et al., 2003).

Compilation of the database was the first step in meeting the study objectives. The data collected from the NED experiment was merged into a single database. Data collected in 2001 only provided information on two treatments, the standard 9/0 j-hook with a 25-35 degree offset and a larger 10/0 j-hook with no offset. Technical efficiency was estimated using DEA. A subset of the data consisting of 1,906 observations was transferred into ONFRONT, a non-parametric math programming software package that was used to estimate the efficiency scores.

3.2 Inputs and Outputs

The decision-making units (DMUs) or observations for this study were the set level observations recorded in the three-year period.[4] Each observation corresponded to a specific gear configuration. The inputs for the analyses included, vessel horsepower (vhp), vessel length, soak duration (sod), haul duration (hd), set duration denoted (sd), gangion distance (gd), mainline length (ml), hook type (ht), number of hooks (hn), number of lightsticks (ln), number of floats (fn), and number of radio beacons (rn) used per set (Table 2).

The outputs used in the analyses were separated into two categories, desired and undesired. The desirable outputs include dressed weights totaled per set of swordfish (sw), Albacore tuna (alb), Bigeye tuna (bet), Yellowfin tuna (yft), Bluefin tuna (bft), and 13 species of sharks (shk), which were aggregated (Table 3). There were two undesirable outputs -- Loggerhead (tlg) and Leatherback (tlb) sea turtles (Table 3). Undesirable outputs were on a count basis and totaled for each set.

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[4] Sets consisted of alternating treatment hooks and therefore DMUs are the set characteristics that are associated with that treatment hook. This means that for a particular set there are two DMUs, one for each treatment hook.

Table 2. Description of Inputs

vessel horsepower (vhp)	total horsepower for the vessels engine
vessel length (vl)	vessel length measured from bow to stern in feet
soak duration (sod)	amount of time to the nearest tenth of an hour, that all gear was in the water
haul duration (hd)	amount of time to the nearest tenth of an hour, it takes to haul in all of the gear for a set
set duration (sd)	amount of time to the nearest tenth of an hour, it takes to set out all of the gear for a set
gangion distance (gd)	the distance in whole feet, between gangions
mainline length (ml)	length to the nearest tenth of a nautical mile, of the mainline for the set
number of hooks (hn)	number of hooks set for the set
number of lightsticks (ln)	number of lightsticks set for the set
number of floats (fn)	number of float set for the set
number of radio beacons (rn)	number of ration beacon set for the set

Table 3. Description of Outputs

Swordfish (swf)	total dressed weight of all swordfish harvest for the set
Albacore tuna (alb)	total dressed weight of all albacore harvested for the set
Bigeye tuna (bet)	total dressed weight of all bigeye harvested for the set
Yellowfin tuna (yft)	total dressed weight of all yellowfin harvested for the set
Bluefin tuna (bft)	total dressed weight of all bluefin harvested for the set
Sharks (shk)	total dressed weight of all sharks harvested for the set
Loggerhead (tlg)	total number of loggerheads caught for the set
Leatherback (tlb)	total number of leatherbacks caught for the set

3.3 Data Envelopment Analysis

Data Envelopment Analysis (DEA) was used to estimate technical efficiency (TE) of each gear configuration at the set level. Each set contained two types of hooks, treatment 1 being the control and the other a specific treatment, which included different size hooks (Table 1).

A TE score was calculated for each DMU. The TE score measured the performance of the individual gear configurations for each treatment hook for all sets conducted during the NED experiment.

Technical efficiency scores were calculated using three DEA approaches in two stages: in stage I, technical efficiency, without consideration of reducing the take of sea turtles, was estimated; and in stage II, technical efficiency, explicitly considering the reduction in the take of sea turtles, was estimated and analyzed. TE was used to assess the influence of different gear components on the productivity of catching target species as well as reducing the incidence of sea turtle takes.

3.3.1 Stage I - Standard output orientation

Stage 1 involved the use of an output distance vector approach with different returns to scale.[5] In stage one, TE was calculated using two models, constant return to scale and variable return to scale. See sections 2.7 and 2.11 and figures 5, 7, 8, and 9 for a review of output distance functions and returns to scale.

3.2.2 Variable Return to Scale[6]

Färe et al. (1994) defined the output-oriented VRS model as:

$$\begin{aligned}
&\max_{\theta,z} \theta \\
&\text{s.t.}\,\theta u_{jm} \le \sum_{j=1}^{J} z_j u_{jm}, m = 1,2\ldots,M \\
&\sum_{j=1}^{J} z_j x_{jn} \le x_{jn}, n = 1,2,\ldots,N \\
&z_j \ge 0, j = 1,2,\ldots,J \\
&\sum_{j=1}^{J} z_j = 1
\end{aligned} \tag{6}$$

where m and M represent the output of the *j*th firm and the output levels of all firms; n and N represent the input of the *j*th firm and inputs of all firms; θ is a scalar and z denotes the intensity variables. The value of θ is the measure of technical efficiency such that $1 \le TE_o \le \infty$. The value of θ is the proportional expansion in outputs that could be achieved

[5] Returns to scale are changes in production that occurs when all resources are proportionately increased in the long run.
[6] Only those sets with sea turtle captured were estimated using the VRS model.

by the *i*th firm with input levels held constant and the firm operating efficiently (Kirkley et al., 1999).

3.3.1.1 Constant Returns to Scale (CRS)[7]

Färe et al (1994) defined the constant returns to scale (CRS) model as

$$\max_{\theta,z} \theta$$
$$\text{s.t.}\ \theta u_{jm} \le \sum_{j=1}^{J} z_j u_{jm}, m = 1,2\ldots, M$$
$$\sum_{j=1}^{J} z_j x_{jn} \le x_{jn}, n = 1,2,\ldots, N \qquad (7)$$
$$z_j \ge 0, j = 1,2,\ldots, J$$

The two models CRS and VRS, only differ by one constraint; that is the convexity constraint ($\sum_{j=1}^{J} z_j = 1$), which is not imposed in the constant returns to scale model. Therefore, the gear configuration is benchmarked against other gear configurations, which are substantially larger or smaller than it. The value of the intensity variables (z) sum to a value greater than or less than one (Coelli et al., 1998). The more constrained the model, the less the chance of an observation being efficient. According to Pascoe et al. (2003), under the CRS model, inputs and outputs change by the same proportion, whereas, with the VRS model the production technology may have varying returns to scale. CRS is only correct when all firms are operating at optimum scale (Coelli, 1998).[8] Another notable difference between the two models is that the CRS model is typically assumed relative to a long-run optimum.

[7] This model was conducted twice. Model 1 in the results indicates the use of all sets while model 2 indicates the separation of sets with turtles and sets without turtles.
[8] This is viewed as the long-run competitive equilibrium.

3.3.2 Stage II - Output-orientated with weak subvector disposability

In Stage 2, TE was estimated in the presence of undesirable outputs using a directional vector. The DEA model imposes weak disposability and null-jointness. Weak disposability means that a proportional contraction of desirable and undesirable outputs is feasible. Weak disposability penalizes undesirable outputs differently from the desired outputs in such a way that when an increase in the desirable outputs is desired, a simultaneous reduction in the undesirable outputs is modeled. According to Färe et al, (2004), null-jointness suggests that if desirable inputs are produced, then undesirable outputs are also produced.

For the second stage, directional vectors were used to calculate TE scores, which allows for the scaling back of the undesirable outputs (e.g., sea turtles). Desirable and undesirable inputs are jointly produced. This means that reduction of undesirable outputs will have a private cost.[9] Undesirable inputs are denoted by $y1 \in R^M$, and undesirable outputs by $y2 \in R^I$, and inputs by $\mathbf{x} \in R^N$; the technology of the output set P(x) can be defined as follows:

$$P(x) = \{(y1, y2): x \text{ can produce } (y1, y2)\}. \quad (8)$$

Undesirable outputs are considered different from the desirable outputs in such a way that when an increase in the desirable outputs is desired, a simultaneous reduction in the undesirable outputs is modeled, and this restricts desirable outputs from increasing as much as they would with no restrictions imposed on the capture of sea turtles.

Let us assume that a set of DMUs j = {1,…,J) use a set of inputs x to produce y outputs of which y1 is desirable and y2 is undesirable.

$X = (x1, x2, \ldots, xm) \in R^m$
$Y1 = (y1_1, y1_2, \ldots, y1_n) \in R^n$
$Y2 = (y2_1, y2_2, \ldots, y2_n) \in R^r$
$Y = (y1, y2) \in R^{+N}$ (9)

The subset y1 and y2 are mutually exclusive and collectively exhaustive of the set y. The Technology set T consists of all vectors (x, y) i.e.,

T= {(x,y): x can produce y = (y1,y2)

Assumptions of the set T:

- the set is closed
- the set of inputs x and the set of desirable outputs y1 are strongly or freely disposable.
- Weak disposability of the undesirable output[10]
- Null-jointness[11]
  If (x, y) is a set of T where y = (y1,y2) and y1=0 then y2=0

For additional information on the weak subvector disposability, which requires equality constraints, see Färe, Grosskopf, and Lovell (1994).

3.4 Probit and Bivariate Probit Model

A Probit and Bivariate Probit model were specified and estimated to assess the probability of capturing a sea turtle given the treatments and various gear characteristics. This was done to identify the effects that treatments and various gear components would have on the likelihood of capture of the two common species of sea turtle captured by the longlining vessels in the North Atlantic Distance Waters (NED).

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[9] 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 longlining vessel the private cost would be fuel, oil, maintenance, depreciation, fishing gear, and even the boat time experienced by the captain and crew.
[10] Weak disposability means that both desirable and the undesirable can be disposed proportionally. It also implies that it is not possible to reduce only the undesirable outputs holding the inputs and the desirable outputs constant.
[11] Null-jointness means that it is technically impossible to produce desirable outputs without producing any undesirable outputs. The only way to have zero undesirable outputs is to stop fishing the desirable outputs.

A Probit model is defined as a model for binary responses where the response probability is the standard normal cumulative distribution function (cdf) evaluated at a linear function of the explanatory variables (Wooldridge, 2003). This model is used to estimate the probability of a specific treatment capturing a sea turtle. In a binary response model, the response probability is defined as

$$P(y = 1|x) = P(y = 1|x_1, x_2, \ldots x_k), \tag{10}$$

where $\boldsymbol{x}$ denotes the full set of explanatory variables.

For example, when y is the chance a set or treatment hook will capture a sea turtle, $\boldsymbol{x}$ might contain various individual characteristics such as vessel horsepower, mainline length, haul duration, and other factors that affect the capture of a sea turtle. The following equation taken from Wooldridge (2003) is a class of binary response models that are used to estimate a response probability that is between zero and one.

$$P(y = 1|x) = G(\beta_o, + \beta_1 x_1 + \ldots \beta_k x_k) = G(\beta_o + \mathbf{x}\boldsymbol{\beta}), \tag{11}$$

where G <G(z) <1, for all real number z.

A standard Probit model is defined as follows:

$$G(z) = \Phi(z) \equiv \int_{-\infty}^{z} \Phi \quad \phi(v)dv, \tag{12}$$

where G is the standard normal (cdf) expressed as an integral , and $\Phi(z)$ is the standard normal density defined as

$$\Phi(z) = (2\Pi)^{-1/2} \exp(-z^2/2). \tag{13}$$

This model is a nonlinear model and must be estimated using maximum likelihood estimation. The Probit model was used to estimate the strength and effect of each experimental treatment and selected gear components on the likelihood of a sea turtle being captured during a set.

A Bivariate Probit is similar to the standard Probit model but recognizes residual correlation across equations, and the fact that there are two possible set of outcomes (e.g the capture of two species of sea turtle). The Bivariate refers to the idea that two sets of outcomes are interrelated such that

$$Y^*_{1i} = X_{1i}\beta_1 + u_{1i}$$
$$Y_{1i} = 1 \text{ if } Y^*_{1i} > 0$$
$$Y_{1i} = 0 \text{ otherwise} \tag{14}$$

$$Y^*_{2i} = X_{2i}\beta_2 + u_{2i}$$
$$Y_{2i} = 1 \text{ if } Y^*_{2i} > 0$$
$$Y_{2i} = 0 \text{ otherwise.} \tag{15}$$

The model allows the errors in the two Probit models to be correlated, reflecting the fact that there are likely to be unobserved factors influencing the likelihood of a gear configuration capturing a sea turtle over another. Testing whether or not the coefficients are equal across the equations will indicate whether different characteristics are associated with the capture of a sea turtle versus not capturing a turtle.

3.5 Tobit Model

A Tobit model was used to further investigate and determine why some sets were efficient while others were not. The efficiency scores estimated using the directional distance function model were regressed against explanatory variables, which included the experimental treatments and various gear components. The Tobit model was used to identify key factors or gear configurations, which are inefficient and relative to the catch of each target species. This information can be used to suggest changes in hook type or gear design that could increase efficiency of the sets.

A Tobit model is often referred to as a censored regression model and is defined by Wooldridge (2003), as a model for a dependent variable that takes on the value zero with positive probability but is roughly continuously distributed over strictly positive values. Censored observations occur when all of the population can be sampled, but for some reason, the observations on the dependent variable are bounded by an upper bound, or a lower bound, or both, with several observation that may occur at or near the boundary or boundaries (Greene, 1990).

A Tobit model, assumes that the observed dependent variable y_i for observations $j = 1,\ldots, n$ satisfy

$$y_j = \max(y_i^*, 0), \tag{16}$$

where the y_i^*'s are latent variables generated by the classical linear regression model.

A latent variable sometimes called the index variable refers to the idea that there is an underlying variable y_i^*, that can be modeled as

$$y_i^* = \boldsymbol{\beta}'\mathbf{x}_i + \epsilon_i,$$

$$\begin{aligned} y_i &= 0 \text{ if } y_i^* \leq 0, \\ y_i &= y_i^* \text{ if } y_i^* > 0 \end{aligned} \tag{17}$$

where x is a k-vector of regressors, and the error term ϵ Normal $(0, \sigma^2)$, is distributed, conditionally on $\mathbf{x}$. The latent y_i^* is only observed if $y^* > 0$. In particular, the actual dependent variable is:

$$y_i = \max(0, y_i^*) \tag{18}$$

Like the Probit, the Tobit uses maximum likelihood estimation to estimate both the β and σ for the model. It is important to note that β estimates the effect of x on the latent variable y_i^*, not y.

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Probit Analysis

A Probit model was used to estimate the probability of a set associated with a particular type of treatment, capturing a sea turtle. The data included 1,906 observations; 251 sets caught sea turtles and 1,655 did not catch sea turtles. The estimates revealed that the probability of capturing a sea turtle varied by treatment (Table 4). Treatments 1, the baseline, and 6 had the highest probability of capturing a sea turtle. Both treatments varied in hook type and size but had similar bait (e.g. squid). Treatment 5 (e.g. larger j-hook with mackerel bait) had the lowest probability for catching a sea turtle.

Table 4. Probability of Capturing a Sea Turtle by Treatment

Treatment	Hook	Offset Angle	Bait	Probability of Capturing a Sea Turtle
1	9/0 J	25 –30	Squid	0.2485
2	18/0 C	0	Squid	0.0776
3	18/0 C	10	Mackerel	0.0962
4	20/0 C	10	Mackerel	0.0885
5	10/0 J	0	Mackerel	0.0703
6	16/0 C	10	Squid	0.2500
7	18/0 C	0	Squid	0.1071

The Probit model cannot predict the probability of each turtle species being captured. A Bivariate Probit model, however, was estimated to measure the effects each treatment and gear component had on the probability of capture of each sea turtle species (Table 5 and 6).

Table 5. Bivariate Probit: Effect of Treatments and Gear Components on Probability of Loggerhead Sea Turtle Capture

	Coefficient	Std. Error	t- ratio
Constant	0.2537	1.3593	0.187
DUMTRT2[12]	-0.5089	0.1515	-3.359*
DUMTRT3	-0.6470	0.1535	-4.216*
DUMTRT4	-0.6124	0.1579	-3.877*
DUMTRT5	-0.9426	0.2531	-3.724*
DUMTRT6	0.6074	0.3035	2.001*
DUMTRT7	0.1423	0.4574	0.311
Vessl Horsepower	0.0010	0.0005	1.754
Vessel Length	-0.0247	0.0111	-2.234*
Hook Number	0.0004	0.0028	0.153
Soak Duration	0.0299	0.0317	0.943
Mainline Length	-0.0055	0.0184	-0.299
Float Number	0.3411	0.0012	2.807*
Lightstick Number	-0.0012	0.0028	-0.443
Radio Beacon Number	0.0037	0.0395	0.094
Set Duration	0.1803	0.1372	1.314
Haul Duration	0.0362	0.0424	0.855
Gangion Distance	-0.0074	0.0049	-1.504

Loglikelihood = -892.4006
* Significant at the 5% level

Table 6. Bivariate Probit: Effect of Treatments and Gear Components on Probability of Leatherback Capture

	Coefficient	Std. Error	t- value
Constant	-0.7451	1.0550	0.706
DUMTRT2	-0.7225	0.1455	-4.967*
DUMTRT3	-0.4506	0.1166	-3.863*
DUMTRT4	-0.5962	0.1273	4.4684*
DUMTRT5	-0.7276	0.1845	3.943*
DUMTRT6	-0.2787	0.3904	-0.714
DUMTRT7	-3.965	126038	0.000
Vessl Horsepower	-0.00005	0.0004	-0.109
Vessel Length	-0.0130	0.0084	-1.548
Hook Number	0.0004	0.0020	0.173
Soak Duration	-0.0213	0.0287	-0.743
Mainline Length	-0.0030	0.0147	-0.204
Float Number	0.0032	0.0009	3.393*
Lightstick Number	-.0008	0.0021	-0.393
Radio Beacon Number	-0.00003	0.0367	-0.001

[12] DUMTRT2 –DUMTRT7 are dummy variables created to indicate whether or not a particular treatment was used for the set.

Set Duration	-0.0216	0.1126	-0.192
Haul Duration	0.0535	0.0391	1.367
Gangion Distance	0.0012	0.3499	0.344

Loglikelihood = -892.4006
* Significant at the 5% level

For loggerhead sea turtle captured, Treatment 2 - 6 were treatments that were significantly different than Treatment 1. These treatments all decrease the probability of a longline set capturing a sea turtle. The model also revealed that vessel length, horsepower, soak duration, float number, radio beacon number, set duration, and haul duration when increased the probability sea turtle capture decreased. The vessel horsepower, mainline length, lightstick number, and gangion distance are all negatively related to the baseline indicating that these components tend to increase loggerhead capture when increased.

Treatments 2-5 are significantly different than the baseline, Treatment 1 when assessing the probability of a catching a leatherback sea turtle. However, Treatment 4 has the highest probability while Treatment 7 has the lowest probability of capturing a Leatherback sea turtle. The probability of capturing a leatherback decreases when there is an increase in the following vessel components: vessel horsepower, vessel length, soak duration, mainline length, lightstick number, radio beacon number, and set duration.

This indicates that for a one-unit increase in any of the aforementioned components, the likelihood of capturing a Leatherback sea turtle decreases.

4.2 Technical Efficiency Analysis Results

Technical efficiency (TE), an indicator of the maximum potential output given existing level of inputs was estimated using DEA. Technical efficiency was further assessed to determine the influences of various gear components on the efficiency of the set. DEA was used to estimate a production frontier made up of the most efficient observations. DEA assigns efficiency scores ranging from one to infinity for an output distance function approach depending on the distance each observation is from the production frontier. An efficiency score of one is considered to be fully efficient, meaning the observation has obtained the maximum output and cannot be expanded without increasing input usage. For a directional distance approach as used in stage two, the efficiency score ranges from zero to one. An efficiency score of zero represents an efficient observation.

4.2.1 Stage one – Output Distance Function Approach Allowing all Outputs to Expand

In stage one, a traditional output distance function was used to calculate technical efficiency scores. This approach allows the expansion of all outputs including undesirable outputs. Based on the output distance function approach using the Constant Return to Scale (CRS) and Variable Return to Scale (VRS) models discussed in the previous chapter, TE scores for all 1,906 observations were estimated. Tables 7 and 8 present the estimated mean efficiency scores of the observations for each model. The results indicated that TE scores ranged from 1.00 to 9.96[13] for those sets in the sample with an average score of 3.68 when using the CRS model (Table 7). The VRS model scores range from 1.00 to 10.00 with an average of 2.67 (Table 8). This means that if the average longline set in the sample was to realize the same level as the most efficient set in the sample; it could expand as much as 3.68 times its observed output without increasing inputs for the CRS model, and 2.67 times under the assumptions of the VRS model.

[13] Observations with technical efficiency score greater than 10 were considered outliers and therefore not included in the analysis.

Table 7. Mean Technical Efficiency Scores by Treatment Allowing all Outputs to Expand for the CRS model.

	N	Mean	Coefficient of Variation	Efficient Sets
Treatment 1	507	3.44	0.56	15
Treatment 2	348	4.05	0.53	11
Treatment 3	426	3.72	0.57	8
Treatment 4	384	3.61	0.57	9
Treatment 5	185	3.66	0.54	4
Treatment6	28	3.15	0.71	1
Treatment 7	28	4.08	0.67	2
All Treatments	1,906	3.68	0.56	50

Table 8. Mean Technical Efficiency Scores by Treatment Allowing all Outputs to Expand for the VRS model.

	N	Mean	Coefficient of Variation	Efficient Sets
Treatment 1	507	2.48	0.63	100
Treatment 2	348	2.80	0.67	71
Treatment 3	426	2.76	0.62	51
Treatment 4	384	2.77	0.60	45
Treatment 5	185	2.83	0.58	18
Treatment6	28	1.56	0.70	18
Treatment 7	28	1.77	0.65	9
All Treatments	1,906	2.67	0.63	312

The constant returns to scale model assumes long-run equilibrium and, therefore, CRS results are only discussed from this point on. Of the 1,906 set observations in the data set, 50 were efficient using the constant returns to scale model. Ten of the 50 efficient observations were sets that captured sea turtles. [14]

Of the 1,906 sets analyzed, Treatment 6 had the highest mean efficiency overall (Table 7); a value of 1.00 indicates that production is efficient and a value > 1.00 indicates inefficient production. Treatment 1, the control treatment, had the next highest mean efficiency. These two treatments are not only different in the type of hook but also

[14] This result further illustrates the need for assessing TE with a directional distance function approach, since the efficient frontier is particularly defined by observations, which include sea turtle.

in terms of size. The bait (e.g., squid), is common to each treatment. Of all the treatments used in the study, Treatment 7 had the lowest mean efficiency. However, Treatment 7 had a greater percentage of efficient sets, which may be due to the low sample number. A Kruskal-Wallis test, a non-parametric test, was conducted to test whether the treatment means come from identical populations (Freund & Walpole, 1980). The test indicates that there was a significant difference in the mean scores of the treatments.[15]

4.3 Tobit Regression Analysis

4.3.1 Efficiency of the set

The empirical estimates of TE of the 1,906 longline set observations show the magnitude of the gains that could be obtained by improving the performance of the gear, given the technology. It is useful to identify the sources of the presence of loss in the efficiency of the gear for policy purposes. This can be done by investigating the relationship between the longline gear components and the estimated TE scores. The Tobit regression was estimated using the technical efficiency score as the dependent variable (TECS)[16] and a set of gear configuration and treatments as regressors. The dependent variable (TECS) is censored on the left and, therefore, the ordinary least square (OLS) approach is biased and inconsistent and would not be appropriate. Instead, as noted in Kirkley (2004), it is common in the literature to use a Tobit model, which uses the maximum likelihood estimate and does not yield biased results (Kennedy, 1992).

[15] The Kruskal- Wallis Test Statistic = 22.888 with a probability of .001 assuming a Chi-square distribution with 6 degrees of freedom.

The model is specified as follows:

Efficiency (TECS) = f(DUMTRT2, DUMTRT3, DUMTRT4, DUMTRT5, DUMTRT6, DUMTRT, VHP, VL, HS, SOD, ML, FN, LN, RN, SD, HD, GD).

DUMTRT2 –DUMTRT7 are dummy variables created to indicate whether or not a particular treatment was used for the set. All other variables are the observed vessel and gear characteristics. All variables used in the Tobit can easily be changed for each set due to the opportunistic nature of the gear. The dummy variable for each treatment hook was included to further identify their effect on influencing the efficiency of the set. The estimated coefficients in the Tobit model explain what variables influence the efficiency of a set (Table 9). The model was estimated using LIMDEP 8.0.

Table 9. Tobit Analysis: Effect of Treatments and Gear Components on the Efficiency of a Set

	Coefficient	Std. Error	t- value
Constant	8.3110	0.9319	8.918*
DUMTRT2	0.5920	0.1284	4.611*
DUMTRT3	0.4131	0.1218	3.391*
DUMTRT4	0.3806	0.1255	3.034*
DUMTRT5	0.4617	0.1592	2.900*
DUMTRT6	0.0633	0.3650	0.179
DUMTRT7	0.9585	0.3661	2.618*
Vessel Horsepower	0.0008	0.0004	1.994
Vessel Length	-0.0090	0.0077	-1.180
Hook Number	-0.0018	0.0011	-1.910
Soak Duration	0.0020	0.0255	0.702
Mainline Length	0.0053	0.0155	0.343
Float Number	-0.0008	0.0008	-1.012
Lightstick Number	0.0030	0.0009	3.220*
Radio Beacon Number	-0.0195	0.0147	-1.329
Set Duration	0.4683	0.1087	4.310*
Haul Duration	-0.7582	0.0336	-22.598*
Gangion Distance	-0.0101	0.0033	-3.077*

Loglikelihood = -3797.806
* Significant at the 5% level

[16] TECS is the technical efficiency score calculated using the CRS output distance model.

A positive coefficient indicates that a set is less likely to be efficient as it deviates from the control (e.g. Treatment 1). All treatments excluding Treatment 6 had a significant negative effect on the efficiency of a set. Of all treatments tested, Treatment 7 had the strongest negative effect on the set being efficient when compared to the control treatment.

Specific aspects of the gear were very effective in improving the efficiency of a set. An increase in vessel horsepower and the number of lightsticks decrease the efficiency of a set. Haul duration and gangion distance have negative coefficients compared to the baseline, which indicate that as those components increase one unit, the sets are more likely to be efficient.

In the previous section, all observations were included in the estimation of technical efficiency. In order to investigate the effects of treatments on the efficiency when sea turtles were captured, the observations were split into two categories: (1), those sets with one or more sea turtles captured in a set, and (2) those with no sea turtle capture. Technical efficiency using the CRS output distance approach was re-estimated using only the 251 observations that had one or more sea turtles (Table 10).

Table 10. Mean Technical Efficiency Scores for Sets with Sea Turtle Capture Summarized by Treatment

	Number of Observations	Number of Sea turtles	Mean	Coefficient of Variation	Efficient Sets
Treatment 1	126	218	2.02	0.46	18
Treatment 2	27	36	2.31	0.35	1
Treatment 3	41	50	2.30	0.40	3
Treatment 4	34	36	2.40	0.43	3
Treatment 5	13	15	1.95	0.27	0
Treatment6	7	17	1.51	0.77	3
Treatment 7	3	4	3.62	0.38	0
All Treatments	251	376	2.15	0.44	28

The re-estimated samples had a lower overall efficiency score compared to the original sample scores. Treatment 6 was the most efficient while Treatment 7 had the highest efficiency score indicating that it was the least efficient of all the treatments. Sets using Treatments 4 and 7 did not have any efficient observations after the re-estimation. This may have been due to the lower number of observations for those treatments.

4.4 Stage two - Directional Distance Function Approach

The directional distance function models and estimates efficiency, recognizing when there is a joint production of desirable and undesirable outputs, and there is a need to reduce undesirable outputs. In this study, the model included a non null-jointness statement, which suggests that the undesirable outputs cannot be produced without desirable outputs and vice versa. In stage two, the sets that captured sea turtles were penalized using a directional distance function approach to contract the undesirable outputs and expand the desirable outputs. The expansion, however, was restricted to less than the expansion allowed without forcing a reduction in undesirable outputs (Table 11).

Table 11. Mean Efficiency Scores Summarized by Treatment imposing a Regulatory Reduction of Sea Turtle Capture

	n	Mean	Coefficient of Variation	Number efficient
Treatment 1	126	0.166	0.845	27
Treatment 2	27	0.165	0.853	5
Treatment 3	41	0.187	0.757	9
Treatment 4	34	0.163	0.728	7
Treatment 5	13	0.192	0.510	0
Treatment6	7	0.036	2.094	5
Treatment 7	3	0.253	0.411	0
All Treatments	251	0.168	0.807	53

For those sets with undesirable output (e.g. sea turtle capture), 53 of 251 sets were efficient in terms of both desirable and undesirable output as indicated by an efficiency score (β) of zero. There were 198 sets that captured sea turtle and were inefficient; with efficiency scores that ranged from 0.01 to 0.7. For inefficient sets, this was the amount by which undesirable outputs, turtles, could be contracted while still allowing desirable outputs to expand. The mean efficiency score for all treatments was 0.168; meaning that on average, desirable outputs could be expanded by 16.8%, while bad outputs could be contracted by the same amount. Treatment 6 had the highest efficiency with the smallest beta of 0.036 when calculating technical efficiency using a directional vector approach. In comparison to the CRS output distance model, which did not impose a regulatory reduction in sea turtle capture, Treatment 6 could expand outputs by 1.5 times its original outputs, both desirable and undesirable, while the directional function model only allows for a 3% increase in desirable outputs and reduction in undesirable.

4.5 Effects of Treatment and Gear Components on the Efficiency of a Set When a Regulatory Induced Reduction is Imposed for Sea Turtle Capture

A Tobit regression was done to investigate the influence of treatments and gear components on efficiency when a regulatory induced reduction of sea turtle captures is imposed (Table 12). In this case, double censoring was required since 0 less than or equal to TE less than 1.0. The analysis revealed that efficiency increased as hook set, soak duration, mainline length, flat number, number of radio beacons, set duration, and gangion distance increased. Based on the results, Treatment 6 was determined to be the only treatment that was significantly different than the baseline. Treatments 2 and 6 were the only treatments that increased efficiency, with Treatment 6 having the highest efficiency.

Table 12. Tobit Analysis: Effect of Treatments and Gear Components on the Efficiency of a Set When a Regulatory Induced Reduction is Imposed for Sea Turtle Capture

	Coefficient	Std. Error	t- value
Constant	0.7299	0.2046	3.567*
DUMTRT2	-0.0175	0.0279	-0.624
DUMTRT3	0.0218	0.0235	0.930
DUMTRT4	0.0046	0.0252	-0.184
DUMTRT5	0.05278	0.0379	1.392
DUMTRT6	-0.1196	0.0575	-2.078*
DUMTRT7	0.1097	0.0771	1.422
Vessel Horsepower	0.00004	0.0001	0.494
Vessel Length	0.0024	0.0016	1.451
Hook Number	-0.000004	0.0001	-0.035
Soak Duration	-0.0051	0.0062	-0.813
Mainline Length	-0.0005	0.0028	-0.192
Float Number	-0.00006	0.0002	-0.331
Radio Beacon Number	-0.0264	0.0084	-3.141*
Set Duration	0.0369	0.0217	1.699
Haul Duration	-0.02364	0.0074	-3.121*
Gangion Distance	-0.0020	0.0007	-2.962*

Loglikelihood = -39.04212
* Significant at the 5% level

4.6 Comparison of Efficient and Inefficient Sets

Of the 251 sample sets, 53 where considered technically efficient. A comparison of inputs and outputs helped to determine the gear components, which affected the efficiency of the entire set. A Kruskal-Wallis test was conducted to test whether or not there was a significant difference in the inputs and outputs between the efficient and inefficient sets. The null hypothesis (Ho) states the individual inputs and outputs have equivalent means for the efficient and inefficient sets. The alternative hypothesis (Ha) states individual inputs and outputs have different means. Table 13 provides the results of the Kruskal –Wallis test comparing efficient and inefficient sets, which captured sea turtles.

Table 13. Results of Kruskal-Wallis Test Comparing Efficient and Inefficient Sets that Captured Sea Turtles

	Efficient Sets	Inefficient Sets	Chi-Square Value	Asymp. Sig.	Reject or Accept Null Hypothesis[a]
Sample Number	53	198			
Inputs					
Vessel Length	68.00	68.49	0.07	0.78	Accept
Vessel Horsepower	433.74	473.03	2.84	0.09	Accept
Soak Duration	7.03	7.09	0.00	0.92	Accept
Haul Duration	8.01	7.21	13.48	0.00	Reject
Set Duration	4.31	4.24	0.43	0.51	Accept
Gangion Distance	203.94	201.69	0.87	0.35	Accept
Mainline Length	32.56	31.93	0.13	0.72	Accept
Hook Number	971.87	967.81	0.00	0.99	Accept
Lightsticks Number	956.94	967.84	0.16	0.69	Accept
Radio Beacon Number	9.26	9.23	0.02	0.88	Accept
Float Number	259.74	277.98	2.36	0.12	Accept
Outputs					
Albacore Tuna	39.39	10.69	8.37	0.00	Reject
Bigeye Tuna	182.42	74.33	6.68	0.01	Reject
Yellowfin Tuna	17.28	1.31	5.73	0.02	Reject
Bluefin Tuna	90.53	2.96	42.41	0.00	Reject
All Tuna	329.62	89.29	36.43	0.00	Reject
Shark	854.73	490.16	6.01	0.01	Reject
Swordfish	1132.84	905.58	0.54	0.46	Accept
Loggerhead Turtle	0.87	0.70	2.78	0.01	Accept
Leatherback turtle	1.19	0.65	12.22	0.00	Reject

From the results, the efficient sets were those in which the vessel used fewer inputs and had greater outputs. Specifically, the efficient sets had fewer inputs including vessel horsepower, vessel length, soak duration, number of lightsticks, and number of floats. The efficient sets also had higher outputs for all species.

4.7 Effect of Hook type and Size on Efficiency

Sets were divided into two groups to identify if there was a significant difference in the efficiency scores between the two hook types. The mean technical efficiency score

[a] Accept implies the sample does not allow us to reject the null hypothesis.

for those treatments having j-hooks was 0.168, whereas those treatments with circle hooks had a mean technical efficiency score of 0.167. This indicates that treatments with circle hooks were slightly more efficient than the j-hooks as a group using the directional distance function.

A Kruskal-Wallis test revealed that mean technical efficiency scores showed no significant differences, indicating that hook type had no effect on the overall efficiency of the gear. In comparison, the assessment of efficiency based on the output-orientation (i.e., allows turtles and desirable outputs to increase) indicated mean scores of j-hook 2.02 and circle hook 2.32 that show a significant difference with a chi square value of 6.22 and a significance of 0.01.

To further investigate the effects of hook type on efficiency, a Kruskal-Wallis was conducted to compare the means of all outputs for all observations with sea turtle capture. The test revealed that all outputs excluding bluefin tuna, shark, and loggerhead turtles, were significantly different (Table 14).

Table 14. Results of Kruskal-Wallis Test Comparing Hook Type of Sets that Captured Sea Turtles

	J- Hook	Circle Hook	Chi-Square Value	Asymp. Sig	Reject or Accept Null Hypothesis
Sample Number	139	112			
Outputs					
Albacore Tuna	24.09	7.65	12.50	0.00	Reject
Bigeye Tuna	113.25	77.19	3.87	0.05	Reject
Yellowfin Tuna	1.57	8.54	4.85	0.03	Reject
Bluefin Tuna	20.55	22.17	0.04	0.84	Accept
All Tuna	161.08	113.93	4.09	0.04	Reject
Shark	599.50	526.99	0.12	0.73	Accept
Swordfish	1048.00	836.37	8.64	0.00	Reject
Loggerhead Turtle	0.86	0.77	0.28	0.60	Accept
Leatherback turtle	0.75	0.88	2.16	0.14	Reject

4.8 Effect of Directed Sets on Efficiency

Sets were separated by directed sets to identify any influences on the technical efficiency of the gear. Treatment 4 was the most efficient when the set was directed for swordfish (e.g. sets where swordfish catch was greater than all other species)[17], while treatments 5 and 3 were the least efficient. For the purpose of the tuna-directed sets, all observations with tuna catch greater than any other was included in the analysis. Treatments 3, 4, and 7 had no observations and were excluded from the analysis. Treatment 6 had only one observation, which was efficient. The least efficient of the treatments when the set was directed for tuna was treatment 2 with an efficiency score of 0.150. When the sets were directed for shark (e.g. shark catch greater than any other species), treatment 6 was the most efficient with an efficiency score of 0.050 while treatment 5 was least efficient with a score of 0.360.

4.9 Tobit analysis of the Efficiency of Capture for Directed Sets

A further investigation into the effect of directed sets on efficiency was completed for swordfish, tuna, and shark on those sets that captured at least one sea turtle using a Tobit analysis (Tables 15-17).

4.9.1 Swordfish-directed

The analysis revealed that swordfish-directed sets increased swordfish catch with an increase in vessel horsepower, number of hooks set, soak duration, number of floats, number of radio beacons, haul duration and gangion distance (Table 15). Only set duration, haul duration, and gangion distance is significantly different than the baseline, with gangion distance being positive and highly significant. Treatment 4, when compared to treatment 1, increase swordfish catch where as Treatments 2, 3, 6, and 7 tend to reduce catch. Treatment 4 and 7 were significantly different than the baseline at the 10% significance level.

Table 15. Tobit Analysis: Effect on Catch When Sets were Directed for Swordfish

	Coefficient	Std. Error	t- value
Constant	-1901.3061	920.7647	-2.065*
DUMTRT2	-296.9704	126.5841	-2.346*
DUMTRT3	-261.7337	106.7558	-2.452*
DUMTRT4	220.4979	113.8709	1.936
DUMTRT5	14.2731	174.4674	0.082
DUMTRT6	-663.8732	239.9404	-2.767*
DUMTRT7	-674.0797	354.9527	1.899
Vessel Horsepower	0.5642	0.3809	1.481
Vessel Length	-13.8525	7.4110	-1.869
Hook Number	0.9328	0.5126	1.820
Soak Duration	10.1421	28.2938	0.358
Mainline Length	-3.6396	12.6339	-0.288
Float Number	1.3818	0.8236	1.678
Radio Beacon Number	16.6827	38.0538	0.438
Set Duration	-412.0948	98.4362	-4.186*
Haul Duration	267.7083	32.8119	8.159*
Gangion Distance	9.8470	3.1030	3.173*

Loglikelihood = -1993.413
* Significant at the 5% level

4.9.2 Tuna-directed

Haul duration was the only gear component to positively affect tuna landings when the set was directed for tuna (Table 16).[18] Treatments 3, 4 and 5, when compared to the baseline negatively affected tuna catch. Treatments 4 and 5 were the only treatment significantly different than the baseline. Treatment 2 and 6 increases tuna landings with treatment 6 having the greatest effect on landings. Vessel length, soak duration, number of floats, number of radio beacons, set duration, haul duration, and gangion distance all increased tuna catch.

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[17] Treatments 6 and 7 exclusively set for tuna and were not included in the analysis.
[18] All treatments with tuna catch greater than swordfish or shark where included in the analysis.

Table 16. Tobit Analysis: Effect on Catch When Sets were Directed for Tuna

	Coefficient	Std. Error	t- value
Constant	-1613.408	596.0649	-2.707*
DUMTRT2	37.2413	78.0555	0.477
DUMTRT3	-81.1999	67.9778	-1.195
DUMTRT4	-462.4379	101.6076	-4.551*
DUMTRT5	-310.4825	121.7751	-2.550*
DUMTRT6	207.1136	140.2579	1.477
DUMTRT7	-2.2746	213.3308	-0.011
Vessel Horsepower	-0.4119	0.2420	-1.702
Vessel Length	7.9452	4.8196	1.649
Hook Number	-0.2763	0.3288	-0.840
Soak Duration	16.6775	17.5485	0.950
Mainline Length	-8.3113	8.4770	-0.980
Float Number	0.5568	0.5257	1.059
Radio Beacon Number	13.5043	24.3700	0.554
Set Duration	23.6293	62.5789	0.378
Haul Duration	97.8614	21.4393	4.565*
Gangion Distance	3.1202	2.0155	1.548

Loglikelihood = -965.0286
* Significant at the 5% level

4.9.3 Shark-directed

For those sets with directed shark sets, sharks catch increased when haul duration increased and when the number of floats decreased by one unit (Table 17). There was no significant difference in the treatments when compared to Treatment 1 at the 5% significance level. At the 10% significance level, Treatment 2 and 3 were significantly different. All treatments tended to reduce shark catch, with Treatment 7 having the greatest effect. Vessel components such as soak duration, mainline length, number of floats, number of radio beacons, haul duration, and gangion distance were positive, with haul duration having the greatest effect of increasing shark catch.

Table 17. Tobit Analysis: Effect on Catch When Sets were Directed for Shark

	Coefficient	Std. Error	t- value
Constant	27.2777	724.1888	0.038
DUMTRT2	-64.7143	99.5331	-0.650
DUMTRT3	-92.9990	83.6131	-1.112
DUMTRT4	-170.5467	89.5397	-1.905

DUMTRT5	-249.1661	137.8072	-1.808
DUMTRT6	-119.8334	188.6912	-0.635
DUMTRT7	-353.7271	279.1377	-1.267
Vessel Horsepower	-0.1705	0.2995	-0.569
Vessel Length	-7.2487	5.8301	-1.243
Hook Number	-0.2037	0.4035	-0.505
Soak Duration	9.6338	22.2471	0.433
Mainline Length	9.5657	9.9346	0.963
Float Number	-1.6212	0.6478	-2.503*
Radio Beacon Number	35.6596	29.9369	1.191
Set Duration	-50.6979	77.3090	-0.656
Haul Duration	89.9118	25.7975	3.485*
Gangion Distance	3.3052	2.4505	1.349

Loglikelihood = -1880.841
* Significant at the 5% level

4.10 Discussion

NOAA fisheries issued an emergency closure after the 2001 biological opinion found an extensive number of takes of endangered and threatened sea turtles occurring in the North Atlantic Distant waters. Area closures usually mean extensive negative impacts on a fishery in terms of reduced revenues. Curtis and Hick (2000) noted "fisheries managers increasing reliance upon area and seasonal closures to mitigate interactions with marine mammals and sea turtles underscores the need for quantitative models that assess the impacts of policy alternatives".

NOAA fisheries tested seven treatments to be used as a qualitative and biological assessment of the fisheries interaction with sea turtles. In order to investigate the practicality and usefulness of the treatments, I completed an assessment of technical efficiency using data envelopment analysis (DEA) to estimate technical efficiency.

The directional distance vector approach allowed for expansion of desirable outputs (e.g. swordfish, tuna, and shark), while reducing the undesirable outputs (e.g. sea turtles). This approach identifies the possibilities for expansion and contraction of outputs at the set level. It provides information that describes the structure of the technology, and the measure of efficiency for each set. The approach is useful in multi-species fisheries, such as longline, where the production is characterized by multiple outputs, both desirable and undesirable. The directional distance approach reveals whether a vessel on a per set basis can reduce sea turtle capture by altering their production mix (e.g. inputs). At the same time, the approach helps to determine if the mitigation of sea turtles is too costly when restrictions are imposed on the type of fishing gear that can be used by the vessel.

In the experiment, 13 vessels were required to fish with two different hook types, which varied in size, offset angle, and types of bait deployed. The vessels were allowed to change various gear settings, such as set duration and gangion distance. The two hook types used were the industry standard j-hook and the circle hook

For sets with sea turtle capture, almost all could be reduced if the sets were efficient. J-Hooks on average captured 1.6763 turtles per set; sets that used circle hooks on average capture 1.2678 sea turtles. If the set was efficient, the amount by which sea turtles could be reduced by is 85.6% for loggerhead and 74.86% for leatherback sea turtles for vessels using standard j-hooks. If the sets were efficient, the number of sea turtles could be reduced by 77.2% for loggerhead and by 88.27% for leatherback sea turtles.

Treatment 1, the industry standard, is more efficient than the experimental treatment in terms of technical efficiency. The experimental treatment, however, on a per set basis, allows for a larger reduction in sea turtle capture. This also indicates that the treatment hooks have a greater potential to increase their catch if operating at full technical efficiency.

Any regulation designed to reduce bycatch of sea turtles could have significant economic ramifications in terms of reduced technical efficiency and revenue. Therefore, the maximum potential output that sets could be expanded, if operating at full technical efficiency, the loss of catch for each species in pounds associated with a regulatory induced reduction is imposed on sets capturing sea turtles, and the revenue associated with the loss will be discussed in the following section for each treatment.

The results indicate that 53 of the 251 sets, which captured sea turtles, were operating at full technical efficiency. The inefficient sets had a potential for improving performance, but this varied among the treatment hooks. The maximum potential output (e.g. swordfish, tuna, and shark), if a set operates at full technical efficiency, can be calculated using the following equation:

$$Exp = \text{Observed output} * TEC, \qquad (18)$$

where observed output is species caught in pounds and TEC is the technical efficiency score calculated using the output distance model.

When a regulatory induced reduction is imposed for sea turtle capture, the maximum potential output, if a set operates at full technical efficiency, can be calculated using the following equation:

$$Exp_{st} = \text{Observed Output} + (\text{Observed Output} * TER), \qquad (19)$$

where observed outputs is species caught in pounds and TER is the technical efficiency score calculated using the directional vector model.

It is important to calculate the loss of output associated with a regulatory induced reduction of sea turtle capture. The loss of output is an integral part of assessing and determining the cost associated with sea turtle mitigation and the adoption of gear modification regulations. The loss can be calculated using the following equation:

$$Loss = Exp - Exp_{st} \qquad (20)$$

Landings data were also collected on a trip level for each vessel participating in the experiment. Total pounds and gross revenue of landed species was recorded along with the average price for the years 2002 and 2003. These values were used to obtain a mean price for each species used in the analysis. An implicit price deflator was used to obtain the constant dollar value for the prices associated with each species to be used to predict revenue losses over the two-year period.

Treatment 1 was the status quo for opening the Grand Banks area. Treatment 1 was a 9/0 j-hook with squid bait. It was the industry standard and has been widely used for many years by the longline fishery and was the control for the experiment. The average maximum potential output was 1790.93 pounds for swordfish, 248.19 pounds for tuna, 965.75 pounds for shark, and a total of 3004.87 pounds. When forcing a regulatory reduction of sea turtle capture, the maximum output was 1167.56 for swordfish, 187.18 pounds for tuna, and 693.39 pounds for shark, with a total of 2048.13 pounds. The average loss associated with a regulatory induced reduction of sea turtles was 623.37 pounds for swordfish, 61.015 pounds for tuna, and 272.36 pounds for shark, with a total loss of 956.75 pounds. The average gross revenue lost when a regulatory induced reduction of sea turtle capture was imposed in 2002, was $1610.94 for swordfish, $258.73 for tuna, and $330.96 for shark and a total of $2200.63. In 2003, the average losses were $1597.68 for swordfish, $136.41 for tuna, and $323.32 for shark, and a total loss of revenue of $2057.41. The average loss of revenue in 2004 would be $1653.61 for swordfish, $229.98 for tuna, and $337.67 for shark, and a total loss of $2057.41.

Treatment 2 was an 18/0 circle hook with squid bait. The average maximum potential output for swordfish using Treatment 2 was 1307.30 pounds, 248.19 pounds for tuna, and 1027.15 pounds for shark and a total of 2628.83. When a regulatory induced reduction was imposed for sea turtle capture, the maximum output was 701.46 pounds for swordfish, 180.11 pounds for tuna, and 612.46 pounds for shark, and a total of 1494.03. The loss associated with the regulatory induced reduction of sea turtle was 605.84 pounds for swordfish, 113.68 pounds for tuna, and 414.69 pounds for shark, and a total of 1134.21 pounds. The average gross revenue lost when a regulatory induced reduction was imposed for sea turtle capture in 2002 was $1429.90 for swordfish, $413.11 for tuna, and $435.75 for shark, and a total loss of $2278.76. In 2003, the average losses were $1681.45 for swordfish, $418.37 for tuna, and $563.75 for shark, and a total loss of 2663.57. The average loss of revenue in 2004 would be $1581.04 for swordfish, $426.68 for tuna, and $504.87 for shark, and a total loss of $2512.59.

Treatment 3 was an 18/0 circle hook with a 10-degree offset that uses squid bait. The average maximum potential output for swordfish using Treatment 3 was 1025.70 pounds, 194.08 pounds for tuna, and 1065.42 pounds for shark, and a total 2285.20 pounds. When a regulatory induced reduction was imposed for sea turtle capture, the maximum output was 909.34 pounds for swordfish, 136.50 pounds for tuna, and 650.42 pounds for shark, and a total of 1696.26 pounds. The loss associated with a regulatory reduction imposed for sea turtles was 642.26 pounds for swordfish, 57.58 pounds for tuna, and 414.99 pounds for shark, and a total loss of 1114.83 pounds. The average gross revenue lost when a regulatory induced reduction was imposed for sea turtle capture in 2002 was $1282.97 for swordfish, $345.53 for tuna, and $490.75 for shark, with a total of $2119.25. In 2003, the average losses were $2065.38 for swordfish, $37.28 for tuna, and $500.76 for shark, with a total of $2603.42. The average loss of revenue in 2004 would be $1665.84 for swordfish, $217.38 for tuna, and $507.92 for shark, which totals $2391.14.

Treatment 4 was a 20/0 circle hook with a 10-degree offset and uses mackerel bait. The average maximum potential output for swordfish using Treatment 4 was 232.83 pounds, 23.436 pounds for tuna, and 895.206 pounds for shark, and a total of 3239.48 pounds. When a regulatory induced reduction was imposed for sea turtle capture, the maximum output was 1376.78 pounds for swordfish, 17.07 pounds for tuna, and 514.25 pounds for shark, and a total of 1908.10 pounds. The average loss associated with the regulatory reduction of sea turtle was 944.05 pounds for swordfish, 6.36 pounds for tuna, and 380.95 pounds for shark, and a total loss of 1231.36 pounds. The average gross revenue lost when a regulatory induced reduction was imposed for sea turtle capture in 2002 was $2743.84 for swordfish, $28.98 for tuna, and $371.77 for shark, and a total of $3144.59. In 2003, the average losses were $1973.60 for swordfish, $15.04 for tuna, and $567.40 for shark, and a total of $2556.04. The average loss of revenue in 2004 would be $2495.13 for swordfish, $23.95 for tuna, and $436.50 for shark, which totals $2982.58.

Treatment 5 was a 10/0 j-hook with a 0-degree offset and uses mackerel bait. The average maximum potential output for swordfish using Treatment 5 was 2310.86 pounds, 103.24 pounds for tuna, and 793.11 pounds for shark, and a total of 3207.21 pounds. When a regulatory induced reduction was imposed for sea turtle capture, the maximum output was 1485.67 pounds for swordfish, 63.80 pounds for tuna, and 521.25 pounds for shark, and a total of 2070.72 pounds. The average loss associated with the regulatory reduction of sea turtle loss was 825.189 pounds for swordfish, 39.44 pounds for tuna, and 271.86 pounds for shark, and a total loss of 1136.49 pounds. The average gross revenue lost when a regulatory induced reduction was imposed for sea turtle capture in 2002 was $2170.25 for swordfish, $143.96 for tuna, and $334.39 for shark, and a total of $2648.60. In 2003, there were no observations for this treatment. The average loss of revenue in 2004 would be $2244.51 for swordfish, $149.09 for tuna, and $345.26 for shark, which totals $2738.86.

Treatment 6 was a 16/0 circle hook with a 10-degree offset and uses squid bait. This treatment was set for tuna. The average maximum potential output for swordfish using Treatment 6 was 522.92 pounds, 323.06 pounds for tuna, and 935.32 pounds for shark, and a total of 1781.30 pounds. When a regulatory induced reduction was imposed for sea turtle capture, the maximum output was 339.98 pounds for swordfish, 316.92 pounds for tuna, and 732.42 pounds for shark, and a total of 1389.32 pounds. The average loss associated with the regulatory reduction of sea turtle loss was 122.95 pounds for swordfish, 6.14 pounds for tuna, and 202.90 pounds for shark, with a total loss of 331.99 pounds. There were no observations for 2002 for this treatment. In 2003, the average losses were $302.45 for swordfish, $22.46 for tuna, and $233.34 for shark, with a total of 558.25. The average loss of revenue in 2004 would be $307.37 for swordfish, $22.83 for tuna, and $237.34 for shark, which totals $567.54.

Treatment 7 was an 18/0 circle hook with a 0-degree offset and uses squid bait. This treatment was set for tuna. The average maximum potential output for swordfish using Treatment 7 was 66.14 pounds, 216.93 pounds for tuna, and 1789.07 pounds for shark, and a total of 2661.14 pounds. When a regulatory induced reduction was imposed for sea turtle capture, the maximum output was 228.66 pounds for swordfish, 94.133 pounds for tuna, and 635.30 pounds for shark, and a total of 958.09 pounds. The average loss associated with a regulatory reduction of sea turtle was 426.48 pounds for swordfish, 122.80 pounds for tuna, and 1153.74 pounds for shark, and a total loss of 665.04. There were no observations for 2002 for this treatment. In 2003, the average losses were $1049.13 for swordfish, $449.42 for tuna, and $1326.84 for shark, and a total of $1361.39. The average loss of revenue in 2004 would be $1066.19 for swordfish, $456.79 for tuna, and $1349.92 for shark, which totals $2872.90.

The maximum potential output of Treatment 1 was considered status quo. If all vessels continue to operate efficiently in 2004, the maximum potential on a per set basis for catching swordfish, tuna, and shark would be a combined total of 3004.87 pounds (Table 18). This equates to approximately $6802.57 in revenue. When a regulatory restriction was imposed to reduce sea turtle capture, total catch decrease. The amount Treatment 1 could potentially harvest would be 2048.13 pounds under the restriction. This reduction in catch would create a loss of $2193.51. When the status quo was compared to Treatment 2, the loss of catch was greater than Treatment 1, when a restriction was imposed. The total catch lost if Treatment 2 was required would be 1510.84 pounds, or $3742.22 lost in revenue. Treatment 3 has a greater maximum potential than Treatment 2 and, therefore, would have less loss if regulatory restrictions were imposed. Treatment 3 would have a total loss of landing estimated at 1308.61 pounds. This would result in a loss of revenue of $3110.79. Treatment 4 when compared to the status quo would have a loss of 1096.77 pounds. The regulatory reduction would cost the vessels $2507.48 in revenue on an average per set basis. Treatment 5 was a larger j-hook than the status quo. It has maximum potential catch of 2070.72 pounds, if regulatory restrictions were imposed. This equates to maximum revenue of $4763.20. The loss of revenue would be less if Treatment 1 was used and regulatory restriction was imposed.

Treatment 6 was directed for tuna, but has a maximum potential of 1389.32 pounds of total catch. The loss associated with a regulatory induced restriction would be 1658.55 pounds and a loss of $3818.47 in revenue. Treatment 7 was also directed for tuna. This treatment has the greatest loss of all the alternative treatments. The loss associated with a regulatory restriction would be 2046.00 pounds of catch and which equates to $5065.01.

Table 18. Comparative Assessment of Catch and Revenues Relative to Total Catch

Trt	Max. Potential Output in lbs.	Max. Potential Output When a Regulatory Induced Reduction was Imposed for Sea Turtle Capture in lbs.	Loss in lbs.	Avg. Loss in Revenue for 2002	Avg. Loss in Revenue for 2003	Total Avg. Loss of Revenue Estimated for 2004
1	3004.87	2048.13	956.75	2200.63	2057.41	2221.26
2	2628.83	1494.03	1134.21	2278.76	2663.57	2512.59
3	2285.20	1696.26	1114.83	2119.25	2603.42	2391.14
4	3239.48	1908.10	1231.36	3144.59	2556.04	2982.58
5	3207.21	2070.72	1136.49	2648.60	0.00	2738.86
6	1781.30	1389.32	331.99	0.00	558.25	567.54
7	2661.14	958.09	665.04	0.00	1631.39	2872.90

Table 19. Comparative Assessment of Catch and Revenues Relative to Swordfish

Trt	Max. Potential Output in lbs.	Max. Potential Output When a Regulatory induced Reduction was Imposed for Sea Turtle Capture in lbs.	Loss in lbs.	Avg. Loss in Revenue for 2002	Avg. Loss in Revenue for 2003	Total Avg. Loss of Revenue Estimated for 2004
1	1790.93	1167.56	623.37	1610.94	1597.68	1653.61
2	1307.89	701.46	605.84	1429.90	1681.45	1581.04
3	1025.70	909.34	642.26	1282.97	2065.38	1665.84
4	2320.83	1376.78	844.05	2743.84	1973.60	2495.13
5	2310.86	1485.67	825.19	2170.25	0.00	2244.51
6	522.92	339.98	122.95	0.00	302.45	307.37
7	655.14	228.66	426.48	0.00	1049.13	1066.19

Table 20. Comparative Assessment of Catch and Revenues Relative to Tuna

Trt	Max. Potential Output in lbs.	Max. Potential Output When a Regulatory Induced Reduction was Imposed for Sea Turtle Capture in lbs.	Loss in lbs.	Avg. Loss in Revenue for 2002	Avg. Loss in Revenue for 2003	Total Avg. Loss of Revenue Estimated for 2004
1	248.19	187.18	61.02	258.73	136.41	229.98
2	293.79	180.11	113.68	413.11	418.37	426.68
3	194.08	136.50	57.58	345.53	37.28	217.38
4	23.44	17.07	6.36	28.98	15.04	23.95
5	103.24	63.80	39.44	143.96	0.00	149.09
6	323.06	316.922	6.14	0.00	22.46	22.83
7	216.93	94.13	122.79	0.00	449.42	456.79

Table 21. Comparative Assessment of Catch and Revenues Relative to Shark

Trt	Max. Potential Output in lbs.	Max. Potential Output When a Regulatory Induced Reduction was imposed for Sea Turtle Capture in lbs.	Loss in lbs.	Avg. Loss in Revenue for 2002	Avg. Loss in Revenue for 2003	Total Avg. Loss of Revenue Estimated for 2004
1	965.75	693.39	272.36	330.96	323.32	337.67
2	1027.15	612.46	414.69	435.75	563.75	504.87
3	1065.42	650.42	414.99	490.75	500.75	507.92
4	895.21	514.25	380.95	371.77	567.40	463.50
5	793.11	521.25	271.86	334.39	0.00	345.26
6	935.32	732.42	202.90	0.00	233.34	237.34
7	1789.07	635.30	115.77	0.00	132.84	1349.92

These estimates were based on the total catch and not at the individual species caught. From the analysis, Treatment 4 has the highest loss of swordfish (Table 19), while Treatment 7 has the greatest loss of tuna (Table 20). In terms of shark loss, by far, Treatment 7 had the greatest loss (Table 21). Treatment 7, however, was a directed tuna set and may be a reason for the associated loss. Of the circle hooks tested, Treatment 4 has the least loss of all alternative treatments. Of the two tuna directed sets, Treatment 6 has the greater potential for catch.

The results also reveal that on a set level basis, treatments with circle hooks have a negative impact on efficiency when using the output distance approach, which allows all outputs to expand. However, when using the directional output approach, in which desirable outputs could be expanded while undesirable outputs could be contracted, there was no significant difference in the efficiency of the two hook types. This means that if regulatory restrictions were imposed on the fishery, the loss associated with the imposed regulation would not differ between the two hooks. Since there was no significant difference it would be beneficial for the fishery to begin using the circle hook if a regulatory induced restriction was imposed on the fishery. Therefore, it is important to discuss the cost of using circle hooks as the new standard.

According to the final supplemental economic impact statement, all hook and bait alternatives would likely have an initial adverse economic impact as most fishermen may have to purchase new hooks to comply with new regulations (NOAA, 2004). These costs, however, would likely be offset in the long run, because circle hooks tend to be less expensive than traditional j-hooks. Fishermen will also experience a short-term loss associated with adjusting to the new hooks and bait types as they learn how to maximize efficiency.

Compliance costs associated with hook cost are estimated to be between $675.25 and $1650.00 for 18/0 circle hooks, and $697.50 and $1,241.75 for 16/0 circle hooks. This cost will be reduced after the initial replacement of hooks. If every hook is lost or needs to be replaced, the annual hook cost is approximated to be around $20,000, which is less than compared to that of the standard j-hook. (NOAA, 2004).

These findings have important policy implications. It is important to acknowledge the cost associated with the process of modifying longline gear, as they may otherwise endanger the long-term success of the gear modification, as well as the continued commercial viability of the fishery. Policy makers may not anticipate these costs when they begin to enforce the use of the modified gear. When financial survivability depends on gear efficiency, it is important to use the gear with the highest value. However, the continued existence of a species outweighs the cost in most cases and requires that vessels use a gear that may be slightly less efficient, but effectively mitigates the capture of threatened and endangered species, such as the loggerhead and leatherback sea turtles.

The results also point to the importance of examining not only technical efficiency, but also the biological interaction and gear configuration determinates when measuring the productivity of the set. Despite the role that higher efficiency level can have on output, producing gains stemming from technology innovations remains of critical importance to the fishery. Therefore, continued research directed toward the generation of new technology should not be neglected.

CHAPTER 5. CONCLUSION

5.1 Summary

This study provides an assessment of technical efficiency for a sample of NED longline sets collected, based on gear configuration and catch data during the 2001-2003 turtle mitigation experiment.

Average set inputs and outputs, both desired and undesired, were analyzed by DEA to estimate a production frontier, which is the basis for deriving set–level technical efficiency measures. The results reveal that TE is not significantly different between the two hooks tested, the industry standard j- hook and the circle hook when a regulatory induced reduction is imposed for sets capturing a sea turtle. The average efficiency score for the j-hook was 0.179, whereas the efficiency score for the circle hook was 0.164. Among the seven treatments, Treatment 6 (e.g.16/0 circle hook, 10 degree offset, squid bait) was the most efficient. Treatment 6, however, was directed for tuna. Treatments 2 (e.g. 18/0 circle hook, 0 degree offset, squid bait) and 4 (e.g. 20/0 circle hook, 10 degree offset, mackerel bait), which were directed for swordfish, were more efficient than the baseline, Treatment 1 (e.g. 9/0 j-hook, 25-30 degree offset, squid bait. Treatment 7 (e.g. 18/0 circle hook, 0 degree offset, squid bait), however, allowed for the largest reduction of sea turtle capture.

A Tobit analysis was done to assess the influence of treatments and gear components on the efficiency of a set. Various gear configurations influence technical efficiency, such as haul duration and gangion distance. Hauls that were longer in duration tended to be more efficient. The hook type did not have a significant influence on efficiency when a regulatory induced reduction is imposed for sea turtle capture. Efficient sets tended to have higher output levels of tuna and shark. However, there was no significant difference in swordfish catch between efficient and inefficient sets. Because the hook types did not have significantly different efficiency levels, it would be advantageous to use a circle hook to reduce capture while maintaining efficiency. Catch, however, decreased significantly with each treatment. If operation were technically efficient, treatments using 16/0 hooks have the least potential for increasing output due to their already high efficiency level. Hook sizes greater than 16/0 have a greater potential for output expansion including Treatments 2, 3, 4, and 7, with Treatment 7 having the highest potential output expansion.

A Tobit analysis was done to assess the effects of treatments and gear components on desirable outputs. For swordfish-directed sets, Treatments 4 and 5 improved swordfish catch compared to Treatment 1. An increase in vessel horsepower, number of hooks set, soak duration, number of floats, number of radio beacons, haul duration, and gangion distance increased swordfish catch. When directed for tuna, Treatments 2 and 6 tend to increase efficiency compared to Treatment 1. Gear components, such as vessel length, soak duration, number of floats, number of radio beacons, haul duration, and catch of tuna increased when gangion distance increased. No treatments increased catch when the set was directed for shark. However, soak duration, mainline length, number of radio beacons, haul duration and gangion distance all increased shark catch. Overall soak duration, number of radio beacons, haul duration, and gangion distance have a positive effect on catch when increased for the shark-directed sets.

The study has important theoretical implications as it shows that gear modification can be an inefficient, yet effective, strategy in dealing with the mitigation of sea turtle capture in the fishery. Fisheries policy requires a balancing of benefits and cost associated with the reduction of bycatch, in this case, sea turtles. This is a substantial loss of catch for all target species when a regulatory induced reduction is imposed for sets that captured sea turtles. The average loss, on a per set basis, of all treatments for all species when a regulatory induced reduction is imposed was 938.67 pounds with a total loss of 6570.67 pounds, which in current dollars would be an average loss of $2,326.70 and a total combined loss of $16,286.87.

Along with the loss of target species, the cost of hook replacement must also be added to adequately demonstrate the cost of reducing sea turtle mortality using an alternate gear technology. The average cost of replacing a set of hooks is between $675.00 and $1,650.00 for 18/0 circle hooks and between $697.50 and $1, 241.75 for 16/0 circle hooks. However, this would be the initial cost since they would replace hooks only when one was lost or damaged, not the entire set.

It is hard to place monetary value on the benefits to society and the ecosystem. However, the reduction of sea turtle incidence and the resulting injury or mortality is important because, as bycatch, it can be classified as waste. This reduces the future yield of the fishery as well as efficiency due to the increase in handling time and damage to the quality of target catch species, and loss of bait and hook. The capture of sea turtles not only affects one vessel, but the fleet, as it reduces the stock and the productivity of the fishery.

While seasonal and temporal closures have been a popular management tool when and where yield is sub-optimal, it is more advantageous to utilize the alterative gear technology (e.g. circle hooks). These treatments are still costly and reduce catch, however, the vessels and the fleet as a whole can still contribute to the economy and provide consumers with a quality product from the Grand Banks fishing area.

5.2 Recommendation

This study recommends the reopening of the Grand Banks, using Treatment 2 when swordfish-directed and Treatment 6 when tuna-directed. This will increase efficiency, but may significantly reduce catch. Reopening the area and restricting the use of j-hooks will provide the most environmentally advantageous results. This is a viable solution to the problem associated with the Grand Banks swordfish fishery, as it serves as a proven and practical method for the reduction of sea turtles while allowing longliners to continue their trade and compete with the foreign fleets.

This proposed policy is a balance of environmental protection and commercial viability. It is important to remember the economic impact that will be forced on the fishermen if the Grand Banks remains closed and they are not allowed to fish at all. This policy is the most practical option as well as the most efficient, without jeopardizing the continued existence of the sea turtle as well as the longline industry.

Sea turtle bycatch is an international problem and cannot be solved by simply restricting U.S. longlining activities. That is not to say that domestic restrictions do not help internationally. However, a domestic strategy without an international strategy is insufficient and will only lead to the decline of the already reduced sea turtle populations. Also, longliners are not a single entity. The longliners that fish the Northwestern Atlantic for swordfish and tuna are very different than those longliners in the Gulf of Mexico, fishing yellowfin tuna. The boats, crew style, fishing strategies, target species, and economics are all different. The only common thread is that all use gear that catch the same desirable species, but also catch the same undesirable species (e.g. sea turtles). This is also true for all international fleets that fish in the world's oceans.

The United States has had two main remedies for dealing with the mitigation of sea turtle bycatch. The first is to close those areas with the highest bycatch, also known as hotspots. This approach was used, and is currently still in use in the Northwest Atlantic[19]. However, due to the gear modification study, the area may be reopened. These types of closures, without corresponding to a reduction in fleet size, can only cause fishing efforts to be shifted. As in the case of the closure of the Northwestern Atlantic, many vessels switched gear or moved to the Gulf and South Atlantic to harvest fish. Another problem associated with this method, is that the data used to assess the stocks are based on historic catches and are in no way able to determine the impact on the bycatch species. This method is merely a Band-Aid for today's immediate problem, in the hopes that it will not do more damage elsewhere. The other approach is gear modification, which this project is focused on.

Policy makers must choose between policies seeking greater efficiency or policies that intend to provide for greater fairness, or equity in the fishery. This often arises when

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[19] Based on the scientific findings of the three-year turtle mitigation study the Grand Banks area was re-opened to longline vessels under strict gear regulations. J- hooks were banned in all Atlantic longline fisheries including the Gulf of Mexico and the U.S. Caribbean. The area of interest, the Grand Banks was re-opened with the following guidelines. All vessels with longline gear onboard that fish in the area of the Grand Banks must possess and use only 18/0 or larger circle hooks with an offset not to exceed 10 degrees. Vessels are also required to bait the hooks with only whole finfish or squid. Therefore, Treatments 2, 3, 4, and 7 can be used in the Grand Banks area.

there are significant economies of scales, so that larger, more capital-intensive units with lower labor requirements are more profitable than small-scale units.

5.3 Limitations

There are several limitations to this study. Human error in data entry may cause noise and outliers in the data, having a dramatic effect on the analysis. DEA does not have the capability to deal with noise and outliers that may have occurred due to data entry error. Another limitation to the study caused by the data, is that some gear components will not be included in the analysis due to their non-numerical coding.

It is important to mention that this study analyzed results from an experiment in the area with colder water temperatures and other special conditions, which make it impossible to duplicate in other regions. Therefore, the analysis is only applicable to the Northwest Atlantic. More studies will need to be completed to test the gear and its efficiency level in warmer regions of the Atlantic, as well as in the Pacific, for efficiency due to sea surface temperature being a key component of the analysis.

The study has limitations. Although our sample represents more than half of the experimental sets, our analysis did not take into account those sets without a treatment associated and any set that was missing information relevant to the analysis. Because of the use of set level data, I cannot examine trip level or seasonal variation in the performance of the vessel. My data analysis focuses only on the technical efficiency of each treatment on a set level. Therefore, further study is recommended to analyze seasonal and location effects on efficiency by collecting trip level data using one hook type. It is also recommend that data be collected following the reopening to compare results.

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VITA

Tara Lee Scott

Born in Farmville, Virginia, on January 6, 1980. After many moves finally settled in Appomattox, Virginia, where she graduated from Appomattox County High School in 1998. Received a Bachelor of Science in Environmental Policy and Planning with a minor in Environmental Science from Virginia Polytechnic Institute and State University in Blacksburg, Virginia in 2002. Entered the School of Marine Science at the College of William and Marine in September of 2002.