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Modeling protected species as an undesirable output: The case of sea turtle interactions in Hawaii's longline fishery

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Abstract

Interactions with sea turtles have occurred at an alarming rate in swordfish longlining in Hawaii in recent years and various regulations have been put forward to protect sea turtles. In order to understand the cost of reducing sea turtle interactions, methods have been developed to derive the shadow price of sea turtle bycatch based on fisher's welfare loss from a specific regulation. This paper illustrates an alternative method of calculating temporal and trip-specific cost of sea turtle bycatch reduction. The advantages of this method lie in the computation of shadow price without assuming specific regulation implementation and its relatively modest data requirement. A parametric output distance function is used to simultaneously model desirable and undesirable catches. Using the duality argument, the revenue-related shadow price of sea turtle bycatch can be derived from the estimated distance function. Average shadow price of sea turtle bycatch for the period 1991–1999 is estimated to be US $30 873 in 1991 dollars. Average shadow prices of sea turtle bycatch by trip characteristics, such as fishing year, trip type and location are also estimated. Such information can be useful for policy makers to analyze tradeoffs and make appropriate policy decisions.

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Keywords: Hawaii's longline fishery; Incidental catch; Output distance function; Sea turtles; Shadow price; Undesirable output

1. Introduction

Incidental take[1] of sea turtles by the Hawaii-based longline fishery is a critical problem facing the industry. More than 634 documented turtle catches were reported by longline logbook records between 1991 and 1999. This number is probably a gross underestimate of actual turtle catches, because Kleiber (1998) has estimated that approximately 700 sea turtles were caught, and around 100 were killed in 1995 alone. In response to the high catch rates of loggerhead and leatherback turtles north of 30° N, fishery scientists have suggested closure of fishing areas north of 30° N to minimize turtle interactions (see for example, Nitta and Henderson, 1993).

The majority of interactions with turtles occur during "shallow set" swordfish longline operations as opposed to tuna-target operations that employ relatively deeper sets. Swordfish longline fishing generally is divided into two major segments: swordfish- and mixed-target fishing. Swordfish fishing techniques have proven more dangerous to turtles than deep-water tuna fishing, because the minimum depth of longline fishing for tuna is set at 328 ft, while the standard depth of a swordfish set ranges from 70 to 100 ft (Ito and Machado, 2001). Table 1 shows that swordfish- and mixed-target fishing trips account for most of the catches of sea turtles in Hawaii's longline fishery, together ranging from 86% to 97% of the total.

The large number of turtle catches in Hawaii's longline fishery has received tremendous attention in recent years. In 1999, the US district court ordered an emergency closure of more than a million square miles of international waters to vessels participating in Hawaii's longline fishery. During this temporary emergency closure, the US National Marine Fisheries Service (NMFS) conducted an analysis of the interactions between sea turtles and longline fishing to

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[1] In this paper, the terms bycatch, incidental take, incidental catch and incidental capture are used interchangeably.

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better delineate the "appropriate time and area closures based upon the greatest benefit to the sea turtles and considering the costs to the Hawaii-based pelagic longline fishery" (Curtis and Hicks, 2000). Before NMFS released the final environmental impact statement (EIS), the Federal Court revised its 1999 order and issued a new order to: (1) close the area between 28° and 44° N latitude from 168° W to 150° W longitude (labeled as Area A in Fig. 1) for fishing throughout the year; (2) restrict the number of longline sets allowed between 28° and 44° N latitude from 173° E to 168° W longitude and from 150° W to 137° W longitude (labeled as Area B) from March 15, 2001 until May 31, 2001; and (3) prohibit swordfish longline fishing between 0° and 28° N from 173° E to 137° W (labeled as Area C).

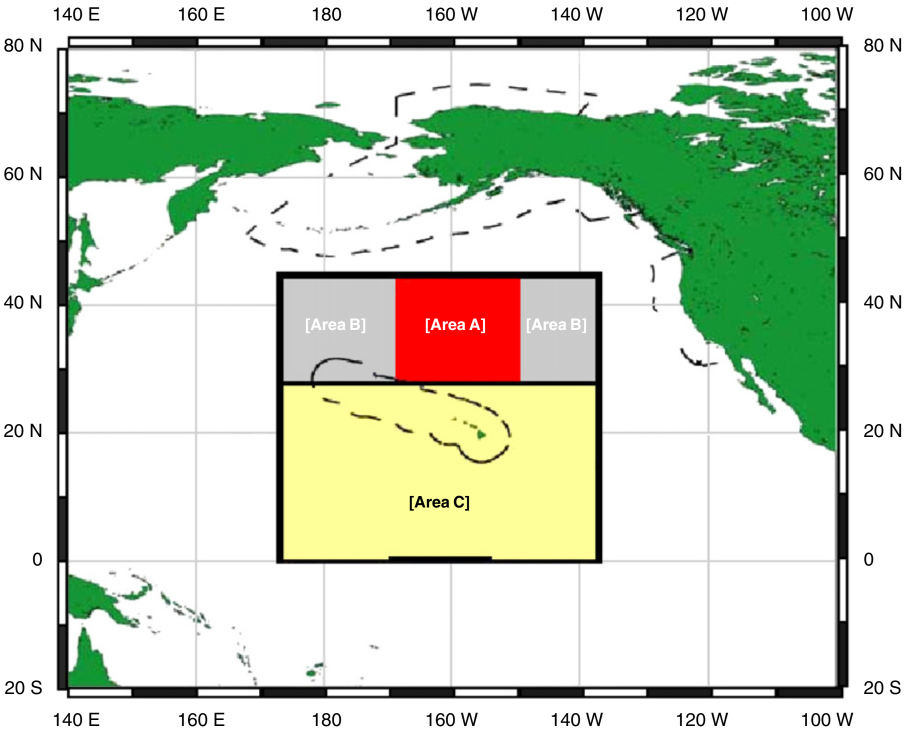
Table 1
Turtle catches by trip type, 1991–1999

Year	Number of turtle catches			% of catch by swordfish and mixed trips
	Swordfish trip	Mixed trip	Tuna trip	
1991	44	10	3	94.7
1992	57	6	2	96.9
1993	71	3	3	96.1
1994	61	2	2	96.9
1995	46	8	9	85.7
1996	38	40	9	89.7
1997	12	30	4	91.3
1998	34	54	10	89.8
1999	12	58	6	92.1
1991–1999	375	211	48	92.4

Source: Longline Logbook, Honolulu Laboratory, NMFS (1991–1999).

In March 2001, to provide maximum protection to the endangered turtles, and to adhere to the recommendations found in the final EIS released by NMFS, the court modified the fishing regulations prohibiting longline sets targeting swordfish. This prohibition included both a ban on swordfish shallow sets and closure of an area south of Hawaii (0–15° N, 145–180° W) for April and May (Masuoka, 2001; Nemoto, 2002).

This swordfish prohibition was not lifted until April 2004 when swordfish fishing was allowed to return with new restrictions: fewer fishing days; observers on board at all times; and strict limits on the number of turtles caught annually (16 leatherback turtles, 17 loggerhead turtles) (Hoover, 2004). At the same time, NMFS investigated a series of management measures and new fishing technologies in an attempt to optimize yields without threatening the existence of sea turtles. Investigated alternatives included a variety of time/area closures, the use of circle



(Source: Honolulu Laboratory, NMFS)

Area A: 44 N - 28 N, 168 W - 150 W

Area B: 44 N - 28 N, 173 E - 168 W and 150 W - 137 W

Area C: 28 N - 0 N, 173 E - 137 W

Fig. 1. Federal-court-ordered closures in 2000. No fishing is allowed in Area A; retricted number of longline sets is allowed in Area B but only with 100% observer coverage; swordfish-style longline fishing in Area C is precluded; Areas B and C are closed from March 15, 2001 until May 31, 2001.

hooks with mackerel type bait in shallow sets, and the use of light sticks which repel turtles but attract fish (for details, see WPRFMC, 2004).

While the effectiveness of both management and technological innovations remains uncertain, much effort has been expended to quantify the economic impacts of regulatory policies on the fishery (see for example, Chakravorty and Nemoto, 2000; Curtis and Hicks, 2000). Since the regulatory regime has changed so rapidly, there is a need to develop a methodology to estimate the economic costs of sea turtle reduction that is independent of regulatory vagaries.

This study uses the distance function methodology to deduce the price of sea turtle bycatch abatement, in which sea turtle bycatch is regarded as an undesirable output in fishery production. This method was originally developed by Fare and Grosskopf (1990) and employed by several economists in deducing shadow prices for pollutants (see for example, Coggins and Swinton, 1996; Cordero, 2003; Fare et al., 1993; Hailu and Veeman, 2000; Hernandez-Sancho et al., 2000; Reig-Martinez et al., 2001; Swinton, 1998).

The distance function methodology has shown promise in environmental control problems. However, the application of this method to study a renewable resource such as incidental catch requires special consideration of the unique characteristics of renewable resources in general. The distinguishing feature of most renewable resource industries is their reliance on the availability of natural stocks (Kirkley et al., 1995). To account for this concern, stock availability is included in the model by modifying the available data set, through division of each of the desirable and undesirable output quantities with its stock index. The cost of sea turtle bycatch abatement will be estimated from the distance function and the estimates will also be compared to those derived from other economic studies on sea turtle protection in Hawaii's longline fishery.

This paper is organized as follows. Section 2 contains reviews of previous studies on the economic cost of sea turtle protection and comparison of methods employed in those works with the one employed in the present study. In Section 3, the analytical model and the empirical method for estimating the shadow price of sea turtles is described. Section 4 describes the data set used and the data transformation method to handle the stock effect. Section 5 presents the empirical results and their interpretations. Concluding remarks appear in Section 6.

2. Previous works

Previous studies on the cost of sea turtle protection were usually based on the economic impact from area closures, and shadow prices of sea turtle bycatch were derived from the forgone welfare. Curtis and Hicks (2000) provided an economic impact study of the then proposed area closures using a random-utility model of effort allocation in Hawaii's longline fishery. Their model identified the factors that influence the fisher's choice of location and fishing strategy. Using the identified factors, they measured changes in fisher's revenue from a reduction in the geographic extent of fishing grounds. Their estimates indicated that, if tuna fishing would be exempted from the seasonal closure, the court-mandated closure would result in a \$41 262 loss per reduction in turtle interactions and \$52 976 projected loss for each turtle saved under the full closure (the area closure definition is slightly different from this paper; for details, see Curtis and Hicks, 2000).

Chakravorty and Nemoto (2000) developed another economic model for the multi-species longline fishery in Hawaii that incorporated the spatial and temporal distribution of effort and fish stocks. The economic impacts of regulatory policies, including conservation of offshore turtle populations, were simulated and examined. Their results were used to compute an implicit price of saving a loggerhead turtle in 1995 using Kleiber's (1998) estimate of 66 loggerhead turtles killed through interactions with longline gears. Their model results indicated that the cost of adopting turtle conserving policies in terms of forgone profits to the longline fleet was approximately \$14 000 per turtle.

Both of the models described above derived implicit valuations of sea turtle bycatch abatement through economic losses from regulatory policies and can be labeled as "regulation constraint" approaches. The present study employs an alternative method in deducing the price of sea turtle bycatch abatement, assuming that sea turtles are a non-marketable and undesirable output in Hawaii's longline fishery.

Two standard approaches exist to determine the value of an undesirable output in the absence of a market. The first approach examines the change in inputs necessary to abate the undesirable output and requires considerable price and quantity information for the input set (Swinton, 1998). The second approach examines the output side, which usually employs a distance function and derives the shadow price of any undesirable outputs using the duality argument, by either applying an output distance function (for example, Coggins and Swinton, 1996; Fare et al., 1993; Swinton, 1998) or an input distance function (for example, Cordero, 2003; Hailu and Veeman, 2000) or more recently a directional distance function (for example, Fare et al., 2004).

Adopting the second approach, the present study specifies an output distance function for a multi-product setting as defined by Shephard (1970), in which an undesirable output (sea turtle bycatch) is considered. This output distance function completely defines the production technology and is dual to the revenue function. Application of the dual Shephard's lemma to the output distance function yields the revenue-related shadow prices of all outputs. Through the assumption that the observed price of one desirable output equals its shadow price, the shadow cost of the undesirable output can be calculated and hence also shadow prices of all other outputs. The shadow cost of the undesirable output, i.e., sea turtle bycatch in our case, provides an indication of the marginal cost to the fishers of reducing their sea turtle bycatch.

The technique employed in this study has certain advantages over other methods used to derive the cost of sea turtle bycatch abatement. The approach used by previous studies generally specifies a welfare maximization behavioral model to calculate the lost welfare related to regulatory policies. The approach employed here does not require information on specific regulatory constraint, but instead uses the derived shadow price to infer the trade-off between desirable and undesirable outputs at the actual mix of outputs. Moreover, these shadow prices are obtained as part of a procedure that generates estimates of the structure of production technology as well as trip-specific measures of productive efficiency (Fare et al., 1993).

Other advantages of the present method include its relatively modest data requirements and its flexibility for shadow price comparison by trip characteristics. In particular, this method only needs information on one desirable output price and on input and output quantity of the fishery in various time periods. Since the model will provide variation of shadow prices by trip, it can be used to reveal the influence of other trip characteristics such as location and trip type. Using time series data, the present model also can estimate shadow prices in a manner that reveals their temporal variation. This contrasts with the "regulation constraint" methods used in previous studies, where usually the costs of sea turtle protection can only be derived for a certain period and it is relatively more difficult to conduct temporal comparison. The additional comparative information from the present study can help regulators develop fishing policy based on the varying costs of sea turtle protection.

In summary, this paper provides an alternative method of calculating the cost of sea turtle protection. This method, instead of calculating the overall welfare forgone because of certain policy implementation, constructs temporal and trip-specific shadow prices for sea turtles. These more specific estimates of the shadow costs offer additional information for policy-makers to analyze the trade-offs between the costs of sea turtle bycatch abatement and the level of sea turtle protection.

3. Specification of output distance function and shadow price derivation

3.1. Output distance function

Suppose a producer employs a vector of inputs denoted by $x = (x_1, \ldots, x_N)$ to produce a vector of outputs denoted by $u = (u_1, \ldots, u_M)$ including both desirable and undesirable outputs. The technology set denoted by T is defined as $T = \left\{(x, u) : x \in R_+^N, u \in R_+^M, x \text{ can produce } u\right\}$. The relationship between inputs and outputs can be represented by the output correspondence

$$P(x) \subset R_+^M$$

defined by

$$P(x) = \{u : (x, u) \in T\}. \tag{1}$$

The output set $P(x)$ denotes all output vectors that are technically feasible given the input vector x. An alternative representation of the technology, conveying the same information, is the output distance function. Following Fare and Primont (1995), the output distance function can be defined as

$$D(x, u) = \min_\theta \left\{\theta : \left(\frac{u}{\theta}\right) \in P(x), \theta \in R_+\right\} \text{ for all } x \in R_+^N, \tag{2}$$

where θ is the amount which projects the observed output bundle along a ray from the origin to the greatest potential output bundle given the input set.

The output distance function is illustrated in Fig. 2. The output set $P(x^\circ)$ is determined by a given input vector x°. For an arbitrarily chosen output vector, u°, $D(x^\circ, u^\circ)$ is the value which brings $u^\circ/D(x^\circ, u^\circ)$ on the boundary of $P(x^\circ)$ and on the ray through u°. In this example, u° is in the interior of $P(x^\circ)$ and thus $D(u^\circ, x^\circ) < 1$. If u° had been on the boundary of $P(x^\circ)$, then the value of the distance function would have been equal to one. It is noted that $u \in P(x)$ if and only if $D(x, u) \leqslant 1$.

After the introduction of a time trend in this particular case to capture technological change, Eq. (2) becomes

$$D(x, u, t) = \min_\theta \left\{\theta : \left(\frac{u}{\theta}\right) \in P(x, t), \theta \in R_+\right\}, \text{ for all } x \in R_+^N, \tag{3}$$

where t is the time trend variable, $P(x, t)$ represents the set of feasible outputs with technology at time t.

Technical efficiency can be derived simultaneously when calculating the output distance function. By the definition of output distance function, the value of the function actually provides an output-based measure of technical efficiency, i.e.,

$$\mathrm{TE}_u(x, u, t) = D(x, u, t).$$

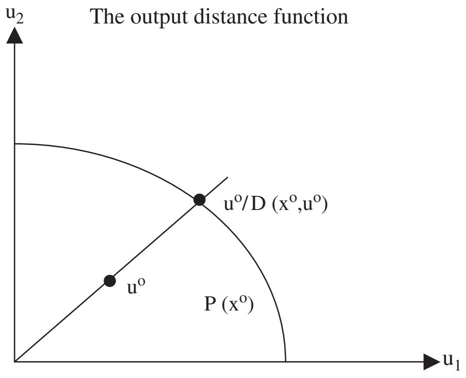


Fig. 2. The output distance function.

In other words, $(1-\mathrm{TE}_u)$ measures the proportion by which outputs would be increased by improving technical efficiency, keeping the inputs constant. If the output distance function has a value equal to one, the producer is operating on the technically efficient frontier. A value less than 1 indicates that the observed production is technically inefficient.

As discussed in earlier works on output distance function, the function, if well-defined, will always be linearly homogenous in outputs (Fare et al., 1993; Fare and Primont, 1995). It is also assumed the technology satisfies the other maintained axioms discussed in Fare (1988) and Shephard (1970). In short, the function has the following properties: it is a decreasing and quasi-concave function of x; and it is continuous, increasing and convex in u for each x. Complete characterization of the production technology also requires that outputs are freely disposable.

For the purpose of treating one output as undesirable, it is also assumed that the technology satisfies weak disposability of the undesirable output in order to capture the idea that reduction of undesirable output has to be achieved with certain cost.[2] To be specific, the disposal of the undesirable output would impose a cost in the form of a reduction of desirable outputs with inputs held constant. The weak disposability assumption of the undesirable output is consistent with the regulations which require reduction of sea turtle bycatch in this case. The reduction has an associated opportunity cost of forgone desirable output because it is resource-using.

Fare and Grosskopf (2004a) also noted that desirable and undesirable outputs are null-jointness, while they are thought to be jointly produced. The null-jointness property means that if desirable outputs are produced, undesirable outputs are also produced. In other words, if no undesirable outputs are produced, it is not possible to produce desirable outputs. In the present study joint production is explicitly modeled with the assumption of this property.

To distinguish between desirable outputs and undesirable outputs, different derivative properties of the distance function are imposed with respect to the two types of outputs. Since the value of output distance function measures the minimum value which brings the output set to the frontier with inputs held constant, the output distance function is non-increasing in undesirable output and non-decreasing in desirable outputs. As described later in this section, these conditions through restrictions on the derivative signs are imposed on the estimation of the parameters for the output distance function. In turn this allows undesirable outputs to have non-positive rather than non-negative shadow prices.

3.2. Shadow price derivation

The distance function approach inherits properties from the traditional means of presenting technology such as the production function. In addition, as it models joint production of multiple outputs, the duality between the output distance function and the revenue function allows retrieving the output shadow prices. The procedure works as follows.

The technology representations $P(x)$ and $D(x,u,t)$ rely only upon the data of input and output quantities. If one actual output price is known and assumed to be equal to its shadow price, the duality between technology and revenue makes it possible to estimate the shadow prices of other outputs. In a multi-output model in which all outputs are desirable, the optimality condition requires that for any two outputs the slope of the production possibilities frontier should equal the ratio of the corresponding output prices. The same reasoning can be applied to the present problem, except that the undesirable output will have negative shadow price, which reveals the marginal cost of undesirable output reduction to the producer. Therefore, the shadow price under the behavioral assumption of revenue maximization can be derived.

Let $r \in R^M_+$ denote a vector of output prices, and let the revenue function be defined from the distance function as the solution to the maximization problem as $R(x,r,t) = \mathrm{Max}_u\{ru: D(x,u,t) \leqslant 1, u \in R^M_+\}$. This equation is the duality relationship between the revenue and output distance function due to Shephard's Lemma. If the technology has convex output sets $P(x)$, for all $x \in R^N_+$, then one can prove that the following duality conditions hold:

$$R(x,r,t) = \underset{u}{\mathrm{Max}}\{ru: D(x,u,t) \leqslant 1, u \in R^M_+\},$$

$$D(x,u,t) = \underset{r}{\mathrm{Max}}\{ru: R(x,r,t) \leqslant 1, r \in R^M_+\}, \tag{4}$$

where ru is the inner product of the output price and quantity vectors. The revenue function can be derived from the output distance function by "maximization" with respect to outputs, while the output distance function is obtained from the revenue function through "maximization" over output prices.

To make use of the duality in finding shadow prices of outputs, the revenue function and distance function are assumed to be differentiable, and the Lagrange problem set for maximizing revenue over outputs can be expressed as

$$\underset{u}{\mathrm{Max}}\ R(x,r,t) = ru + \lambda(D(x,u,t) - 1). \tag{5}$$

Fare et al. (1993) showed that the corresponding first-order condition results in the solution vectors which satisfy

$$r = R(x,r,t) \cdot \nabla_u D(x,u,t), \tag{6}$$

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[2] The directional distance functions (see for example, Fare and Grosskopf, 2004b; Fare et al., 2005) have different property concerning undesirable outputs. The methodology of input or output distance functions forces all reductions in undesirable outputs through weak disposability constraint, while the directional distance function allows for simultaneous expansion of desirable outputs and contraction of undesirable outputs, at either the same or different rate.

where ∇ denotes the gradient operator. Let r^* denote the shadow price of an output, using second part of the duality conditions (4), the vector expression $\nabla_u D(x,u,t) = r^*(x,u,t)$ can be derived. Then, Eq. (6) becomes

$$r = R(x,u,t) \cdot r^*(x,u,t) \tag{7}$$

and the following alternative formula can be used to calculate the ratio of the shadow price of output i to that of output j:

$$\frac{r_i^*}{r_j^*} = \frac{\partial D(x,u,t)/\partial u_i}{\partial D(x,u,t)/\partial u_j}. \tag{8}$$

From Eq. (8), the ratio of the shadow prices is equal to the trade-off between the two outputs. If i denotes an undesirable output, j denotes a desirable output, the shadow price ratio between the two outputs is equal to the units of output j the producer would be willing to forgo for the right to reduce one more unit of undesirable output i. If it is assumed that the observed price of u_j equals its shadow price, the shadow price r_i of undesirable output u_i can be calculated according to following formula:

$$r_i^* = r_j^* \frac{\partial D(x,u,t)/\partial u_i}{\partial D(x,u,t)/\partial u_j}. \tag{9}$$

This formula is used in the present study to calculate shadow price for sea turtle bycatch.

3.3. Functional form and estimation of parameters

Following Christensen et al. (1973), the flexible translog function is chosen as a parametric form representing the production technology. It can be expressed as follows:

$$\begin{aligned}\mathrm{Ln}\, D(x,u,t) &= \alpha_0 + \sum_{n=1}^{N} \alpha_n \ln x_n + \sum_{m=1}^{M} \beta_m \ln u_m \\ &+ \frac{1}{2}\sum_{n=1}^{N}\sum_{n'=1}^{N} \alpha_{nn'} \ln x_n \ln x_{n'} + \frac{1}{2}\sum_{m=1}^{M}\sum_{m'=1}^{M} \beta_{mm'} \ln u_m \ln u_{m'} \\ &+ \frac{1}{2}\sum_{n=1}^{N}\sum_{m=1}^{M} \gamma_{nm} \ln x_n \ln u_m + \alpha_t . t + \frac{1}{2}\alpha_{tt} t^2 + \sum_{n=1}^{N} \alpha_{nt} t \ln x_n \\ &+ \sum_{m=1}^{M} \beta_{mt} t \ln u_m,\end{aligned} \tag{10}$$

where n indexes the vector of inputs such that the subscripts 1, 2 represent, respectively, gross tonnage of the vessel and number of hooks used in that trip; m indexes the output vector such that 1, 2, and 3 represent quantity of swordfish catch, tuna catch, catch of other species, respectively, while 4 represents the undesirable output, sea turtle in this study.

Aigner and Chu (1968) showed that the parameters of the distance functions could be estimated by linear programming. A similar parameter estimation approach has been used in several studies (see for example Coggins and Swinton, 1996; Fare et al., 1993; Swinton, 1998). This is accomplished by solving the maximization problem:

$$\mathrm{Maximize}_{(\alpha,\beta,\gamma)} \sum_{k=1}^{212} \ln D(x,u,t) - \ln 1 \tag{11}$$

subject to

(i)

$$\ln D(x,u,t) \leqslant 0, t = 1,\ldots,9,$$

(ii)

$$\frac{\partial \ln D(x,u,t)}{\partial u_m} \geqslant 0, t = 1,\ldots,9, m = 1,2,3,$$

(iii)

$$\frac{\partial \ln D(x,u,t)}{\partial u_m} \leqslant 0, t = 1,\ldots,9, m = 4,$$

(iv)

$$\sum_{m=1}^{4} \beta_m = 1,$$

$$\sum_{m'=1}^{4} \beta_{mm'} = 0 \quad m = 1,\ldots,4,$$

$$\sum_{m=1}^{4} \gamma_{nm} = 0 \quad n = 1,2,$$

$$\sum_{m=1}^{4} \beta_{mt} = 0$$

(v)

$$\alpha_{nn'} = \alpha_{n'n} \quad n,n' = 1,2,$$

$$\beta_{mm'} = \beta_{m'm} \quad m,m' = 1,\ldots,4.$$

Since the distance function takes a value of less than or equal to one, the natural logarithm of the distance function value is less than or equal to zero, the maximization of the objective function is equivalent to minimizing the sum of the deviations of observations from the unknown frontier that is being estimated. Inequality restrictions are included to represent the asymmetric treatment of desirable and undesirable outputs. The first set of constraints (i) requires each individual observation to be within the technology frontier. Constraint sets (ii) and (iii) ensure that the distance function be non-decreasing in desirable outputs and be non-increasing in the undesirable output. Thus, the desirable outputs have non-negative shadow prices and the undesirable output has non-positive shadow price. Constraint set (iv) imposes the linear homogeneity condition in outputs, which also ensures the technology satisfies weak disposability of outputs. The final set of constraints (v) imposes the symmetry conditions for the translog functional form. In summary, the estimation of the parameters for the output distance function with an undesirable output is carried out by minimizing the sum of deviations from unity subject to the set of specified constraints. These are feasibility constraints, monotonicity constraints relating to desirable outputs and undesirable outputs, linear homogeneity conditions, and translog symmetry restrictions. The linear program is solved using the Excel Solver to derive the parameter estimates.[3]

4. Data

The method described in this paper has never been applied to bycatch problems in renewable resources before. When applying the output distance function approach to turtle bycatch in fishery resources, a particular feature of the renewable resource has to be considered, i.e., how standing stock might affect catch. Production functions are especially influenced by the natural stocks. Harvests of different fish species may be very sensitive to recruitment and subsequent harvestable stocks. Estimated stock sizes or abundance indices are often used as proxies for stock availabilities and are included in fishery production models to provide indicators of resource conditions over the period of analysis. The present study follows the approach used by Koundouri et al. (2004) to include stock size by normalizing the catches in each time period using stock indexes, i.e., the catch in each time period is divided by the stock index in that time period. This data transformation is necessary to ensure that stock availability is explicitly considered when determining technical efficiency. For example, considering trips with the same technical efficiency, those facing larger stocks are assumed to have proportionally increased catches. By weighting output with the stock index, a measure of technical efficiency that excludes stock effects can be calculated.

To derive stock indices for the three major desirable outputs, tuna, swordfish and other marketable fishes, catch and effort data from the merged data set of logbook and HDAR (Hawaii Division of Aquatic Resources) (1991–1999) are used, following similar CPUE (Catch Per Unit of Effort) standardization procedures conducted for many fisheries (for example, Goni et al., 1999; Hoey et al., 1997; Kimura and Zenger, 1997; Large, 1992). Seemingly Unrelated Regression (SUR) is employed to analyze CPUE of the three desirable outputs between 1991 and 1999 and to provide consistent indices of abundance.[4] The estimated stock index of each month is used as a proxy for the stock size of that period. Similarly, the incidental catch is also normalized by its index of population abundance. In the present study, the population index for each month is constructed by averaging each individual trip level's CPUE of sea turtles.

Previous efficiency studies in fisheries have used capital, capital utilization, and stock size as key inputs. Physical measures of capital generally include measure of vessel size (for example GRT, length, width, etc.) and engine power (in kW or horsepower), while measures of capital utilization generally involve some measure of time fished, such as days, hours or trips (Pascoe et al., 2003). In this study, the physical measure of capital input employed is the gross tonnage of the boat, which is found to be highly correlated with vessel length, width, and horsepower of the engine. Number of hooks used during each trip is employed in the analysis as a proxy of capital utilization, which is correlated with trip length (days fished) in Hawaii's longline fishery.

The Logbook and HDAR data for Hawaii's longline fishery for the period 1991 to 1999 are the key sources of information used to construct the variables in the present model. The logbook data provide information on number of hooks, trip type, fishing location, landing date and number of sea turtle bycatch. The HDAR data provide information on total pounds of fish caught and sold as well as price of swordfish for each trip. The observations of sea turtle catch are extracted from the logbook data and they are merged with HDAR data to form an unbalanced panel data set consisting of 54 vessels, 212 swordfish and mixed trips. The merged subset of data used in the analysis represents two thirds of the extracted logbook data with sea turtle catch for the study period.[5] Besides the above-mentioned data, additional vessel-specific information such as gross tonnage is obtained from the data maintained by the US Coast Guard. Each of these 212 observations includes data on the three desirable outputs, one undesirable output, and two inputs as described in the previous

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[3] The stochastic frontier procedure was also attempted to estimate the parameters of the output distance function. The results, however, were not satisfactory as the feasibility and monotonicity constraints cannot be readily imposed. Without imposing the monotonicity constraints, it was found that more than 2/3 of the trips would violate the monotonicity conditions. We therefore chose to use the deterministic procedure of linear programming as it can impose all of the constraints.

[4] The SUR model is a multivariate approach which allows the error for different species response variables such as CPUE in the same time period to be correlated. To investigate the variation of catch rates of swordfish, tuna and other species with vessel fishing power, as represented by vessel class, and with trip types, year, month, and region, the following loglinear model is used for each output: $\ln \mu_{csyqa} = \varphi + \delta_c + \phi_s + \lambda_y + v_q + \eta_a + \varepsilon_{csyqa}$, where μ_{csyqa}: expected catch rate for vessel class c in month s of year y in region a by trip type q; φ: catch rate obtained by a tuna trip of vessel class 1 in January 1991 in region 1; δ_c: catch rate by other vessel classes relative to vessel class 1; ϕ_s: abundance in month s relative to January; λ_y: abundance in year y relative to 1991, v_q: catch rate change by other trip types (mixed trip or swordfish trip) relative to tuna trip; η_a: abundance in region a relative to region 1. Interactions of the independent variables are considered after testing for their significance.

[5] The mean statistics between the extracted logbook data with sea turtle catch and the merged data are similar. For example, swordfish trip and mixed trips account for 70% and 30%, respectively of the total in merged data, and 68% and 32%, respectively in the extracted logbook data. Yearly observations from 1991 to 1999 account for (12% vs 14%), (14% vs 16%), (12% vs 15%), (11% vs 12%), (12% vs 9%), (11% vs 10%), (9% vs 8%), (11% vs 9%), and (8% vs 7%) for the extracted logbook data vs merged data, respectively.

paragraph. Summary statistics for the data used are reported in Table 2.

5. Results and discussion

The maximization problem (Eq. (11)) is solved as a linear programming problem using the 212 observations and subject to the set of constraints (i)–(v). The resulting parameter estimates appear in Table 3. These estimates are used to calculate the value of the output distance function according to Eq. (10). The value of the function, which is also a measure of technical efficiency, indicates where each trip lies relative to the estimated efficient frontier. Catching more fish from a given input set moves a trip's output bundle closer to the frontier and $D(x, u, t)$ closer to 1. The average values of distance function for each year appear in column 2 of Table 4. The overall average value across all trips is approximately 0.7647, indicating that the sample trips on average operate at 76% of their potential.

The computation of technical efficiency is not the primary focus of this work, but rather the focus is on the trip-specific shadow price of the undesirable output. The shadow price of reducing turtle bycatch as undesirable output for each trip is calculated using Eq. (9) and it represents the marginal value of the revenue forgone to reduce turtle bycatch. As discussed in Section 3, in a multi-output model including both desirable and undesirable outputs, the optimality condition requires that any two outputs produced on the production possibilities frontier should equal the ratio of the corresponding absolute output prices. To derive the absolute cost of reducing sea turtle bycatch, it is assumed that the absolute shadow price of one desirable output is equal to its observed market price. In this study, the observed market price of swordfish is used as its shadow price for the following reasons: swordfish is the major catch of the sampled trips in this study, accounting for more than 70% of the total outputs (see Table 5); and shallow sets targeting for swordfish substantially increase the risk of incidental capture of sea turtles, indicating a certain cause–effect relationship between swordfish catch and sea turtle bycatch. In accordance with the optimality condition and the assumption that swordfish market price equals its shadow price, the shadow price of sea turtles can be derived.

Table 2
Descriptive statistics of variables included in the analysis, 1991–1999 (54 vessels, 212 obs.)

Variable (units)	Mean	Std. dev.	Min	Max
Inputs				
Gross tonnage	127.88	37.31	57	199
Hooks (thousands)	12.63	5.10	0.75	25.40
Desirable outputs				
Swordfish (thousand pounds)	20.42	12.29	0.62	66.39
Tuna (thousand pounds)	4.13	3.45	0*	16.09
Other (thousand pounds)	1.18	1.40	0*	9.46
Undesirable outputs				
Turtle (number)	1.84	1.41	1	10
Ex-vessel price				
Swordfish ($/pound)	3.19	0.58	0.53	5.21

Note: The translog function selected in present study requires all desirable outputs and undesirable outputs to be >0. This is not the case for every observation in the data set used. There are 10 observations having zero outputs in tuna or other species. In order to include these observations, a very small number 0.001 (1 pound) is used to replace the zero value when estimating the parameters.

Table 3
Parameter estimates of the output distance function

α_1	−0.8038	β_{11}	0.0014	β_{44}	0.0652	α_t	−0.0632
α_2	−0.0122	β_{12}	−0.0265	γ_{11}	0.0105	α_{1t}	0.0104
β_1	0.0609	β_{13}	0.0021	γ_{12}	0.1221	α_{2t}	0.0020
β_2	0.6062	β_{14}	0.0191	γ_{13}	0.0442	β_{1t}	0.0057
β_3	0.1932	β_{22}	−0.1098	γ_{14}	−0.0916	β_{2t}	−0.0199
β_4	0.1397	β_{23}	−0.0092	γ_{21}	0.0082	β_{3t}	−0.0246
α_{11}	0.1870	β_{24}	−0.0234	γ_{22}	0.0034	β_{4t}	−0.0075
α_{12}	−0.0210	β_{33}	0.0036	γ_{23}	−0.0003	α_0	−0.1876
α_{22}	0.0085	β_{34}	0.0577	γ_{24}	−0.0965	α_{tt}	0.0129

Table 4
Yearly average technical efficiency and shadow price

Year	Technical efficiency	Shadow price (in 1991 USD)	No. of turtle/ 1000 lb swordfish
1991	0.7901	24 380	0.209
1992	0.7096	20 130	0.280
1993	0.6180	21 688	0.206
1994	0.7785	26 263	0.135
1995	0.8718	33 104	0.100
1996	0.8575	33 445	0.132
1997	0.8242	34 887	0.130
1998	0.8339	34 551	0.136
1999	0.8222	33 602	0.147
1991–1999	0.7647	30 873	0.182

Column 3 of Table 4 presents the average shadow prices of sea turtle bycatch for all trips in each year and the overall shadow price for the entire period. The overall average shadow price of a marginal decrease in sea turtle bycatch is $30 873 in constant 1991 dollars. This is the major finding of the present study. Meanwhile, the shadow prices of sea turtle bycatch for different years can also be compared to the results from other studies. For example, the 1997 average shadow price of $34 887 (in 1991 dollars) is comparable to the costs estimated by Curtis and Hicks (2000). They found that the average cost of reducing longline interactions with sea turtles was $41 262 ($33 843 in 1991 dollars) per turtle with partial seasonal closure, with a projected cost of $52 976 ($43 509 in 1991 dollars) per turtle under the full closure. Their estimated costs also represent forgone revenue from swordfish longline activities. Another study by Chakravorty and Nemoto (2000) found that the average price for each loggerhead sea turtle

Table 5
Characteristics of two trip types in sample data (1991–1999)

Trip type	Number of sets	Hooks per set	Light sticks per set	Average set time	Swordfish catch percentage
Swordfish	2464	823	647	6:00 pm	79
Mixed	745	800	425	7:00 pm	70

in 1995 was $14 000 ($12 343 in 1991 dollars). This figure is much lower than our result for 1995 ($33 104 in 1991 dollars) as it was computed on lost profit instead of lost revenue. Pradhan and Leung (2005) recently also estimated the shadow prices by employing a multi-objective programming model incorporating sea turtle interactions. They used the sea turtle catch data of 1993 and estimated that the shadow price per sea turtle bycatch was about $56 060 on average ($52 231 in 1991 dollars) in terms of lost revenue. Their number is much higher than the estimate from the present study ($21 688 in 1991 dollars), as it represents the average shadow prices measured at various "optimal" levels of sea turtle interactions rather than the actual observed levels.

The shadow prices from 1991 to 1999 presented in Table 4 demonstrate a temporal variation. The trip mean shadow prices of sea turtle bycatch are relatively lower during 1991 and 1994, ranging from $20 130 to $26 563 per sea turtle bycatch. The estimated shadow price increases to $33 104 in 1995 and becomes relatively stable thereafter. Shadow prices of sea turtles are determined by multiplying the marginal rates of transformation between sea turtle bycatch reduction and swordfish catch by the price of swordfish. The temporal variations reflect the fact that the trips that have a lower ratio of sea turtle bycatch to swordfish catch in the sample and are therefore more environmentally efficient have higher shadow prices than inefficient trips. In addition to bycatch rate, shadow prices of swordfish also affect the shadow prices of sea turtles. With a higher price of swordfish, it is relatively more costly to reduce one unit of sea turtle bycatch if the marginal rate of transformation remains constant. Column 4 of Table 4 presents the catch rate of sea turtles averaged across trips for each year. Since the prices of swordfish are not significantly different for most of the years from 1991 to 1999, lower turtle catch rates, in general, are associated with higher shadow prices.

Other than fishing year, average shadow prices can be computed for different trip types. As presented in Table 5, mixed and swordfish trip types involve a slightly different production technology, such as number of hooks, light sticks per set and average setting time, which may affect the shadow price of undesirable output. Table 6 presents average shadow prices across trips by trip type. Shadow prices of sea turtles captured in swordfish trips are relatively higher than mixed trips in most years. Across all trips from 1991 to 1999, a reduction of sea turtle bycatch could be achieved at a lower cost for mixed trips, about $6677 less per sea turtle, than for swordfish trips.

Table 6
Mean shadow prices by trip types

Year	Swordfish	Mixed
	Shadow price (in 1991 USD)	Shadow price (in 1991 USD)
1991	25 771	19 775
1992	22 293	12 970
1993	22 626	18 583
1994	27 249	22 999
1995	35 414	25 457
1996	37 170	21 114
1997	34 268	36 936
1998	39 137	19 370
1999	34 875	29 388
1991–1999	32 422	25 745

The average shadow prices of sea turtle bycatch reduction are also computed for different areas. The fishing region is divided into three major fishing areas as defined by the court orders in 2000 (Fig. 1) and the estimated average shadow prices of sea turtles in the three areas are presented in Table 7. The sum of sea turtle catch by area is also reported for comparison. It is found that Area A and Area B had relatively more takes of sea turtles compared to Area C during 1991–1999. The shadow prices of sea turtle bycatch in the three areas, however, are very close in magnitude. This indicates that restricting swordfish fishing from these areas will result in different levels of protection of sea turtles, while the average cost of reducing one sea turtle bycatch is the same no matter which area is involved.

6. Summary and conclusions

The incidental takes of sea turtles in Hawaii's longline fishery have led to various fishing restrictions to reduce the incidental captures of sea turtles, including area and seasonal closure to swordfish longline fishing. To inform regulators and to better understand the cost of reducing sea turtle interactions, different methods have been used to compute the shadow price of sea turtle bycatch based on fisher's welfare loss from a certain regulation. This paper illustrates an alternative method of calculating temporal and trip-specific cost of sea turtle bycatch reduction without assuming a specific policy implementation. A parametric output distance function that incorporates both desirable outputs and an undesirable output is employed as the main analytical framework. The output distance function can accommodate multiple outputs and allow for weak disposability of undesirable output. Using the

Table 7
Sea turtle catch and shadow prices by area

Year	Area A		Area B		Area C	
	Shadow price (in 1991 USD)	Number	Shadow price (in 1991 USD)	Number	Shadow price (in 1991 USD)	Number
1991–1999	28 796	160	32 873	173	29 831	53

duality argument, one can combine the estimated distance function with the price of swordfish, the major desirable output, to derive the shadow price for sea turtles. This analytical framework computes the shadow cost of turtle bycatch reduction from the trade-offs of desirable output and undesirable output.

One major advantage of the method presented here is that it provides the shadow price of sea turtle bycatch without imposing any policy constraints in the estimation. Another advantage of the approach lies in its modest data requirements. It relies only on readily available observed output and input data and requires no information concerning individual vessel production costs. Since shadow price is trip-specific, average shadow prices can be computed by certain trip characteristics such as time period, trip type, and location. This type of information could assist regulators in setting regulations according to trade-offs between number of incidental captures of sea turtles and costs of bycatch abatement.

Using the estimated output distance function, the overall average shadow price per sea turtle bycatch is estimated to be $30 873 for swordfish fishing. The estimates for different years are also compared to results from other studies and the figures are found to be of relatively similar magnitude.

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