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ANALYSIS

Incorporating sea turtle interactions in a multi-objective programming model for Hawaii's longline fishery

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ABSTRACT

There has been a growing concern about the interactions of endangered sea turtles with the pelagic longline fishery in Hawaii recently. Some tough measures including a swordfish harvest ban have been put into effect since 2000 to protect these turtles. Accounting for protected turtle species interactions with the longline fishery by the fishery management has become an increasingly important policy goal lately. A multi-objective programming model has been extended to incorporate sea turtle interactions as one of the fishery management goals in the Hawaii's longline fishery. The model result indicates that there is a tradeoff between fleet-wide profit and turtle interactions. It also indicates that there are possibilities of significantly higher profit and reduced turtle interactions compared to the base case scenario by reconfiguring fishing efforts. However, the current fishery policy related to sea turtle interactions disallows tapping of all the potential efficiency gain, as the number of turtles allowed to get interacted severely limits swordfish-targeted longline fishing that uses the conventional technologies. Banning longline activities are also costly, as the average shadow price per turtle in terms of lost profit is about $9120, and in terms of lost revenue is about $56,060. Adaptation to 'turtle-friendly' fishing technologies is among the many strategies that would allow for higher optimal fishing efforts leading to higher overall welfare.

1. Introduction

The concerns for environmental impacts of fishing activities continue to pose a serious challenge to fishery managers in devising fishery management policies that are both economically and environmentally sound. Fishery managers are considering more pragmatic regulatory measures to resolve issues primarily on the ecological front. Addressing these issues is particularly important with a view towards the ecosystem-based fishery management as a preferred approach for sustainable fishery management. The Magnuson Fishery Conservation Act of 1976 also embraces to achieve multiplicity of goals of both economic efficiency and environmental friendliness in the United States fisheries. However, these objectives are inherently conflicting and delicate to balance.

Having endured for millions of years, some of the sea turtle species are now categorized as critically endangered or threatened species. The latter half of the 20th century has been marked by catastrophic declines of sea turtle population (WPRFMC, 2002). Recently the pelagic longline fishery, a major component of Hawaii's commercial fishery, has been facing the challenge of protecting endangered or threatened sea turtles. Higher incidences of sea turtle interactions have been

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noticed after an influx of large number of technologically advanced longline fishing vessels to the state from the continental United States in the late 1980s. There has been a growing concern about increased turtle interactions with the longline fishery. Accounting for their interactions with the fishery has received much attention in fishery management decisions recently.

To protect the endangered sea turtles, there have been some tough policies being put into effect since 2000 governing Hawaii's longline fishery. As a result, the ban on the longline fishery to harvest swordfish (*Xiphias gladius*) had posed a larger risk of shutting down the fishery. A large number of longline vessels left Hawaii's water seeking opportunities elsewhere (Pradhan and Leung, 2004a). Stricter policies would obviously result in a more pronounced tradeoff between tangible economic benefits and environmental amenities. Both are desirable if can be attained simultaneously to their maximum or minimums (i.e., desired extremes). Absolute ban of the fishery, however, may not be a solution as the negative externality may be transferred to other locations or jurisdictions with less regulations and enforceability. It is important to determine how best to exploit desired fishery resources while minimizing undesired outputs i.e., sea turtle interactions. Beside the objective of maximizing profit from the fishery, the issue of minimizing sea turtle interactions has been, therefore, identified as an equally important policy goal by the fishery management recently.

With a goal to best utilize the fishery resources of Hawaii, different fishery management decision models, which are primarily based on the mathematical programming approach, have been in situ. These models have been used to analyze the potential impact of limited entry programs on the economic performance of various fisheries and fleets. However, these models were found to be rather limited as they couldn't realistically depict the actual fisheries for reasons such as the inherently nonlinear production relationship in fisheries, fleet non-homogeneity in cost, catch, and capacity. Further, they focused on the sole objective of profit maximization, but omitted fishers' micro-decision behaviors. Maximizing fleet-wide profit is one of many policy goals, but fishery policy problem is typically characterized by more than one goal to be optimized. A multi-objective approach has to be undertaken in order for any models to be useful for policy analysis (Leung et al., 1999). Consequently, a multi-objective programming model was developed and applied to study the relationships between Hawaii's commercial and recreational fisheries (Pan et al., 2001). The model aimed to maximize both the profit and recreational opportunities by accounting for fishers' micro-decision behaviors as well. Given the recent concerns on sea turtle interactions with the longline fishery in Hawaii, research and development for "turtle-friendly" improved fishing technologies are also concurrently underway to minimize sea turtle interactions with the fishery. Considering these facts, the primary objectives in this study are to trace out the economically and environmentally efficient loci of fishing efforts by estimating the optimal level of profit, fishing efforts, and corresponding sea turtle takes; examine the nature of tradeoff between fleet-wide profit and turtle interactions; and estimate shadow costs of sea turtle interactions. The multi-objective mathematical programming model by Pan et al. (2001) has been, therefore, modified to incorporate the issue of sea turtle interactions. Rest of the paper discusses sea turtle interaction issues in Hawaii's longline fishery, setup of the model with its assumptions and the parameters used, and the model results with some policy suggestions.

2. The longline fishery in Hawaii

The longline fishing technology was introduced to Hawaii by the Japanese in 1917. Longlining allows a single vessel to spread effort over a large area to harvest fish. Longline fishing gear consists of a monofilament main line strung horizontally across the ocean supported by vertical float lines at regular intervals. Fishing depth depends on the length of the float lines and the sag in the main line. Fishing depth and timing affects the efficiency with which different fish species are captured—shallower depth to target swordfish during nights, but deeper ones for bigeye tuna (*Thunnus obesus*) during days (Boggs and Ito, 1993). Bigeye tuna are targeted by deploying 12 to 25 hooks between floats with enough sag to reach depths of about 400 m, but only three to six hooks are deployed when targeting swordfish (Dalzell, 2000).

The Hawaii-based longline fishery is a year-round, limited entry, high seas fishery targeting various billfishes and tunas in the Central Pacific Ocean. Most fishing activity takes place in the region bounded by 0–45° N latitude and 180–140° W longitude (Pooley, 1993). By the 1930s the longline fishery was second only to the pole-and-line fishery in landed volume of fish, and accounted for most of the yellowfin (*Thunnus albacares*), bigeye tuna and albacore (*Thunnus alalunga*) landed in Hawaii. The fishery peaked in the mid 1950s, and then declined steadily through lack of investment in boats and gears until the late 1980s. The revitalization of the longline fishery was due to the development of local and export markets for fresh tuna to the continental United States and Japan, and the discovery of swordfish stocks around Hawaii. Bigeye tuna has been a major target species of the longline fishery since the 1950s. Swordfish was a minor species until the 1990s (Dollar, 1992; Curran et al., 1996).

The longline fishery has grown to be the largest and most prominent commercial fishery in Hawaii in a short span of time. Participation in the Hawaii longline fishery almost quadrupled from 37 vessels in 1987 to as high as 141 vessels in 1991. This number then leveled off at about 120 vessels from 1992 through 1994, declined slightly to 103 vessels in 1996, and increased to 125 vessels in 2000 (Ito and Machado, 2001). The older longline vessels measure about 43–70 feet and are capable of taking two-week trips, while the more modern vessels average 70–100 feet and can travel for 2–3 months (WPRFMC, 1995). The revitalized fleet also adopted modern longline gear and multitude of efficient technologies, such as acoustic doppler, current profilers, chromoscope fish finders, satellite navigation systems, and color video echo sounders (Dollar, 1992; Dalzell, 2000). The commercial pelagic catch totaled about 36 million pounds with ex-vessel revenue of $59 million in 1999 (WPRFMC, 2001). The longline fishery contributed to 28.3 million pounds with ex-vessel revenue of $47.4 million in 1999; however, the longline landings and sales declined to about 17.2 million pounds and $37.5 million, respectively, in 2002 after the swordfish harvest ban (WPRFMC, 2004a). Currently, the Hawaii fishery represents about 2.7% of the longline hooks deployed in the entire Pacific (Dalzell, 2000). Until recently, swordfish harvest was banned due to the concern over sea turtle interactions with the shallow-hooked longline swordfish fishing, and only deep-hooked longline tuna fishing was permitted. However, over fishing of bigeye tuna by various fleets has recently been a new concern.

3. Sea turtle interaction issue

Early on in the re-expansion of the Hawaii longline fishery it became apparent that the vessels fishing close to the Northwestern Hawaiian Islands would on occasion catch animals protected under the Endangered Species Act (ESA), namely the Hawaiian monk seal and the green sea turtle (*Chelonia mydas*). The displacement of the longline fishery from the shore solved the problem of interactions between monk seals, green turtles and small boat fishermen. However, longline vessels continued to interact with other sea turtles (Dalzell, 2000). The most common sea turtle species so far observed to interact with the fishery are green turtles, loggerhead (*Caretta caretta*), leatherback (*Dermochelys coriacea*), and olive ridely (*Lepidochelys olivacea*) (Kleiber, 1998). Higher interactions are reportedly with the fishing activities targeting swordfish. The issue has received much attention by policy-makers, fishers, and other stakeholders after the rapid expansion of the longline fleet in Hawaii recently.

There is a poor understanding about the basic sea turtle population, their distribution, habitat, migratory behavior, and magnitude of threats. Nest counts and turtle census are difficult to quantify; total number of breeding adults are still unknown for many breeding beaches; and the age class structure or composition of the population are poorly understood. While one can indicate a trend, there are still a lot of unknowns (Cousins, 2002). The National Marine Fisheries Services (NMFS) conducted a review of the fishery resulted in the issuance of the Biological Opinion and Incidental Take Statement (Opinion) in May 15, 1991. Under the Biological Opinion, the fishery agency must determine the level of interactions and mortalities, and compare these with population dynamics of the affected populations. The Opinion can then set limits on the volume of interactions and fatalities, which, if exceeded, require a fresh Biological Opinion (Dalzell, 2000).

A turtle take is defined as an interaction between a turtle and the fishing vessel or gear, and usually implies that the turtle become entangled in the line or was caught on a hook (McCracken, 2000). An allowable take up to 25 turtles per year was set based on hearsay information about the takes and opinions on the status of turtle stocks. Beginning in November 1990, NMFS had also set up to collect detailed information about the longline fishing activities from each fisher at the end of the fishing trip. In June 1992, the NMFS found that the incidental take of turtles reported in the 1991 logbooks exceeded the level set in the Opinion. Therefore, the NMFS conducted a second consultation to review the reported takes and the status of the turtle stocks using recent assessments. In a June 10, 1993 Opinion, the NMFS (1) determined that the Hawaii-based longline fishery did adversely impact the turtle species taken in the fishery, but was not likely to jeopardize their continued existence; (2) required the establishment of an observer program, and an annual review of turtle take using the observer data; and (3) revised the allowable take to 752 and mortality to 299 with no more than 150 leatherback turtle's mortality or serious injury (Skillman and Kleiber, 1998). A federally mandated observer program was put into effect since February 1994 to closely monitor the Hawaii-based pelagic longline fishing activities. The number of turtle takes by species, their conditions and circumstances, other species of concern, etc. are recorded by the observer for each longline set.

Table 1 presents an estimate of the magnitude of turtle interaction with Hawaii's longline fishery during 1991–2002. The turtle CPUE in Hawaii's longline fishery during 1994–2002 has remained about 0.0071 turtles per 1000 hooks in the tuna-targeted longline trips, and 0.1302 in the swordfish-targeted longline trips. Sea turtle interaction rate in Hawaii's longline fishery is considered relatively low compared to the other fisheries in the Atlantic and Pacific Ocean. However, in an attempt to conserve sea turtles, Earthjustice filed a lawsuit representing the Center for Marine Conservation and Turtle Island Restoration Network against the NMFS accusing negligence in its duty to protect endangered turtles in February 1999. The plaintiffs were concerned about all sea turtles but focused on the leatherback turtle, as its population in the Pacific had declined considerably over the past two decades. During the hearing in November 1999, the federal court judge found in favor of the defendants (NMFS) with

Table 1 – Estimates of turtle takes and kills in Hawaii's longline fishery during 1991–2002

Turtles species		1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Loggerhead	Takes	355	514	581	501	412	445	371	407	369	246	18	19
	Kills	62	90	102	88	72	78	65	71	64	106	8	8
Olive Ridley	Takes	118	108	115	107	143	153	154	157	164	113	36	31
	Kills	30	27	29	36	47	51	51	52	55	65	27	29
Leatherback	Takes	190	173	185	109	99	106	88	139	132	132	10	6
	Kills	8	7	8	9	8	9	7	12	11	45	3	2
Greenback	Takes	31	28	30	37	38	40	38	42	45	65	11	3
	Kills	0.5	0.5	0.5	5	5	5	5	5	6	35	8	3
Total	Takes	694	823	911	754	692	744	651	745	710	556	75	59
	Kills	101	125	140	138	132	143	128	140	136	251	46	42

Source: Kleiber (1998) for the years 1991–1993; and WPRFMC (2004b) for the years 1994–2002.

respect to their Biological Opinion on the sea turtles and their interactions with the Hawaii-based longline fishery. This meant that while interactions and some fatalities occurred, the judge agreed with the defendants that this had little influence on turtle population. However, the judge agreed with the plaintiffs that NMFS was delinquent under another government statute, the National Environmental Policy Act (NEPA), under which federal policies, laws, and regulations must be assessed with respect to their impact on the environment (Dalzell, 2000).

Based on the data provided by NMFS the majority of turtle interactions, particularly with loggerheads and leatherbacks, occurred to the north of Hawaii were possibly associated with the oceanic convergence zone. Consequently, the judge closed off ocean north of 28° N latitude and between 150° W and 168° W longitudes; ordered all vessels to carry clippers and dip nets to untangle any hooked turtles; and requested NMFS to conduct an analysis of the best combination of time-area closures and for the parties in the case to review the results and make their own recommendations. On June 23, 2000, the judge announced his order for the fishery that included a closure of all waters between 30° N and 44° N latitudes and bounded by 137° W and 173° E longitudes, with fishing allowed only south of 30° N to 6° N latitudes that reduced average annual effort by 95%. It also required observer coverage in all fishing trips to monitor fishing, and to close the restricted area in April and May. Following an intense period of protests and media campaigns launched by the Hawaii's Longline Association a stay was placed on the execution of the order and the judge agreed to work with the parties to seek a reasonable compromise. The negotiation acknowledges that Hawaii's longline fishery is not homogenous and that vessels targeting swordfish are responsible for the majority of turtle interactions. It maintains more or less the same area coordinates, but the southern boundary is now at the equator. Fishing north of 30° N latitude was banned except for a limited number of sets (i.e., 370 sets) for scientific observations with the condition that they must all be accompanied by observers. The ruling was to remain in effect until the completion of an environmental impact statement scheduled for April 1, 2001 (Dalzell, 2000).

The ban on swordfish longline activities had forced some of the vessels primarily targeting swordfish either to leave Hawaii or to switch to tuna fishing. Later in early 2004 the regulations governing longline fishery targeting swordfish were relaxed by the court conditionally as per the recommendation of the Western Pacific Fishery Region Management Council (Council). The final rule establishes a number of conservation and management measures for the fisheries to achieve the optimum yield while avoiding the likelihood of jeopardizing the continued existence of any species listed under the ESA. The rule eliminates a seasonal closure for longline fishing in an area south of the Hawaiian Islands and reopens the swordfish-targeted longline fishery based in Hawaii. This final rule implements both a regulatory amendment recommended by the Council under the Fishery Management Plan for the Pelagic Fisheries of the Western Pacific Region and Court rulings made in Hawaii Longline Association v. NMFS that vacated a June 12, 2002 rule containing protective measures for sea turtles, effective April 1, 2004 (Federal Register, 2004).

In order to minimize adverse impacts on sea turtles, the swordfish-targeted longline fishery has been subjected to some restrictions. The final rule establishes an annual effort limit that may be collectively exerted by Hawaii-based longline vessels in the amount of 2120 shallow-sets to the north of the equator. It requires to use only mackerel-type bait and circle hooks sized 18/0 or larger with a 10° offset (in contrary to the conventional J-type hooks) when making shallow sets, and to carry NMFS-approved turtle de-hooking devices. The rule also specifies the annual limits on the number of leatherback and loggerhead turtles allowed to be interacted at 16 and 17, respectively while engaged in shallow-setting. The shallow-setting component of the Hawaii-based longline fishery will be closed for the remainder of the calendar year when either of the two limits is reached. The number of interactions will be monitored with respect to the limits using year-to-date estimates derived from data recorded by NMFS vessel observers. The fishers are required to notify the Regional Administrator in advance of every trip whether the longline sets made during the trip will involve shallow-setting or deep-setting and require that they follow the type of setting declared throughout the fishing trip (Federal Register, 2004).

The above suggests the gravity of the sea turtle interaction issue associated with the longline fishery in Hawaii. Since pelagic longline fishery of Hawaii represents about half of the total domestic swordfish production, it is conjectured that restricting swordfish harvest in Hawaii may result in the supply of swordfish from other geographic regions or may lead to the identification of other transshipment points resulting in a degradation of marine environment. More turtle interactions may occur in the unregulated regimes due to the transferred market effect, as the demise of the U.S. swordfish landings from the Hawaii fishery may be balanced by increased landings from less regulated foreign fisheries that have a much higher take of turtles, which indeed appears to have been the case. A consorted international effort would certainly be necessary to reduce their interactions and mortalities.

4. The model

There are advantages of using mathematical programming over the optimal control theory and simulation techniques when one has to deal with a very large number of decision variables in a multi-objective and multi-level environment (Pan et al., 2001). This study modifies Pan et al.'s multi-objective programming model by incorporating the policy objective of minimizing sea turtle interactions with the longline fishery in Hawaii. The model specification also considers fleet heterogeneity and fishers' micro-behaviors to depict the fishery realistically and to capture the potential efficiency gains. Ideally, the holistic specification might include turtle biology, turtle and fish dynamics, economic cycles, policy dynamics, ecological and ocean conditions, etc. The current model is basically a static one, as it does not consider the inter-temporal dimension. The major components of the model-decision (control) variables, constraints and objective functions will be discussed in the following sections. The mathematical setup of the multi-objective programming model is presented below.

4.1. Objective functions

$$\text{Maximize } \Pi = \sum_i^3 \sum_j^2 \pi_{ij} \cdot E_{ij} \quad (1)$$

where

$$\pi_{ij} = \sum_k^6 p^k \cdot \hat{Y}_{ij}^k - c_{ij} - \omega \cdot L_{ij} \cdot D_{ij} - f_{ij} \quad (1a)$$

$$\text{Minimize } \Gamma = \sum_i^3 \sum_j^2 \tau_{ij} \cdot E_{ij} \quad (2)$$

where,

$$\tau_{ij} = t_{ij}^{\theta} \cdot \exp(X_{ij}\beta). \quad (2a)$$

4.2. Constraints

4.2.1. Trip and vessel constraints

Total trips for fleet:

$$\sum_i^3 \sum_j^2 E_{ij} - \sum_i^3 \varepsilon_i V_i \le 0 \quad (3)$$

Total trips for a vessel size:

$$E_i - \varepsilon_i V_i \le 0 \quad (4)$$

Total vessels in the fleet:

$$\sum_i^3 V_i - 141 \le 0. \quad (5)$$

4.3. Entry conditions

Trip entry condition:

$$N_{ij} E_{ij} \ge 0 \quad (6)$$

where,

$$N_{ij} = \sum_k^6 p^k \cdot \hat{Y}_{ij}^k - c_{ij} \quad (6a)$$

Crew entry condition:

$$\sum_i^3 \sum_j^2 \alpha_i N_{ij} \cdot E_{ij} - \sum_i^3 \sum_j^2 \omega \cdot L_{ij} \cdot D_{ij} \cdot E_{ij} \ge 0. \quad (7)$$

Owner entry condition:

$$\sum_i^3 \sum_j^2 (1-\alpha_i) N_{ij} \cdot E_{ij} - f_{ij} \cdot E_{ij} \ge 0. \quad (8)$$

4.4. Catch and effort relations and stock constraint

Catch per unit of effort (CPUE):

$$\frac{Y_{ij}^k}{F_{ij}} = q_{ij}^k \cdot B_s^k \quad (9a)$$

or,

$$Y_{ij}^k = q_{ij}^k \cdot F_{ij} \cdot B_s^k \quad (9b)$$

Operational model to estimate Eq. (9b):

$$\hat{Y}_{ij}^k = q_{ij}^k \cdot F_{ij} \cdot I_s^k \quad (9c)$$

Stock constraint for major targets:
Bigeye tuna catch limit:

$$\sum_i^3 \sum_j^2 E_{ij} \hat{Y}_{ij}^{be} \le H_{mx}^{be} \quad (10a)$$

Swordfish catch limit:

$$\sum_i^3 \sum_j^2 E_{ij} \hat{Y}_{ij}^{sw} \le H_{mx}^{sw}. \quad (10b)$$

4.5. Indices, variables, and parameters

Indices

- s — sth season (quarter) of a year
- i — fleet or vessel size (1=small, 2=medium, 3=large)
- j — trip types or target species (swordfish and tuna trips)
- k — species (swordfish, bigeye, yellowfin, albacore, marlins, and others)

Variables

- Π — Total fleet-wide net economic welfare (US$ per year)
- Γ — Number of turtles interacted per year
- N_{ij} — Net revenue excluding labor and fixed cost in the ith fleet and jth trip type ($ per trip)
- Y_{ij}^k — Observed catch of kth species in the ith fleet and jth trip type (pounds per trip)
- $\hat{Y}_{ij}^k$ — Estimated catch of kth species in the ith fleet of jth trip type (pounds per trip)
- $\hat{Y}_{ij}^{be}$ — Estimated catch of bigeye tuna in the ith fleet of jth trip type (pounds per trip)
- $\hat{Y}_{ij}^{sw}$ — Estimated catch of swordfish in the ith fleet of jth trip type (pounds per trip)
- E_i — Number of trips per year by the ith fleet ($E = \sum_j^2 E_{ij}$)
- E_{ij} — Number of jth type trips per year by the ith fleet
- V_i — Number of vessels per year in the ith fleet
- L_{ij} — Number of crews per jth type trip by the ith fleet
- D_{ij} — Trip length in days (fishing and travel) by the ith fleet of jth trip type
- F_{ij} — Number of hooks (fishing effort) by the ith fleet and in jth trip type
- B_s^k — Stock or biomass level of the kth species at sth season of a year
- I_s^k — Stock index of the kth species at sth season of a year
- X_{ij} — A vector of explanatory variables (hooks per float, proxy of turtle population, soak time, fishing location, and dummies for season, bait type, lightstick color, and previous history of sea turtle interaction specific to the vessel) for the sea turtle interactions in the ith fleet and jth trip type
- t_{ij} — Trip length in days by the ith fleet and in jth trip type.

Parameters

- π_{ij} — Net profit (US$ per trip)
- τ_{ij} — Number of turtles interacted per jth type trip in the ith fleet
- c_{ij} — Expected variable cost excluding labor and fixed cost ($ per trip)

f_i	Expected fixed cost for the *i*th fleet ($ per vessel per year)
f_{ij}	Per trip fixed cost for a vessel in the *i*th fleet and *j*th trip type ($ per trip)
p^k	Expected price of the *k*th species
ω	Expected wages of crews ($ per day)
q_{ij}^k	Catchability coefficient (stock index adjusted) of *k*th species by *i*th vessel in *j*th trip type
ε_i	Maximum average number of trip per year of a fleet size class during 1991–1998
α_i	Share of net revenue after the variable trip expenses received by the crew
θ	The coefficient of trip days
β	A conformable matrix of unknown parameters to be estimated in the turtle interaction model.
H_{mx}^{be}	Historical maximum bigeye tuna catch by the longline fleet during 1991–1998 (pounds)
H_{mx}^{sw}	Historical maximum swordfish catch by the longline fleet during 1991–1998 (pounds)

4.6. *Decision variables*

Fisheries in the United States are often managed by regulating fishing efforts of various forms, such as limited entry, area or seasonal closures, trip and catch quotas, restrictions on size and type of fishing vessels, etc. Hence, the major decision (control) variable considered in the present model is the fishing efforts (E_{ij}) in terms of the annual number of *j*th type trips by the *i*th vessel size class.

4.7. *Objective functions*

Generally in natural resource management studies, objectives are classified under three categories: economic, social, and environmental. Fisheries management is characterized by multiple objectives, and decision making is often impeded by different stakeholders placing different importance on these objectives. Conflict between interest groups is caused by a lack of understanding of the importance of objectives held by the various interest groups involved. Multiple objectives in fisheries management can not be simultaneously optimized. However, policy direction must still be identified (Wattage et al., 2005). Two policy objectives considered in the multi-objective programming model in this study are: (1) maximize the fleet-wide profit and (2) minimize sea turtle interactions with the longline fishery. The objective functions are as represented in Eqs. (1) and (2). These objectives are primarily from the point of view of maximum utilization of fishery resources and the protection of marine environment. Fleet-wide welfare is measured by the aggregates of net profit or economic rent to the longline fishing community, i.e., the income from fish sales after deducting variable and fixed expenses is the basic economic incentive or behavioral assumption in this analysis. While carrying out longline fishing operation at sea some negative environmental externalities may be expected, and the damage to the sea turtles is of primary concern. The estimation of the profit (π_{ij}) from fishing operation is based on catch estimates as established from the stock index adjusted catch per unit of effort (CPUE) relationships by vessel and trip types.[1] Similarly, the amount of negative externality by vessel sizes and trip types is represented by a set of sea turtle interaction parameters (τ_{ij}) as in Eq. (2a). These parameters were estimated using the Poisson and negative binomial distribution model of turtle incidences derived from Pradhan and Leung (in press).[2] Finally, a tradeoff between these two conflicting but economically and environmentally important goals will be examined by tracing the efficient *Pareto frontier*.

4.8. *Constraints*

4.8.1. *Trip and vessel constraints*

The relationship between the number of trips and the annual fleet size is illustrated by Eqs. (3) to (5). Constraints on the number of vessels and trips allowed for fishing were imposed in a way that they would not overexploit the longline fishery resource base. Therefore, the total number of vessels is capped to the historical maximum. Although the policy allows to operate 164 longline vessels in any given year the maximum number of vessel operating in a year during 1991–1998 had remained at only 141 (Eq. (5)). Vessels operating during transition years 1999 and 2000 were excluded as many of the vessels had already ceased operation for those years in anticipation of the swordfish fishing ban. Further, the total trips taken by vessels of the *i*th size is bounded from above by the product of the maximum number of vessel for that size category and the maximum annual average number of trips during 1991–1998 (Eq. (4)).[3] Finally, the total combined trips (tuna and swordfish trips) are constrained to be allocated between tuna and swordfish trips, and it is not allowed to exceed its historic maximum trips for a trip type in a vessel size class (Eq. (3)).

4.8.2. *Entry conditions*

A set of entry conditions were placed to capture the micro-behavior of fishers so as to avoid unrealistic solution. These conditions were needed as fishers make a fishing decision with some expectations. These conditions are the trip-entry condition (Eq. (6)), the crew-entry condition (Eq. (7)), and the owner entry condition (Eq. (8)). The trip-entry condition ensures that short-run profitability of a fishing trip is met, i.e., revenues must cover variable expenses. The owner-entry condition would require the owner's net income should exceed the fixed

[1] The profit per trip (π_{ij}) in swordfish trip has been estimated as ($3168), $874, and $18,147 for the small, medium, and large vessels, respectively, in 1993. Similarly, the profit per trip in tuna trip is estimated as $7325, $5509 and $8338 for the small, medium, and large vessels, respectively, in 1993.

[2] The parameter τ_{ij} in swordfish trip has been estimated as 0.4900, 0.7800, and 1.2300 turtle per trip for the small, medium, and large vessels, respectively. Similarly, the τ_{ij} in tuna trip has been estimated as 0.0026, 0.0370, and 0.249 turtle per trip for the small, medium, and large vessels, respectively.

[3] During this period the maximum number of vessels of a size class operating in a year were 28 (small), 61 (medium), and 49 (large). The maximum average number of trips per year taken by a vessel of a size class during the same period was 16.60 (small), 12.50 (medium), and 11.20 (large). The product of these two maximums would give a maximum feasible 465 (small), 763 (medium), and 349 (large) trips (by different vessel size categories).

costs (opportunity costs of investment, depreciation, maintenance, insurance, etc.). Finally, the crew-entry condition would require that crew's net income to be higher than the opportunity cost of their labor. In other words, the portion of crew share of revenue should exceed the shadow price of their labor evaluated at State's minimum wages for the days they are in fishing activities. The crew share of net revenue (α_i) is set as 0.50, as the crew gets about 50% of the net income from the vessel owner. It is further assumed that the weighted average wage of the crew including the vessel captain is approximated at about $5 per hour in 1993 and crews are expected to work 12 h a day while they are on board for fishing.[4] All the resources are assumed to value at their opportunity costs, i.e., the direct costs for variable and fixed expenses including interests and depreciation on capital investments, but labor is approximately valued at the assumed minimum wages. The variable and fixed costs for the swordfish trip in this analysis are the weighted average costs of the mixed trip and swordfish trips with about two-third of weight to mixed trips from the cost-earning survey of 1993 (Hamilton et al., 1996). Excluding labor cost, the variable costs per trip for tuna trips in 1993 were $9808 for small vessels, $10,876 for medium vessels, and $12,060 for large vessels. Similarly, the variable costs for swordfish trips were $21,259 for small vessels, $28,496 for medium vessels, and $38,531 for large vessels. The fixed costs per trip for tuna trips in 1993 were $5665 for small vessels, $6911 for medium vessels, and $8430 for large vessels. Similarly, the fixed costs for swordfish trips were $8325 for small vessels, $9703 for medium vessels, and $12,137 for large vessels.

4.8.3. *Stock constraint*

Conservation of fishery resources is an important goal in any fishery management for a sustainable harvest. No explicit mathematical constraint was put for stock level since we do not have the estimates of stock or biomass level, but this goal is embraced in the profit maximization objective in a way that the expected catch used in the profit function is estimated using the stock index adjusted catch per unit of effort (CPUE) for each species by season, year, trip type, and vessel size (Eq. (9c)). The CPUE relationship is established by Eqs. (9a)–(9c). Since we do not have the stock or biomass level of individual species, catch estimates in Eq. (9b) is estimated using species-specific stock index as a proxy of stock or biomass level as in Eq. (9c). Using a stock index as a measure of relative stock abundance can also be found in Dupont (1990), Pradhan et al. (2003), Pradhan and Leung (2004a,b) and Sharma et al. (2003). Following Pradhan et al. (2003), the index is created using the CPUE for each species by year, season, and trip type. The number of fish landed per 1000 hooks was used as a basis for the measure of stock abundance. The trip-level species-wise CPUE was later seasonally averaged for each year and by trip type. The CPUE is then normalized to create an index by the CPUE of a specific time period in the past as a base. In this study, the CPUE of the 1992 fall season by trip type is used as the base. The resulting index is 1 for the 1992 fall season. The value greater (smaller) than 1 for any given season of a year implies a better (worse) stock situation for that season relative to the 1992 fall season. The seasonal stock indices were created in a way that all fishers for a given trip type face the same stock or population level in a season of a year for the given species. The indices thus created also implicitly capture seasonal and annual stock variation, as well as the migratory pattern, recruitment, and other ecological aspects affecting CPUE.

A seemingly unrelated regression estimates (SURE) model was used to estimate the stock index adjusted catchability coefficient (q_{ij}^k) using the trip level observations and it was in turn used to estimate the per trip catch level for the kth species by vessel and trip types. Estimated catch ($\hat{Y}_{ij}^k$) can be derived by plugging q_{ij}^k in Eq. (9c) at the mean values of effort levels (F_{ij}) by trip type and vessel sizes and stock index levels (I_s^k). The estimated per trip catch level ($\hat{Y}_{ij}^k$) is then used in estimating the expected revenues or the profit functions. Stock index adjusted expected catch as in Eq. (9c) also captures the seasonal and yearly variation of the pelagic stocks. Furthermore, we impose a total catch constraint for the major targeted species in the model as in Eqs. (10a) and (10b). The optimal catch level of swordfish and bigeye tuna resulting by solving the model was constrained not to exceed significantly from their historical maximum catches.[5] By this way, it is assumed that the optimal solution from the model would not overexploit key species in the fishery.

4.9. *Data and other assumptions*

The data sources on catch, efforts, prices, and other relevant information for the analysis are primarily from the NMFS's logbook and observer records, Hawaii Division of Aquatic Resources (HDAR) revenue and landing information, the 1993 cost-earning survey of longline fishery (Hamilton et al., 1996), and various other published and unpublished sources for the model parameters. Information from various sources is clustered annually, and trips are aggregated to two categories, i.e., tuna- and swordfish-targeted trips.[6] The year 1993 is selected as a typical year for the pre-litigation decade preceding 2000, and also for reasons of the availability of cost earning data in that particular year as well.

5. Results and discussion

The Frontline System Solver, the mathematical programming Excel add-in, was used to solve the model in this study (Frontline Systems, 2003). The primary purpose of this study is to examine the tradeoffs between the management

[4] The minimum wage rate for crew is assumed at $4.25 per hour and for captain at $9.50 per hour. The crew : captain ratio boarded in a vessel during a typical fishing trip is assumed to be 4 : 1.

[5] Since the actual stock levels of major fish species (swordfish and bigeye tuna) were not available, we opted to constrain the optimal catches to be within the historical maximal catch levels of these species. The reference period for the historical maximum catch level is 1991–1998. The catch levels were estimated by using the optimal efforts solved and the trip level catch estimates of major species of fishes by trip type and vessel size categories.

[6] Mixed trips recorded in NMFS logbook record are considered as the swordfish trip as the fishing method used is nearly similar to as in targeting swordfish in the swordfish trip.

objectives of achieving economic efficiency and environmental healthiness. Each of the single objective function was optimized first and a tradeoff frontier between these two management goals, i.e., the fleet-wide profit and turtle interaction, was traced out using the non-inferior set estimation (NISE) method of Cohen et al. (1979).[7] The NISE method is the most effective technique to solve two objective problems. The method employs a weighted objective function to generate a tradeoff curve that represents the set of non-inferior solutions on the feasible region in the decision space (Pan et al., 2001). The optimal outcome from the tradeoff frontier will be a basis of turtle related fishery policy evaluation as compared to the base scenario. The result focused on the optimal profits, efforts, fish catches, and the amount of turtle interactions for a given effort and profit level. Finally, shadow prices of turtles were estimated in lost profits and revenues at different segment of the estimated tradeoff curve. By comparing the optimal solutions that resulted from the tradeoff frontier curve policy decision makers may choose appropriate measures to tackle the core issues in the fishery. The basic results are presented in Tables 2 and 3. They are also illustrated graphically in Fig. 1.

The existing level in 1993 with a fleet wide profit of about $7.23 million and revenue of about $49.65 million will be considered as a *base* scenario for subsequent comparisons. The total targeted bigeye tuna and swordfish catches for that year were about 4.72 million and 7.42 million pounds, respectively. Fishing activities in terms of the number of trips taken were as follows: 183 swordfish trips and 145 tuna trips by small vessels; 298 swordfish trips and 250 tuna trips by medium-sized vessels; and 201 swordfish trips and 176 tuna trips by large vessels. With this amount of longline activities the fishery experienced scores of turtle interactions. The estimated number of turtle interactions 583 turtles of which 89 turtles were estimated to be dead. About 88% of the interactions were associated with the swordfish-targeted longline activities. Of the total turtle interactions, loggerhead alone accounted for about 64% of the total at 372 takes, and leatherback accounted for about 20% of takes at 118 takes. The kill rates for these species from their own takes were estimated to be about 17% and 4% for the loggerhead and leatherback turtles, respectively.[8] The magnitude of interactions of these two species alone seems to be alarming and the number suggests the basis for recent policy scrutiny focusing on these species.

Following the NISE procedure the tradeoff between fleet-wide profit and turtle interaction was traced first by solving the two objective functions individually. The optimal solution to minimization of sea turtle interaction (*p2 min*) as in Eq. (2) suggests halting of all fishing operation. However, it is not pragmatic to halt all fishing operation. Solving for maximizing the fleet-wide profit individually (*p1 max*) resulted in the fleet-wide profit of about $12.40 million and corresponding revenue of about $65.20 million which is about 72% and 31% increase in profit and revenue from the base scenario, respectively. At the fleet-wide profit maximum total bigeye tuna and swordfish catches for the year 1993 would be about 5.59 million and 9.47 million pounds, respectively. This can be achieved by reconfiguring the fishing activities to 195 tuna trips by the small fleet; 339 swordfish trips and 424 tuna trips by the medium fleet; and 384 swordfish trips and 164 tuna trips by the large fleet. This would correspondingly require increasing the harvests of bigeye tuna and swordfish stocks by 18% and 28% more from base scenario, respectively. With this amount of longline activities, the fishery would also experience higher amount of sea turtle interactions. For example, about 756 sea turtle interactions could have occurred at this fleet-wide profit maximum, which is about 30% higher turtle interactions from the base scenario. Further, an estimate of 116 turtle kills might have occurred at *p1*. At the maximized profit level 97% of the turtle interaction is attributed to swordfish-targeted longline trips. At this optimum (*p1 max*) there could be as much as 482 (*85*) takes (*kills*) of loggerhead, and 154 (*7*) takes (*kills*) of leatherback turtles.

The maximum fleet-wide profit and minimum turtle interaction levels at points *p1* and *p2*, respectively, are ideal solutions but obviously conflicting. Hence, other efficient points were traced out between these two extremes of maximizing fleet-wide profit and minimizing turtle interaction. The tradeoff curve is not necessarily linear between the two extreme loci *p1* and *p2*, because the degree of conflict between the two objectives can vary in different parts along the tradeoff curve. Therefore, by using the NISE method the *p3* locus was traced from *p1* and *p2*. Similarly, the point *p1* and *p3* gave rise to *p4*; the point *p6* was generated from *p1* and *p4*; and the point *p5* was generated from the point *p3* and *p2*. The process continued till it ceased to generate new points. Connecting the new sets of efficient loci between two extremes *p1* and *p2* would give a convex *Pareto frontier* of fleet-wide profit and turtle interactions as illustrated in Fig. 1. The new set of points between *p3* and *p2* are not relevant to policy, as the turtle interactions in that range is of very negligible level. Moreover, at *p3* there is no swordfish longlining. However, the locus between *p3* and *p1* is of policy interests where there exists higher efficiency in both profit and turtle interactions as compared to the base scenario. Fig. 1 depicts the tradeoff between fleet-wide profit and turtle interaction. Tables 2 and 3 summarize number of swordfish trips, sets, number of trips by trip type and fleet categories, the amount of turtle interaction in terms of takes and kills number, and the shadow prices of sea turtles corresponding to each efficient (optimal) fishing locus.

When fishing is allowed to operate to maximize profit, it would yield 723 swordfish trips or 7475 sets by all vessel sizes. However, the recent policy related to the sea turtle regulation has capped 2120 sets for swordfish fishing (which corresponds

[7] In the NISE method each objective (Z_i) is given a weight (w_i) before all the objectives are added to a single objective function. The new objective function would become $\max_{\bar{x}\epsilon F_d} w_1 Z_1(\bar{x}) + w_2 Z_2(\bar{x})$ *s.t.* technical constraints, where $\bar{x}$ is a *n*-dimensional vector of decision variables and F_d is the feasible region. Subsequently, the efficient set is generated through parametric variation of weights.

[8] The estimates are from Kleiber (1998) that used a statistical procedure to estimate the turtle takes and kills for individual turtle species for each year during 1991–1997. The kill rates are the average ratios of the number of kills to the number of takes for the given species during 1991–1997.

Table 2 – Fleet-wide profit, revenue, catches of major target species, and fishing efforts (trips) at base scenario and different optimum points, Hawaii longline fishery 1993

1993	Profit $ million	Revenue $ million	Catch (million pounds)		Number of trips					
					Small		Medium		Large	
			Bigeye	Swordfish	Swordfish	Tuna	Swordfish	Tuna	Swordfish	Tuna
Base	7.2348	49.6456	4.7223	7.4197	183	145	298	250	201	176
p1 (max)	12.4022	65.2022	5.5961	9.4726	0	195	339	424	384	164
p6	12.1065	50.4226	4.6433	6.7182	0	195	0	424	384	165
p4	11.4375	47.5967	4.7699	5.5781	0	195	0	424	316	233
p3	5.7066	24.0493	3.7376	0.2102	0	195	0	424	0	233
p5	3.3709	12.6510	1.9705	0.1011	0	195	0	0	0	233
p2 (min)	0.0000	0.0000	0.0000	0.0000	0	0	0	0	0	0
Historical maximum (1991–98)			7.11	13.10	280	195	474	424	384	241

to approximately 205 swordfish trips or 10.32 sets per swordfish trip). Since the number at maximum profit level is way higher than what the recent policy has capped the number of sets for swordfish fishing, the next number closer to this policy would be at *p4* with 3267 sets or 316 swordfish trips. This number is still 54% higher than the one fixed by the recent policy on the maximum allowed sets. Further, at *p4* it can result in about 410 turtles takes.

The locus *p6* or *p4* has substantially higher profit level and lower turtle interactions compared to the base scenario. This suggests the policy makers may want to consider the reconfiguration of fishing efforts in order to achieve better economic efficiency and environmental soundness. However, the number of turtle interactions at those points is still much higher than the recent policy. The recent policy is stiff in the sense that it requires to halt the fishing operation for the rest of the year whenever the longline operation interacts with either of 16 loggerhead or 17 leatherback turtles. The loggerhead and leatherback turtles are of special interest here. Since the recent policy is in terms of the number of turtle takes but not kills, the fishery would have to operate at much lower level of efforts somewhere in the section between *p4* and *p3*. Potential gain in economic efficiency may not be captured despite much lower level of turtle interaction compared to the base scenario. However, if the policy is in terms of the number of turtle kills, the number of leatherback kills at *p1* would be only 7. In this case, the number of leatherback turtle interactions should not be a constraint for the fishery to operate at the maximum level as suggested by the model. However, the number of loggerhead takes (*kills*) alone at *p4* and *p3* are 261 (46) and 14 (2), respectively. The loggerhead takes and kills at *p4* is substantially higher than the policy limit which requires to abruptly reducing swordfish targeted longline fishing that uses conventional technology of fishing, such as J-type hooks. A further reassessment of loggerhead population dynamics in the fishery or the use of 'turtle-safe' fishing technology may lead to some room to accommodate for a higher optimal fishing efforts. Imposing the turtle regulation only in areas where loggerhead and leatherback forage and/or mostly get interacted would be another policy strategy of turtle mitigation measures.

The cost to the longline fishery or the shadow price of a sea turtle in terms of lost profit or the corresponding revenue because of turtle regulation is also estimated at various points along the tradeoff frontier. The marginal shadow price in terms of lost profit per turtle is $1124 at *p6*, $8060 at *p4*, and $14,770 at *p3*. Similarly, the corresponding marginal shadow price in terms of lost revenue per turtle is $56,196 at *p6*, $34,047 at *p4*, and $60,689 at *p3*. The average shadow price per turtle when fishery is halted to operate from *p1* to *p3* (i.e., the slope of points between *p1* and *p3*) is about $9120 in terms of lost profit, and $56,060 in terms of lost revenue. Further restriction of fishing effort beyond *p3* can result in much higher shadow cost per turtle. The shadow price estimates here does not take into account of lost opportunities in post-harvest value added economic activities to the local economy.

Table 3 – Fleet-wide turtle interaction and shadow prices of turtles at base scenario and different optimum points, Hawaii longline fishery 1993

	Turtle interactions in		Total turtle kills	Loggerhead		Leatherback		Shadow price (US$ per turtle)	
	All trip	Sword trip		Takes	Kills	Takes	Kills	Lost revenue	Lost profit
Base	583	569	89	372	65	118	5		
p1 (max)	756	736	116	482	85	154	7	–	–
p6	493	472	75	314	55	100	4	56,196	1124
p4	410	388	63	261	46	83	4	34,047	8060
p3	22	0	3	14	2	4	0	60,689	14,770
p5	6	0	1	4	1	1	0	712,394	145,981
p2 (min)	0	0	0	0	0	0	0	2,108,516	561,817

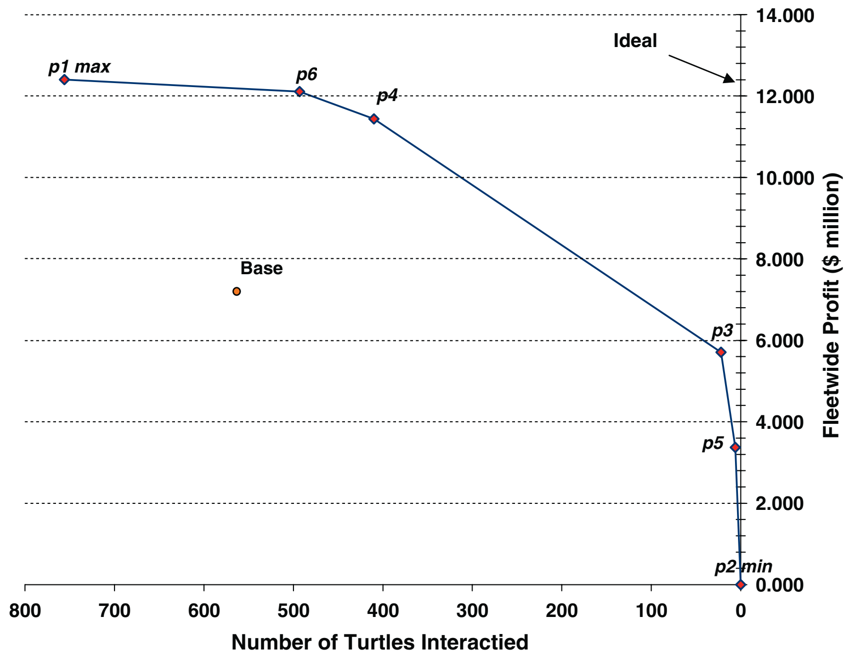

Fig. 1 – A tradeoff curve of fleet-wide profit to sea turtle interaction at various efficient locus, Hawaii longline fishery 1993.

The average shadow price estimates in this study are more or less close to the results from other studies. The study by Chakravorty and Nemoto (2000) find that the cost of adopting turtle conserving policies in terms of foregone profits to the Hawaii longline fleet is approximately $14,100 per turtle (loggerhead). This figure is higher than our result as it considers only one turtle species in estimating the shadow price. Curtis and Hicks (2000) suggests the average cost of reducing longline interaction with sea turtles is $41,262 per turtle with partial seasonal closure, and $52,976 per turtle projected cost under the full closure. These costs are in terms of forgone revenue from the swordfish-targeted longline activities. Our estimates are also comparable to those recently estimated by Huang and Leung (2005) using a parametric input distance function that incorporates both desirable and an undesirable output as an analytical framework for calculating the shadow price of sea turtle in Hawaii longline fishery. They estimated that the average shadow price per sea turtle bycatch is about $32,561. Therefore, the amount of income lost to the local economy due to turtle regulation is certainly not insignificant. As Chakravorty and Nemoto (2000) suggest these types of implicit valuations can be used by policy-makers to analyze tradeoffs and make appropriate policy decisions.

6. Conclusion

The analysis carried out in this article is novel as it incorporates the protected species interaction in the multi-objective programming model. The study can be further enriched by adding the spatial and temporal dimensions in the model. The results from the study indicate a significantly higher profit and reduced turtle interactions possibility by reconfiguring fishing efforts compared to the base scenario. In other words, a reduction in sea turtle interaction is possible without decreasing total fleet profits by reallocating fishing effort. There is a clear indication of an existence of a win–win situation in Hawaii's longline fishery. However, the current fishery policy related to sea turtle interaction may disallow the tapping of all the potential efficiency gain as illustrated from the model results, as the number of turtles allowed to get interacted severely limits swordfish-targeted longline fishing activities that use the conventional technologies (e.g., J-hooks). There is also a clear tradeoff between fleet-wide profit and turtle interactions. Where to limit the fishing effort along the frontier largely depends on the precise estimates of turtle kills rate or the growth rate for the key critical species. The use of turtle-safe fishing technologies would obviously leave some room to accommodate for higher optimal fishing efforts.

Banning longline activities that disallow targeting swordfish are costly, as the average shadow price per turtle in terms of lost profit is about $9120 and in terms of lost revenue is about $56,060. Furthermore, the shadow price estimates here does not take into account of post-harvest lost opportunities in value added economic activities to the local economy. In the long run, it would be advantageous to continue researching on turtle mitigation measures, or to implement turtle related fishery policies only in areas of high turtle incidences, or during the season when the turtles often get interacted. Rehabilitation and replenishment of endangered sea turtles and their habitats with the cultured sea turtles is another strategy one might consider so as to keep the longline fishery viable. Sea turtles may also be reared in developing countries and imported from there at low cost. The Council's proposed regulatory amendment was accompanied by proposals to implement or continue implementing five off-site sea turtle conservation projects. These projects are aimed at protecting affected sea turtle populations on their nesting beaches and in their near-shore foraging grounds at sites in Southeast Asia, Mexico, and Japan. These projects were considered and assessed by the Council in conjunction with the regulatory elements of its proposed action and were found to be important components of sea turtle conservation in the Pacific (Federal Register, 2004).

Since sea turtles are shared international resources, conservation and management of sea turtle population requires more than strongly focused domestic programs with more policy dialogues and cooperation among the coastal nations. The closure of longline fishery may have a transferred market effect and a degradation of marine environment may be anticipated from the less regulated regimes. All the coastal communities have equal responsibility for an environmentally sound responsible fishing, and a consorted international effort would be necessary to reduce their interactions and resulting mortalities.

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