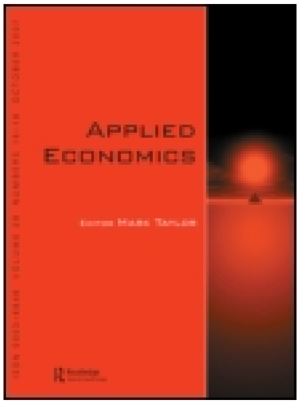

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Sea turtle interactions with Hawaii's longline fishery: an extended multi-objective programming model incorporating spatial and seasonal dimensions

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Endangered and protected sea turtle interactions with the pelagic longline fishery have become an important fishery policy concern recently. A multi-objective programming model for Hawaii's longline fishery that incorporated sea turtle interactions (Pradhan and Leung, 2006a) has been extended with spatial and seasonal dimensions. The synergetic effect of these added features indicate that there exists better economic and environmental efficiency gains in terms of higher profit and reduced turtle interactions, compared to the base case without these added dimensions, by reconfiguring fishing efforts across space and seasons. There also exists a trade-off between fleet-wide profit and turtle interactions. The current fishery policy related to sea turtle interactions disallows capturing all the potential efficiency gain, as the number of turtles allowed to get interacted severely limits swordfish-targeted longline fishing that uses conventional technologies. Restricting longline fishery to operate sub-optimally would result in average shadow value of $15 957 and $60 908 per turtle in terms of lost profit and revenue, respectively. These shadow values are higher than those estimated from earlier model without the spatial and seasonal dimensions. Adaptation to 'turtle-friendly' fishing technologies is among the many strategies that would allow for higher optimal fishing efforts and also leading to higher overall welfare and towards more responsible fishery.

I. 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 have been considering more pragmatic regulatory measures to resolve issues primarily on the ecological front and for more responsible fishery. 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

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also embraces to achieve multiplicity of goals of both economic efficiency and environmental friendliness in the US fisheries. However, these objectives are inherently conflicting and delicate to balance.

Sea turtles are considered to be highly revered and as part of the heritage in many religions, cultures and communities. They are also icons in some region's economic landmarks, such as Hawaii's tourism and hospitality industries. Having endured for millions of years, some of the sea turtle species are now categorized as critically endangered or threatened species because of the recent catastrophic declines of their population in the later half of the 20th century (WPRFMC, 2002). There has been a growing concern in Hawaii about the interactions of endangered sea turtles with the pelagic longline fishery. Higher incidences of sea turtle interactions have been noticed after an influx of a large number of technologically advanced longline fishing vessels to the State from the continental US in the late 1980s. Accounting for their interactions with the fishery has received much attention in fishery management decisions very recently as an approach towards a more responsible fishery. Some tough measures including a swordfish *Xiphias gladius* harvest ban have been put into effect since 2000 to protect these turtles. The ban on the longline fishery to harvest swordfish had posed a serious risk of shutting down the fishery as a large number of longline vessels have left Hawaii's water-seeking opportunities elsewhere (Pradhan and Leung, 2004). This ban was conditionally lifted in early 2004 and replaced with several alternative measures to protect the sea turtles. Stricter policies would obviously result in a more pronounced trade-off between tangible economic benefits and environmental amenities. Both are desirable if they can be attained simultaneously to their maximum or minimum (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 harness desired fishery resources while minimizing undesirable interactions with sea turtles. The issue of minimizing sea turtle interactions has been, therefore, identified as an equally important policy goal by the fishery management recently.

With a view to best utilize the fishery resources of Hawaii there are few decision support models developed and put into practice in the past. The earlier models analysed 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 could not realistically depict the actual fisheries for reasons such as: nonlinear production relationship in fisheries; fleet nonhomogeneity in cost, catches and capacities; and omission of fishers' micro-decision behaviours. Furthermore, maximizing fleet-wide profit is one among many policy goals as fishery policy problem is typically characterized by more than one goal to be optimized. Therefore, Leung *et al.* (1999) suggested that a multi-objective approach would be essential for policy analysis. Consequently, a multi-objective programming model was developed and applied to examine the relationships between Hawaii's commercial and recreational fisheries by Pan *et al.* (2001). The model aimed to maximize both the profit and recreational opportunities by accounting for fishers' micro-decision behaviours as well.

Given the recent concerns of sea turtle interactions with Hawaii's longline fishery, research and development for improved 'turtle-friendly' fishing technologies has also been underway. Considering these concerns, the multi-objective mathematical programming model by Pan *et al.* (2001) was, therefore, modified to incorporate the issue of sea turtle interactions by Pradhan and Leung (2006a). The work by Pradhan and Leung has been further expanded in this study by adding spatial and seasonal dimensions, as it is presumed that a more refined optimization in terms of economic and environmental efficiency gains may be achieved with these added features. The rationale for this presumption is that certain location of the sea in certain season of a year is more productive for harvesting some fish than other locations and seasons. The same may also hold true on the foraging habit of sea turtles in the sense that they may be less frequent in certain area of the sea and season of a year than other locations and seasons. The synergism between these factors could lead to a better optimal result, i.e. more of desired outputs (targeted fish species) and less of nuisance commodities (sea turtles by-catches). By considering these new features in the model, this study is designed to (1) trace out the economically and environmentally efficient loci by estimating the optimal level of fishing efforts, profit level and corresponding sea turtle takes; (2) examine the nature of trade-off between fleet-wide profit and turtle interactions; and (3) estimate shadow costs of sea turtle interactions when the fishery is operated sub-optimally. Readers interested in the detailed description about the longline fishery and sea turtle interaction issues in Hawaii's longline fishery are referred to Pradhan and Leung (2004, 2006a,b). Rest of the article discusses the setup of the extended model with its assumptions and the parameters used and discussion of the model results with some policy suggestions.

II. The Model

The model in Pradhan and Leung (2006a) is expanded by including spatial and seasonal dimensions. The model considers fleet heterogeneity and fishers' micro-behaviours to realistically depict the fishery and to capture the potential efficiency gains. The major components of the model–decision (control) variables, constraints and objective functions – will also be discussed in this section. The mathematical setup of the multi-objective programming model is presented as follows:

Objective functions

$$\text{Maximize } \Pi = \sum_a^5 \sum_s^4 \sum_i^3 \sum_j^2 \pi_{asij} \cdot E_{asij} \tag{1}$$

$$\text{where, } \pi_{asij} = \sum_k^6 p^k \cdot \hat{Y}_{asij}^k - c_{ij} - \omega \cdot L_{ij} \cdot D_{ij} - f_{ij} \tag{1a}$$

$$\text{Minimize } \Gamma = \sum_a^5 \sum_s^4 \sum_i^3 \sum_j^2 \tau_{asij} \cdot E_{asij} \tag{2}$$

$$\text{where, } \tau_{ij} = t_{ij}^{\theta} \cdot \exp(X_{ij}\beta) \tag{2a}$$

Constraints

Trip constraints

$$\text{Total trips for fleet: } \sum_a^5 \sum_s^4 \sum_i^3 \sum_j^2 E_{asij} - \sum_i^3 \sum_j^2 \bar{E}_{ij} \leq 0 \tag{3}$$

$$E_{asij} \geq 0 \tag{3a}$$

Entry conditions

$$\text{Trip entry condition: } N_{asij} E_{asij} \geq 0 \tag{4}$$

$$\text{where, } N_{asij} = \sum_k^6 p^k \cdot \hat{Y}_{asij}^k - c_{ij} \tag{4a}$$

Crew entry condition:

$$\sum_a^5 \sum_s^4 \sum_i^3 \sum_j^2 \alpha_i N_{asij} \cdot E_{asij} - \sum_a^5 \sum_s^4 \sum_i^3 \sum_j^2 \omega \cdot L_{ij} \cdot D_{ij} \cdot E_{asij} \geq 0 \tag{5}$$

$$\text{Owner entry condition: } \sum_a^5 \sum_s^4 \sum_i^3 \sum_j^2 (1-\alpha_i) N_{ij} \cdot E_{asij} - f_{ij} \cdot E_{asij} \geq 0 \tag{6}$$

Catch and effort relations and stock constraint

$$\text{Catch per unit of effort (CPUE): } \frac{Y_{asij}^k}{F_{asij}} = q_{asij}^k \cdot B_{as}^k \tag{7a}$$

$$Y_{asij}^k = q_{asij}^k \cdot F_{asij} \cdot B_{as}^k \tag{7b}$$

Operational model to estimate Equation 7b:

$$\hat{Y}_{asij}^k = q_{asij}^k \cdot F_{asij} \cdot I_{asij}^k \tag{7c}$$

Stock constraint for major targets

Bigeye tuna *Thunnus obesus* catch limit:

$$\sum_a^5 \sum_s^4 \sum_i^3 \sum_j^2 E_{asij} \hat{Y}_{asij}^{be} \leq H_{mx}^{be} \tag{8a}$$

$$\text{Swordfish catch limit: } \sum_a^5 \sum_s^4 \sum_i^3 \sum_j^2 E_{asij} \hat{Y}_{asij}^{sw} \leq H_{mx}^{sw} \tag{8b}$$

Indices, variables and parameters

Indices

a: a-th fishing area or zone:

Central:	15°–25°N & 150°–163°W
Northcentral:	> 28°N & 150°–170°W
South:	< 15°N
East/Northeast:	> 15N & < 150°W; 25°–28°N & < 158°W
West/Northwest:	25°–28°N & > 158°W; > 15°N & > 163°W

s: s-th season of a year (fall, winter, spring and summer)

i: Fleet or vessel size (1 = small, 2 = medium, 3 = large)

j: Trip types or target species (swordfish and tuna)

k: Fish species (swordfish, bigeye, yellowfin *T. albacares*, albacore *T. alalunga*, marlins (Blue marlin *Makaira mazara*, Striped marlin *Tetrapturus audax* and Black marlin *M. Indica*) and other pelagics)

Variables

Π: Fleet-wide total profit (economic rent) (US$ per year)

Γ: Fleet-wide total number of turtles interacted per year

N_{asij}: Net revenue after variable expenses excluding labour and fixed cost in a-th area and s-th season by i-th fleet of j-th trip type (US$ per trip)

Y^k_{asij}: Observed k-th catch in a-th area and s-th season by i-th fleet of j-th trip type (pounds per trip)

$\hat{Y}^k_{asij}$: Estimated k-th catch in a-th area and s-th season by i-th fleet of j-th trip type (pounds per trip)

$\bar{E}_{ij}$: Number of trips per year by the i-th fleet of j-th trip type (1992–1998 historical average)

E_{asij}: Number of trips per year in a-th area and s-th season by i-th fleet of j-th trip type

L_{ij}: Number of labours (crews) per trip by i-th fleet of j-th trip type

D_{ij}: Trip length in days (fishing and travel) by i-th fleet of j-th trip type

F_{asij}: Number of hooks (fishing effort) in a-th area and s-th season by i-th fleet of j-th trip type

B^k_{as}: Stock or biomass level of the k-th species in a-th area and s-th season

I^k_{asij}: Stock index of the k-th species in a-th area and s-th 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 colour, & previous history of sea turtle interaction specific to the vessel) of the sea turtle interaction model in the i-th fleet and j-th trip type

t_{ij}: Trip length in days by the i-th fleet and in j-th trip type

Parameters

π_{asij}: Profit in a-th area and s-th season by i-th fleet of j-th trip type (US$ per trip)

τ_{asij}: No. of turtles interacted per trip in a-th area and s-th season by i-th fleet of j-th trip type

c_{ij}: Expected variable cost for i-th fleet of j-th trip type (US$ per trip)

f_i: Expected fixed cost for the i-th fleet (US$ per vessel per year)

f_{ij}: Expected fixed cost for the i-th fleet of j-th trip type (US$ per trip)

p^k: Expected price of k-th species

ω: Expected wages of crews (US$ minimum wage per day)

q^k_{asij}: Catchability coefficient (stock index-adjusted) of k-th species in a-th area and s-th season for i-th vessel of j-th trip type

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^{be}_{mx}: Historical maximum bigeye tuna catch by the longline fleet during 1991–1998 (pounds)

H^{sw}_{mx}: Historical maximum swordfish catch by the longline fleet during 1991–1998 (pounds)

Decision variable(s)

Fisheries in the US 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 longline fishing efforts (E_{asij}) in terms of the number of trips per year in a-th area and s-th season by i-th vessel size class of j-th trip type.

Objective functions

Fisheries management is characterized by multiple objectives and decision making is often impeded by different stakeholders placing different importance on these objectives. Conflict between these different interest groups is caused by a lack of understanding of the importance of objectives held by the various interest groups involved (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, as represented in Equations 1 and 2, respectively. These objectives are primarily from the point of view of maximizing the utilization of fishery resources as well as maintaining the marine environment by protecting sea turtles. Fleet-wide welfare as measured by the aggregates of profit or economic rent accruing to the longline fishing community is the basic economic incentive or behavioural assumption in this analysis as well. The estimation of the profit (π_{asij}) from fishing operation is based on catch estimates as established from the stock index adjusted CPUE relationships for a fleet and trip category in a given area and season for the year 1993. Similarly, the amount of negative externality by vessel sizes and trip types in a given area and season is represented by a set of turtle interactions parameters (τ_{asij}) as in Equation 2a. These parameters were estimated using the Poisson and negative binomial distribution model of turtle incidences derived from Pradhan and Leung (2000b).[1] The seasonal significance of turtle interaction is also incorporated in the estimation of turtle interactions parameters in the present analysis. The magnitude of sea turtle interactions differs by vessel size and trip types as well as being adjusted for seasonal variations. However, we were unable to account for their spatial variations as we did not have sufficient information to estimate the turtle interactions parameters area-wise. The associated negative externalities in terms of damage to the sea turtles during fishing operation is depicted by a trade-off between these two conflicting but economically and environmentally important goals and it will be examined by tracing the efficient *Pareto frontier*.

Constraints

Trip constraints. Constraints on the number of trips allowed for fishing were imposed in a way that they would not overexploit the longline fishery resource base. Therefore, the total number of trips is very conservatively capped to the historical average (1263 swordfish- and tuna-targeted trips) during 1992–1998 (Equation 3).[2] Further, the total trips by all vessels of *i*-th size and *j*-th trip type in an area and season is bounded from above by the respective historical maximum number of trips during 1992–1998. Vessel constraint is not explicitly imposed in the model, as it is operationally difficult and hard to segregate the vessels in the model with spatial and seasonal dimensions where the same vessel may be taking different types of trips in different areas and seasons. However, the vessel constraint is assumed implicit in the trip constraint in a way that the total optimal trips (tuna and swordfish trips) would not exceed the maximum allowed longline fleet size of 164 vessels per year as set by the current policy. However, the historical average of 1263 trips (589 swordfish-targeted trips and 674 tuna-targeted trips) would translate into 134 vessels of which 62 vessels are expected to be dedicated solely for the tuna-targeted trips and 71 vessels for the swordfish-targeted trips.[3] By this way, the fishery would be made to operate within the available capital resource (vessels) constraint as well.

Entry conditions. The trip-entry condition (Equation 4) ensures that a fishing trip is profitable in the very short run, i.e. sales revenues must cover the variable expenses. The owner-entry condition (Equation 5) requires that the owner's capital is recovered, i.e. net income should exceed fixed costs (opportunity costs of investment, depreciation, maintenance, insurance, etc.). Finally, the crew-entry condition (Equation 6) requires that crew's net income to be higher than the opportunity cost of their labour. In other words, the portion of crew share of net revenue should exceed the shadow price of their labour valuated at State's minimum wages for the days they are in fishing activities. The crew share of net revenue (α_i) is set to 0.50. 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 other resources are valued at their respective opportunity costs, i.e. the direct costs for variable and fixed expenses including interests and depreciation on capital investments. The variable and fixed costs for the swordfish trips in this analysis are the weighted

[1] The parameter τ_{asij} in swordfish-targeted trip has been estimated as 0.4900, 0.7800 and 1.2300 turtle per trip for the small, medium and large vessels, respectively. These estimates were applied uniformly to all fishing areas and seasons except in winter. The turtle catches for swordfish-targeted trip during winter has been estimated as 1.3600, 1.5681 and 1.8086 turtle per trip for the small, medium and large vessels, respectively. Similarly, τ_{asij} in tuna-targeted trip has been estimated as 0.0026, 0.0370 and 0.0249 turtles per trip for the small, medium and large vessels, respectively. These estimates were applied uniformly to all fishing areas and seasons except in spring. The turtle catches for tuna-targeted trip during spring has been estimated as 0.0009, 0.0381 and 0.0330 turtles per trip for the small, medium, and large vessels, respectively.

[2] The historical average number of trips targeting swordfish and tuna were 589 and 674 trips, respectively. The number of swordfish-targeted trips by small, medium, and large vessels was about 135, 271 and 183 trips, respectively. The number of tuna-targeted trips by small, medium, and large vessels was 160, 327 and 187 trips, respectively.

[3] The computation was based on an estimate by Pradhan and Leung (2004) where a longline vessel based in Hawaii takes about 2.7 tuna-targeted trips and 2.08 swordfish-targeted trips in a season.

[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.

average costs of the mixed trips and swordfish trips with about two-third of weight to mixed trips derived from the cost-earning survey of 1993 (Hamilton *et al.*, 1996). Excluding labour 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. The costs for a given category of vessel size and trip type were applied uniformly across all areas and season.

Stock constraint. Conservation of fishery resources is crucial in any fishery to sustain the harvest. No explicit mathematical constraint was included for the stock level as estimates of stock or biomass level is not available. However, this goal is incorporated in the profit maximization objective in a way that the expected catch used in the profit function is estimated using the stock-index adjusted CPUE for each species by area, season, year, trip type and vessel size (Equation 7c). This CPUE relationship is captured by Equations 7a–7c. Since we do not have the stock or biomass level of individual species in any fishing area and season, the catch estimates in Equation 7b is estimated by using the species-specific stock index for a given area and season as a proxy of stock or biomass level by fleet and trip type as in Equation 7c. Species-specific stock index served as a proxy of stock or biomass level of each species. Use of the species-specific stock index as a measure of relative stock abundance can also be found in Dupont (1990), Pradhan *et al.* (2003) and Pradhan and Leung (2004). 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 (August–November) 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) procedure was used to estimate the stock index-adjusted catchability coefficient (q^k_{asij}) using the trip level observations during 1991–2002. The coefficient was then used to estimate the per trip catch level for the k-th species in an area and season by vessel and trip types.[5] Thus, estimated catch ($\hat{Y}^k_{asij}$) was derived by plugging q^k_{asij} in Equation 7c at the mean values of effort levels (F_{asij}) and stock index levels (I^k_{asij}) for an area in a particular season by trip type and vessel size. The estimated per trip catch level ($\hat{Y}^k_{asij}$) is then used in estimating the expected revenues or the profit levels. The estimated total catch and revenue levels for the year 1993 were quite close to their actual values. Stock index-adjusted expected catch specific to a fishing area as in Equation 7c also captures the seasonal and annual variation of the pelagic stocks. Further, the optimal catch levels of swordfish and bigeye tuna were constrained to not to exceed significantly from their historical maximum catches as in Equations 8a and 8b. By this way, it is assumed that the optimal solution from the model would not overexploit key species in the fishery.

Data and other assumptions

The data on catch, efforts, prices and other relevant information for the analysis are taken primarily from the NMFS's logbook (1991–2002) and observer's records (1994–2002), Hawaii Division of Aquatic Resources (HDAR) revenue and landing information (1991–2002), the 1993 cost-earning survey of longline fishery (Hamilton *et al.*, 1996) and various other published and unpublished sources for estimating the model parameters. Information from various sources was clustered by season and fishing area and fishing trips were aggregated into two categories, i.e. tuna- and swordfish-targeted trips. 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

[5] When applying the SURE procedure, outlier observations were excluded by vessel size and trip type. An observation was considered to be an outlier if the bigeye tuna catches exceeds by 2σ and the swordfish catches exceeds by 2.5σ from the respective mean catch levels. Further, observations for some areas and seasons were also excluded when there were not enough pooled observations in some areas and seasons to execute the SURE procedure for a given vessel size and trip type.

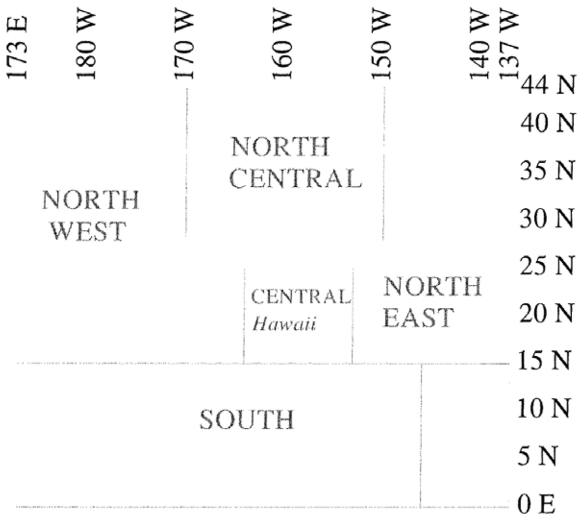

Fig. 1. Zoning of fishing ground in Hawaii longline fishery for the analysis
Source: Nemoto *et al.* (2003)
Note: MHI = Main Hawaiian Island.

year as well. Longline fishing ground is divided into five areas or zones – Central (C), North/Northcentral (N), South (S), East/Northeast (E) and West/Northwest (W) as in Fig. 1. The zones represent some homogeneity of environmental characteristics that may affect catches. The basis for this zoning was initially demarcated by the Hawaii federal court when it delivered the verdict of the sea turtle litigation case to regulate Hawaii-based swordfish-targeted longline fishery (Federal Register, 2000). NMFS researchers at the Honolulu Laboratory have since adopted this demarcation for other research purposes (Nemoto *et al.*, 2003).

III. Results and Discussion

The Frontline System Solver (1993), the mathematical programming Excel add-in, was used to solve the model in this study. Each of the single objective function was optimized first and a trade-off frontier between the two management goals, i.e. maximizing fleet-wide profit and minimizing turtle interactions, was traced out using Cohen *et al.*'s (1979) noninferior set estimation (NISE) method.[6] The NISE method is the most effective technique to solve two-objective problems. It employs a weighted objective function to generate a trade-off curve representing the set of noninferior solutions (Pan *et al.*, 2001). The optimal outcome from the trade-off frontier will form the basis of turtle related fishery policy evaluation when compared to the base scenario. The focus is on the optimal profits, efforts, fish catches and the amount of turtle interactions for a given effort and profit level. Finally, shadow values of turtles were estimated in terms of profit and revenue lost at different segments of the trade-off curve. By comparing different sets of the optimal solutions for different parameters along the trade-off frontier curve, policy decision makers may choose appropriate measures to tackle the turtle related issues in the fishery. The basic results are presented in Tables 1 and 2 *vis-à-vis* illustrated in Fig. 2.

The existing level in 1993 with a fleet wide profit of about \$12.484 million and revenue of about \$55.476 million will be considered as a *base* scenario for subsequent comparisons. Based on our estimates, the total bigeye tuna and swordfish catches for the base year were about 3.999 and 9.584 million pounds, respectively.[7] The fishery experienced scores of turtle interactions with this amount of fishing activity. In the base year, there were 1253 trips taken of which 183 swordfish trips and 145 tuna trips were taken 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. In our analysis, we were able to include only 1168 trips as the model excludes some of the infrequent trips in certain fishing area and season of the year by some fleet categories for certain trip types. Despite this an estimate of about 807 sea turtles were interacted of which 90 loggerhead turtles and 7 leatherback turtles are estimated to be dead. The figure is close to the 911 turtles interacted for the same year as estimated by Kleiber (1998). About 88% interactions are associated to the swordfish-targeted longline activities. Of the total turtle interactions, the takes (takes rate) of loggerhead turtles and leatherback turtles were 515 (64%) and 90 (20%), respectively. The kill rates for

[6] In the NISE method each objective (Z_i) is given a weight (w_i) before the two objectives are consolidated into a single objective function. The new objective function would become $\max_{\bar{x} \in F_d} w_1 Z_1(\bar{x}) + w_2 Z_2(\bar{x})$ s.t. technical constraints, where $\bar{x}$ is an n-dimensional vector of decision variables and F_d is the feasible region. Subsequently, the efficient set is generated through parametric variation of weights. The level of turtle interactions in the model is also implicit in the NISE procedure where it enters through the weighted objective maximization.

[7] The actual recorded catches of bigeye tuna and swordfish in the longline fishery were 4.660 and 13.100 million pounds, respectively, in 1993. The catches in 1994 were 3.940 and 7.000 million pounds of bigeye tuna and swordfish, respectively (Ito and Machado, 1999).

Table 1. Fleet-wide profit, revenue, catches of major target species, number of turtle takes and kills and shadow prices of turtle at various optimal points, Hawaii longline fishery

					Expected number of turtles takes and kills in 1993						Marginal shadow prices ($ per turtle)	
Locus	Profit (mil US$)	Revenue (mil US$)	Bigeye (mil pounds)	Swordfish (mil pounds)	Turtles takes	Turtles kills	Loggerhead takes	Loggerhead kills	Leatherback takes	Leatherback kills	Lost profit	Lost revenue
*p*2 min	0	0	0	0	0	0	0	0	0	0		
*p*10	17.11	36.932	4.768	1.318	204	31	130	23	41	2	44 333	92 476
*p*9	18.972	40.816	4.842	2.347	246	38	157	28	50	2	29 144	76 845
*p*8	21.799	48.27	5.122	4.355	343	53	219	38	70	3	41 218	89 036
*p*3	24.066	53.167	5.294	5.572	398	61	254	45	81	4	22 413	70 832
*p*4	28.728	67.9	5.972	9.346	606	93	387	68	123	5	11 071	53 657
*p*5	29.503	71.656	6.092	10.35	676	103	431	76	137	6	2857	59 429
*p*6	29.543	72.488	6.129	10.537	690	106	440	77	140	6	815	32 463
*p*1 max	29.587	74.241	6.185	10.92	744	114	475	83	151	7	0	0
Base	12.484	55.476	3.999	9.584	807	124	515	90	164	7		
Historical maximum (1991–1998)			7.110	13.100								
Average (*p*1 to *p*3)											15 957	60 908

Table 2. Optimal allocation of longline fleet efforts (number of trips) by vessel size, trip type, area and season in Hawaii longline fishery 1993

Fleet, Trips, Area		3s_C	3s_E	3s_N	3s_W	2s_C	2s_E	2s_N	2s_W	1s_C	3t_C	3t_W	3t_S	2t_C	2t_W	2t_S	1t_C	Total
Optimal points/Seasons																		
*p*1 max	Fall		13		30				23			4	7	42	10			129
	Spring	10	19	97	20		8	61	14		19	10	20	67	25	46		416
	Summer		36	25	34		20	14	18		12	10	22	54	23	34		302
	Winter			67	30		7	40			34	10	4	80	50	10	84	416
	Total	10	68	189	114	0	35	115	55	0	65	34	53	243	108	90	84	1263
*p*2 min	Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
*p*3	Fall				30				23			4	7	42	10			116
	Spring								14		19	10	20	67	25	46		201
	Summer		36	25	34			14			12	10	22	54	23	34		264
	Winter			67				40			34	10	4	80	50	10	84	379
	Total	0	36	92	64	0	0	54	37	0	65	34	53	243	108	90	84	960
*p*4	Fall				30				23			4	7	42	10			116
	Spring			97	20			61	14		19	10	20	67	25	46		379
	Summer		36	25	34		20	14			12	10	22	54	23	34		284
	Winter			67				40			34	10	4	80	50	10	84	379
	Total	0	36	189	84	0	20	115	37	0	65	34	53	243	108	90	84	1158
*p*5	Fall		13		30				23			4	7	42	10			129
	Spring	10	19	97	20		8	61	14		19	10	20	67	25	46		416
	Summer		36	25	34		20	14			12	10	22	54	23	34		284
	Winter			67			7	40			34	10	4	80	50	10	84	386
	Total	10	68	189	84	0	35	115	37	0	65	34	53	243	108	90	84	1215
*p*6	Fall		13		30				23			4	7	42	10			129
	Spring	10	19	97	20		8	61	14		19	10	20	67	25	46		416
	Summer		36	25	34		20	14	18		12	10	22	54	23	34		302
	Winter			67			7	40			34	10	4	80	50	10	84	386
	Total	10	68	189	84	0	35	115	55	0	65	34	53	243	108	90	84	1233
*P*8	Fall				30				23			4	7	42	10			116
	Spring										19	10	20	67	25	46		187
	Summer			25	34			14			12	10	22	54	23	34		228
	Winter			67				40			34	10	4	80	50	10	84	379
	Total	0	0	92	64	0	0	54	23	0	65	34	53	243	108	90	84	910
*p*9	Fall											4	7	42	10			63
	Spring										19	10	20	67	25	46		187
	Summer			25				14			12	10	22	54	23	34		194
	Winter			67				40			34	10	4	80	50	10	84	379
	Total	0	0	92	0	0	0	54	0	0	65	34	53	243	108	90	84	823
*p*10	Fall											4	7	42	10			63
	Spring										19	10	20	67	25	46		187
	Summer										12	10	22	54	23	34		155
	Winter			67				40			34	10	4	80	50	10	84	379
	Total	0	0	67	0	0	0	40	0	0	65	34	53	243	108	90	84	784
Base 1993	Fall	1	2	17	30	16	1	16	23	2	7			36			44	196
	Spring	2	4	82	5	23	8	61	7	7	6			54	11	2	60	332
	Summer	24	25	20	28	68	20	14	16	7	4			48			41	316
	Winter	4	1	67	18	24	1	40	10	1	8			64	2		84	324
	Total	31	32	186	80	131	31	131	55	18	25	0	0	202	13	2	229	1168

Notes: Area: C = Central, N = Northcentral, S = South, E = East/Northeast, W = West/Northwest.
Vessel size: 1 = Small, 2 = Medium, 3 = Large.
Trip type: s = Swordfish, t = Tuna.

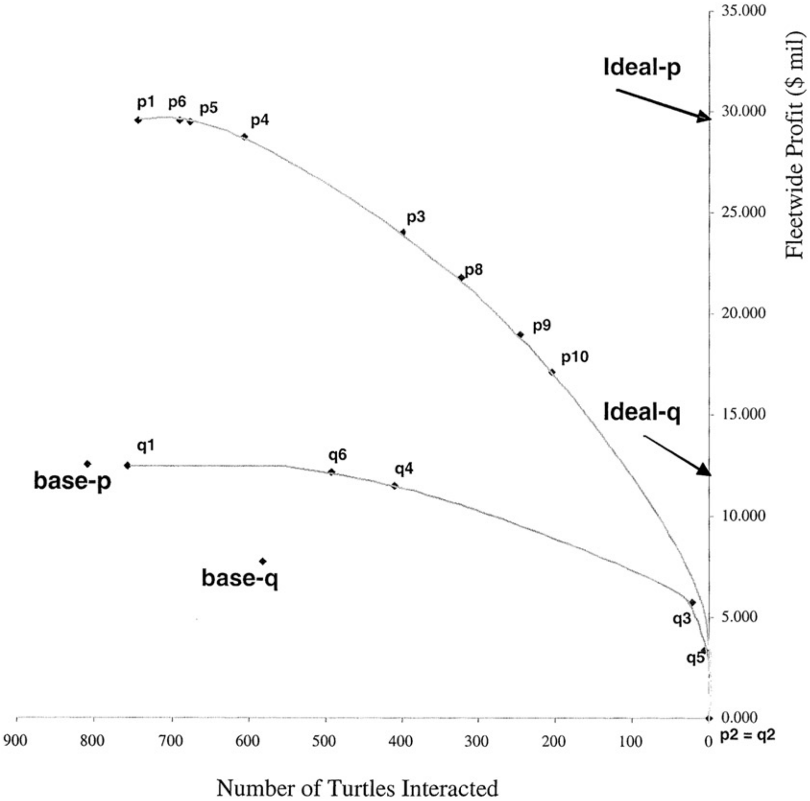

Fig. 2. Comparative trade-off curve of fleet-wide profit and sea turtle interactions with and without spatial and seasonal dimensions in the model, Hawaii Longline Fishery 1993

Notes: *p*-series curve: with spatial and seasonal dimensions in the model.
q-series curve: without spatial and seasonal dimensions in the model.

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 trade-off between fleet-wide profit and turtle interactions was traced first by solving the two objective functions separately. Maximizing the fleet-wide profit objective separately (*p*1 max) resulted in the fleet-wide profit of $29.587 million and corresponding revenue of $74.241 million which are about 136 and 34% increase in profit and revenue from the base scenario, respectively. Solving for maximizing the fleet-wide profit separately (*p*1 max) without the spatial and seasonal dimension in the model resulted in the fleet-wide profit of only about $12.400 million and corresponding revenue of about $65.200 million (Pradhan and Leung, 2006a). Thus, one can see the dramatic increase in efficiency with the added dimensions. Minimization of the sea turtle interactions objective (*p*2 min) as in Equation 2 suggests halting of all fishing operations. However, it is not pragmatic to halt all fishing operations. At the maximum fleet-wide profit the total bigeye tuna and swordfish catches as estimated by the model were 6.185 and 10.920 million pounds, respectively. This can be achieved by reconfiguring the fishing efforts distributed to tuna trips and swordfish across the most efficient areas and seasons in terms of higher income and lower turtle interactions. The reconfigured fleet allocation by fleet size, trip type, area and season are given in Table 2. This would

[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.

correspondingly require increasing the harvests of bigeye tuna and swordfish by 54 and 14% more from the base scenario, respectively. These catches are well within the bounds of historic maximum catches for these species, thus, removing any fear of over-fishing. With this new configuration of fleet across different areas and seasons, the fishery would experience slightly lower amount of sea turtle interactions. It is obvious by virtue of the modelling that fishing trips would be selected from the most efficient locations and seasons in a way it would increase profit derived from catches but reduce sea turtle interactions. About 744 sea turtles would be interacted at the maximum fleet-wide profit, which is about 8% lower turtle takes than the base scenario. Further, an estimate of 114 turtle kills would have occurred at *p*1. At the maximized profit level, 97% of the turtle takes is attributed to swordfish-targeted longline trips. At this optimum (*p*1 max) there could be as much as 475 (83) takes (*kills*) of loggerhead and 151 (7) takes (*kills*) of leatherback turtles.

The maximum fleet-wide profit and minimum turtle interactions levels at points *p*1 and *p*2, respectively, are ideal solutions but certainly conflicting. Hence, other efficient points were traced out between these two extremes of maximizing fleet-wide profit and minimizing turtle interactions. The trade-off curve is not necessarily linear between the two extreme loci *p*1 and *p*2, because the degree of conflict between the two objectives can vary in different parts along the trade-off curve. Therefore, by using the NISE method the *p*3 locus was traced from *p*1 and *p*2. Similarly, the points *p*1 and *p*3 gave rise to *p*4; the point *p*5 was generated from *p*1 and *p*4; and the point *p*6 was generated from the points *p*1 and *p*5. Similarly, the locus *p*8 was generated from *p*3 and *p*2; the locus *p*9 was generated from *p*8 and *p*2; and finally the locus *p*10 from points *p*9 and *p*2. The process continues till it ceased to generate new points. The amount of fleet-wide profit, revenue, fish catches and turtle incidences at various optimal loci and their corresponding fleet effort configuration by vessel size, trip type, area and season are summarized in Tables 1 and 2. Connecting the new sets of efficient loci between the two extreme points *p*1 and *p*2 would produce a convex *Pareto frontier* of fleet-wide profit and turtle interactions as illustrated in Fig. 2. It depicts the trade-off between fleet-wide profit and turtle interactions. This frontier level is higher with the spatial and seasonal dimensions in the model (i.e. *p-series*) than the one derived from the model without these dimensions (*q-series*). The area or distance between two trade-off frontier curves indicates the potential efficiency gain in terms of fleet-wide profitability for a given level of turtle interactions due to the synergetic effects of spatial and seasonal dimensions in the enhanced model. The locus between *p*3 and *p*1 are of policy interests where there exists higher efficiency in both profit and turtle interactions as compared to the base scenario. The new set of points between *p*3 and *p*9 may also be of some interests to policy-makers as the profit level and turtle catches are better than the base case. However, the points between *p*9 and *p*2 may not be of interest as profit and revenue are significantly lower when compared to base case. It is very convincing that there is possibility of significantly higher efficiency gain in terms of higher fleet-wide profitability and reduced turtle interactions by reconfiguring efforts of each fleet to more productive fishing grounds and seasons.

At *p*1, the point of maximized profit, it would call for 586 swordfish trips or 6048 sets for the year. However, the recent policy related to the sea turtle regulation has capped annual swordfish fishing to 2120 sets (which corresponds to approximately 205 swordfish trips or 10.32 sets per swordfish trip). The next closest number to 2120 sets would be at *p*3 with 2920 sets or 283 swordfish trips. This is still 34% higher than the capped level and furthermore, at *p*3 it can result as many as 398 turtle takes.

The locus *p*6 or *p*3 have higher profit and lower turtle interactions compared to the base scenario. This suggests policy makers may want to consider the reconfiguration of fishing efforts of each fleet to various trip types across different areas and seasons to achieve better economic efficiency and environmental protection. However, the number of turtle interactions at those points is still higher than the one set by the recent policy to regulate Hawaii's longline fishery so as to protect sea turtles. The recent policy is stiff in the sense that it requires to halt fishing for the rest of the year whenever the longline operation interacts with either 16 loggerhead or 17 leatherback turtles. 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 beyond the locus *p*10 towards *p*2 should the fishermen continue to use the conventional technology, such as *J*-type hooks instead of prescribed circled hooks. In such case, potential gain in economic efficiency may not be captured in the section between *p*1 and *p*3 despite much lower level of turtle interactions compared to the base scenario. This requires to abruptly reducing swordfish-targeted longline fishing trips that use conventional technology of fishing. However, the use of 'turtle-safe' fishing technology such as the circled-hooks or restricting swordfish-targeted longline fishing only in seasons and areas where these turtles mostly forage or get interacted would lead to some room to accommodate for a higher optimal fishing efforts.

The cost to the longline fishery in terms of lost profit and revenue due to limited fishing activities for concerns of turtle interactions was also estimated at various points along the trade-off frontier. The estimated marginal shadow cost in terms of lost profit per turtle at various points along the trade-off frontier was \$825 for limiting fishery away from the maximum point $p1$ to $p6$; \$2857 from $p6$ to $p5$; \$11 071 from $p5$ to $p4$; and \$22 413 from $p4$ to $p3$. Similarly, the corresponding marginal shadow cost in terms of lost revenue per turtle at various points along the trade-off frontier is \$32 463 for limiting fishery away from the maximum point $p1$ to $p6$; \$59 429 from $p6$ to $p5$, \$53 657 from $p5$ to $p4$ and \$70 832 from $p4$ to $p3$. The average shadow cost per turtle from $p1$ (when fishery is halted to operate) to $p3$ (i.e. the slopes of points between $p1$ and $p3$) is about \$15 957 in terms of lost profit and \$60 908 in terms of lost revenue.[9] On the other hand, further restriction of fishing effort beyond $p3$ can result in much higher shadow cost per turtle; however, it may not be necessary depending on the policy's desired degree of environmental protection in the fishery. The shadow cost estimated here, however, does not take into account of lost opportunities in post-harvest value-added economic activities to the local economy.

The average shadow cost estimates in this study are more or less similar 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). Curtis and Hicks (2000) suggests that the average cost of reducing longline interactions 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 can also be compared 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 value of sea turtle in Hawaii's longline fishery. They estimated that the average shadow cost 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 policymakers to analyse trade-offs and make appropriate policy decisions.

IV. Conclusion

We present a rigorous bio-economic model of Hawaii's longline fishery with a heterogeneous fleet specification through variations in the mix of vessel types and trip types to capture the potential efficiency gains in terms of higher profitability and reduced sea turtle interactions. The analysis carried out in this article is novel, as it incorporates the interactions of the protected species like sea turtle in a multi-objective programming model by considering spatial and seasonal dimensions. The results from the study indicate the possibility of a significantly higher profit and reduced turtle interactions by reconfiguring fishing efforts across different areas and seasons. As a result of the synergetic effect of these added dimensions, the present results indicate that the fishery could achieve better optimal outcome than without these added dimensions. The area or distance between the two trade-off frontier curves indicates the potential efficiency gain in terms of fleet-wide profitability for a given level of turtles interaction due to the synergetic effects of spatial and seasonal dimensions in the enhanced model. This is a clear testament for an existence of a win-win situation in Hawaii's longline fishery. There also exists a trade-off between fleet-wide profit and the number of turtles interacted. However, the current fishery policy related to sea turtle interactions may limit capturing all the potential efficiency gains as illustrated from the model results, since the number of turtles allowed to get interacted severely limits swordfish-targeted longline fishing trips if fishers use conventional technologies. Where to limit the fishing effort along the frontier largely depends on the reasonable estimates of growth rate for the key critical turtle species and the degree of environmental protection the policy desires. The use of turtle-safe fishing technologies would leave some room to accommodate for higher optimal fishing efforts which indeed have been the case where there has been a significant reduction in the number of sea turtles interacted after the use of circled-hooks very recently.

Restricting longline fishery to operate sub-optimally has average shadow cost of about \$15 957 and \$60 908 in terms of lost profit and revenue per turtle, respectively. The shadow costs are also higher

[9] In a similar situation but without spatial and seasonal considerations in the model, the average shadow cost per turtle is estimated to be about \$9120 in terms of lost profit, and \$56 060 in terms of lost revenue (Pradhan and Leung, in press-a).

with the spatial and seasonal dimensions in the model than the case without these dimensions. The shadow cost estimates here do 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 and seasons with high turtle interactions. 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. All the coastal communities have also equal responsibility for an environmentally responsible fishing and a consorted international effort would be necessary to reduce sea turtle interactions.

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