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Fishing behavior across space, time and depth: with application to the Gulf of Mexico reef fish fishery [Fishing behavior across space and time]

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Keywords

spatial temporal fishing behavior, multiples-species, targeting costs, regulations

Disciplines

Economics

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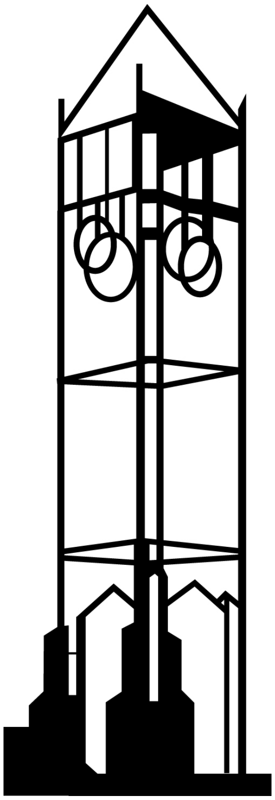

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Fishing behavior across space and time

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We introduce a model of fishing behavior that features costly targeting of a spatially and temporally heterogenous, multiple-species fish stock. We characterize fishing behavior under species-specific regulations including time-area-depth closures, per-trip landings limits and tradable harvest permits. Our behavioral model yields a system of Kuhn-Tucker necessary conditions which form the basis of our empirical estimation. Data from the Gulf of Mexico commercial reef fish fishery are used to estimate the model. The estimated harvest technology exhibits local weak output disposability which are linked to spatially and temporally dependent stock conditions in the reef fish fishery. The model predicts harvests, discards and fishing profit across multiple species, and importantly across continuous space and time dimensions. Policy simulations further identify behavioral responses to closure regulations, individual tradeable quota management and recent sea turtle bycatch management rules which impose limits on fishing depth. Our model overcomes limitations of discrete choice spatial fishing behavioral models, and offers a powerful tool for improving regulation of spatially and temporally heterogeneous, multi-species fisheries.

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1 Introduction

Fisheries management problems have been recently linked to a reliance on overly simplistic models of marine ecosystems (Worm et al., 2009). Management policies are often designed around single-species principles that ignore complex ecological interactions among multiple species and treat spatially heterogeneous metapopulations as spaceless whole fish stocks.[1] Similar criticisms can be leveled on economic models of fishing behavior which often exhibit a disconnect between ecological complexity, decision processes of fishermen and the outcomes of interest to resource managers such as harvests across space, time and depth, discards, and regulatory response. We introduce and estimate a model of fishing behavior that explicitly links the composition of a multiple-species fish stock across time and space, prices, and regulations under which harvesting operations are conducted with profit-maximizing harvest and discard choices of commercial fishermen. Data from the US Gulf of Mexico reef fish fishery is used to estimate the model and demonstrate its effectiveness for evaluating regulations commonly used in commercial fisheries.

A workhorse in the analysis of spatial fishing behavior is the discrete choice random utility model (RUM).[2] A standard application to the analysis of spatial fishing behavior begins by dividing the fishing grounds into a finite number of mutually exclusive regions or sites. The RUM assumes that on each trip from port, fishermen select the site that yields highest expected utility. A multinomial logit or probit regression is used to estimate the unknown parameters of a utility function defined over sites by matching observed site choices in the data to a measure, typically the researchers estimate, of the expected payoffs and associated utility at each site in the choice set.[3] The fitted model predicts the

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[1] A growing view among fisheries scientists and marine ecologists is that a more holistic approach will improve the management of ocean fisheries resources (Brodziak and Link, 2002; Pikitch et al., 2004; U.S. Commission on Ocean Policy, 2004). The challenges and opportunities that accompany spatial fisheries management are discussed in Wilen (2004). Herrera (2006) outlines the potential benefits of spatial fishing regulations.

[2] The random utility model (RUM) was developed by Daniel McFadden to study transportation choices. The original set up assumes that a particular transportation choice yields utility U which is known fully by the decision maker. Utility is decomposed as $U = V + e$, where only V is observable by the researcher; e is an unobserved component known to the decision maker. In empirical applications V may be conditioned on observables such as distance to a destination, average traffic patterns, road conditions, etc. Bockstael and Opaluch (1983) and Eales and Wilen (1986) present early applications of the RUM framework to study spatial fishing behavior. Numerous applications of the RUM to spatial fishing data have appeared in the resource economics literature. A special issue of Marine Resource Economics (Volume 19, Number 1, 2004) is dedicated to analysis of spatial fishing behavior. Modifications of the basic model structure include Mistiaen and Strand (2000); Haab et al., (2008), Haynie and Layton (2010) and Abbott and Wilen, (2011).

[3] Payoff expectations at competing sites must be estimated from observed data and typically involve regressing past payoff on observed data, e.g. site and/or fisherman characteristics, to form a predicted payoff across sites. The model yields an estimate of the likelihood that a fishermen will select a size given the site observables. Smith (2000) provides an overview of the methodology. Berman (2007) and Curtis and McConnell (2004) discuss limitations in analysis of spatial fishing behavior.

likelihood of taking a trip to a particular site, conditional on observable characteristics of the sites, the fishermen and the market for factor inputs and harvested output.[4]

Our model relaxes several restrictive assumptions implicit in discrete choice RUM approach and circumvents limitations encountered in their application. First, we begin with a standard model of production behavior where fishermen are assumed to organize factor inputs and select the mix of harvested species to maximize profits. The optimization is subject to the constraints imposed by the technology, market prices, stock conditions, and regulations imposed by the management authority. Regulations often take the form of species-specific landings limits, or time, depth and/or area closures. Regulations thus impose constraints on the vector of feasible landings. A system of Kuhn-Tucker necessary conditions characterize profit maximizing fishing behavior. These conditions form a system of Tobit equations which we use to estimated a parametric cost function following the method of Wales and Woodland (1983). Our cost functional form features the property of crucial property of local weak output disposability which captures costly targeting in a multiple species fishery (Turner, 1995; Singh and Weninger, 2009). Importantly, our unit of analysis is a vector of spatially, temporally and depth-delineated profit maximizing harvests and at-sea discards which are predicted under profit maximization if, for example, a species if fish is unmarketable or its landings are prohibited by regulation. The model thus directly predicts outcomes of management interest, harvest, discard and profits, for given stock conditions, prices and regulations.

Our approach avoids the curse of dimensionality that limits RUM applications to spatial fishing behavior (Berrmann, 2007). We assume that multiple-species reef fish fish stock abundance varies smoothly across space and time. The ecological spatial scale in our model matches reality and the spatial scale at which commercial fishermen operate. Commercial fishermen select fishing locations, dates, and depths to harvest targeted species, and avoid species whose harvest is unprofitable or prohibited by regulation. Preferred locations may be a few or hundreds of kilometers apart. Fisheries typically span vast areas containing thousands of potential fishing *sites.* In the discrete choice RUM framework, researchers are forced to make untenable assumptions concerning the spatial choice set facing fishermen, and the information that is available regarding the fishing opportunities at each location.[5] We estimate a structural, multiple-species target cost *surface* that describes fishing profit

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[4] One limitation of the approach is that a second model is needed to predict the on-site harvest and discard activities of the fisherman.

[5] See Berrmann (2007) for a discussion of the curse of dimensionality in estimation of discrete choice models. Dimensionality and spatial resolution limits of data force researchers to place artificial limits on the number of choices for which preferences are estimated. This forces coarse geographical division of the fishing grounds, and coarse descriptions of spatial fishing patterns. Branch et al. (2005) discusses a related problem where the spatial grid used to divide fisheries geographically—typically latitude and longitude designations determined by political considerations—may be unrelated to the locations of productive fishing sites.

opportunities across continuous space and time. The model offers a powerful tool to assess the ecological and economic implications of commonly used regulatory policies such as area, time and depth closures.

Application to the Gulf of Mexico, hereafter GOM, reef fish fishery demonstrates the model's strengths.[6] For example, we are able to show how prices and regulations which include spatial and temporal closures and per-trip landings limits directly affect targeted harvesting mortality and bycatch of individual species in the GOM reef fish fishery. Simulations show how regulations can redirect fishing effort toward unregulated species and across space and time; patterns that are observed in our data. Spatial-temporal discard patterns are also impacted by price and regulatory changes. The model predicts that when fuel prices rise, reef fish fishermen are less likely to target higher priced reef fish species, and instead are more willing to land a harvest mix with low targeting costs, i.e., a mix of reef fish species that requires less search and vessel steaming time and less fuel. The preferred harvest strategy under higher fuel prices also involves fewer at-sea discards.

The remainder of the paper is organized as follows. The next section presents background information for the GOM reef fish fishery and a discussion of the regulations used to conserve the stock. The background frames the fishing behavioral model which we introduce in section 3. Section 3 presents necessary conditions for profit maximization which form the basis for our empirical estimation. Data and estimation are presented in section 4. Section 5 reports results. Section 6 and presents policy analysis and simulations. Conclusions follow in section 7.

2 Background

The GOM reef fish fishery is a complex of mid-column and bottom-dwelling species consisting of snappers, groupers, tilefishes, amberjacks, triggerfishes, grunts, porgies, and a host of others. Fishermen also intercept coastal pelagic species including mackerel, dolphin (wahoo), sharks and tuna. Total landings in the fishery, all species combined, has declined from 20.65 million pounds in 2005 to 12.94 million pounds in 2010. Dockside revenue ranged between \$35.07 to \$48.57 million during this same period (all values are reported in 2010 dollars).

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[6] Our approach can be used in any fishery where the composition of the stock exhibits predictability across spatial and temporal dimensions. Movements of some fish species, e.g., tunas in the pacific ocean, may be largely random. For many fish species, however, habitat quality is linked to (stable) bottom substrate, or exhibits seasonal and temporal patterns. Our approach reflects this predictability through spatial-temporal variation in harvest opportunities and profits.

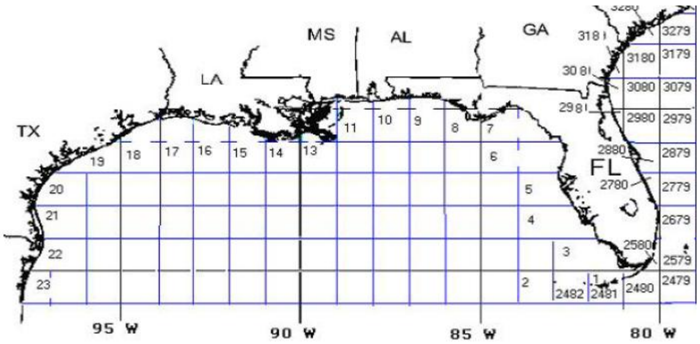

Figure 1: Gulf of Mexico Region Designations

The US portion of the fishery extends from the US border with Mexico in the western Gulf to the Florida Keys. Figure 1 denotes 21 subregions of the fishery located in US waters. Hereafter, subregions 13-21 will be referred to as the western Gulf region, and subregions 1-12 as the eastern Gulf region of the reef fish fishery.

The composition of reef fish stocks varies across space. Groupers are most prominent, by pounds landed and revenue, in the eastern region with red grouper dominating at 29.7% of landings and 33.9% of revenues in 2010. The largest volume and revenue species in the western Gulf is red snapper accounting for 43.8% of landed pounds and 53.6% of total revenue in 2010.

In 2005, over 13,000 reef fish fishing trips were taken by 1,049 vessels. Trips averaged 3.72 days in length. In 2010, total trips numbered 7,558, with 717 vessels participating. The two major gear types are vertical hook and line gear and longline gear. Trolling gear, gill nets, traps, and dive gear are used to a much lesser extent and will not be analyzed further.

2.1 Regulations

Regulations in the reef fish fishery vary by species and gear type, and have changed substantially during our data period. A GOM Reef Fish Fishery Management Plan was first implemented in 1984. The original plan enacted a few simple harvesting regulations that prohibited fishing practices considered damaging to the marine environment. Amendment 1 to the management plan set total annual harvest limits for individual reef fish species. These limits are adjusted from year to year depending on the condition of the stock. Prior to 2007, managers relied on input controls to ensure the commercial harvest did not exceed the annual limit. Input controls consisting of gear restrictions, seasonal closures, area closures and vessel per-trip catch limits have been used extensively in the fishery.

Red snapper, the most heavily regulated of all reef fish species, has been managed with seasonal closures and trip catch limits, from 1991 - 2006, and with individual fishing quotas beginning in 2007. Under individual fishing quotas, managers issues tradable harvest permits in an amount that corresponds to the annual total allowable catch limit. Fishermen can land any quantity they choose as long as sufficient quota to cover landings is held in their possession. Several other reef fish species, groupers and tilefish, switched from inputs controls to individual fishing quotas in 2010.

2.1.1 Input controls

Landings are prohibited during a fishery closure. Closures may apply to individual species or to groups of species. Periodic closures/openings were adopted in the reef fish fishery to spread harvests more evenly throughout each year with the goal of moderating the flow of harvest to processing plants and consumer markets, and thus avoiding marketing gluts and low prices. During 1991-2006 a typical pattern for red snapper was to open the fishery for the first 10 days of each month. This pattern continued until the red snapper total annual allowable catch had been landed. Closures were implemented in the red and gag grouper fishery from mid-February through mid-March to protect spawning aggregations. Groupers were otherwise open to fishing until the annual allowable catch for the species group was met. Deep water groupers and tilefish were open to commercial fishing at the beginning of each year and closed when the total annual allowable catch was reached.

Maximum per-trip landings limits, applied to individual species or groups of species, were used in conjunction with the closure policy. The red snapper endorsement system was in place from 1992-2006. Under this regulation, fishermen were allocated either class 1 or class 2 endorsement permits based in historical participation in years preceding the introduction of the program.[7] Class 1 permitted fishermen were allowed to legally land a maximum of 2,000 pounds of red snapper per trip during a red snapper opening. Fishermen who were allocated class 2 permits could land 200 pounds of red snapper per trip during fishery openings. Fishermen who did not hold endorsement permits were prohibited from landing red snapper at all times.

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[7] Reef fish fishermen who landed at least 5,000 pounds of red snapper during the 1990-92 seasons were granted endorsement permits allowing them to land 2,000 pounds of red snapper per trip. All other qualifying fishermen were restricted to landing 200 pounds or less. In 1998 a licensing system was adopted. Class 1 endorsement permits were allocated to 138 qualifying vessel operators. Class 2 endorsement permits were allocated to 559 vessel operators. The endorsement permit regulation ended in 2007 with the adoption of ITQ management.

In 2006, managers adopted a maximum 6,000 pound per trip landing limit for all shallow water grouper species; red, gag and black groupers and other shallow water grouper species.

Temporal and depth closures are also used to reduce fishing pressure on reef fish. The February 15 - March 15 closure for red and gag grouper discussed above is an example. Depth restrictions have been in place since 2008 to reduce bycatch of endangered sea turtles by longline vessels. In May 2008 an emergency rule enacted three measures designed to reduce interactions between turtles and longline fishing gear. Longline fishermen were prohibited from setting gear shoreward of a line approximating the 35 fathom contour eastward of the 85 degree, 30 minute longitude (most of the Florida Gulf coast). Second, longline fishermen were permitted to carry no more that 1,000 hooks onboard the vessel of which 750 could be rigged for fishing. Hook limits constrain the length of the longline, which effectively reduces the soak time for the gear. Longer soak times tend to be positively correlated with sea turtle encounters and mortality. Finally, managers limited the number of vessels that can use longline gear. Reef fish boats can be re-fitted with vertical line or longline gear. Managers hoped that limiting longline gear deployment would reduce fishery-wide turtle encounters. The May 2008 emergency rule became permanent in Amendment 31 which was approved in May, 2010.

A minimum size limit regulation is in place for several reef fish species. Fish that do not meet the minimum length limit must be discarded.[8] Our data do not allow us to distinguish discards that result from closures and landing limits from undersize discards. Size limit regulations were stable during our study period and therefore we interpret harvest and discards of undersized fish an unavoidable constraint on harvesting activities. We do not consider the behavioral implications of the minimum size limit regulations further.

Regulations in the GOM reef fish fishery control quantities of individual reef fish species that can be legally landed at the fishing dock. At-sea discarding is not monitored and is legal.[9] In fact, when a fishery is closed, fish that is intercepted by the gear, intentionally or not, must be discarded at sea. Deep-water grouper species are an exception as they do not survive dramatic depth changes. Deep water groupers that are harvested must be landed at port.

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[8] Size limits serve multiple management goals. First, restricting the minimize size of landed fish lowers mortality for a given amount of fishing effort. A second goal of length limit policy is to slow the process of growth overfishing, i.e., harvesting small but rapidly growing fish counteracts the management goals of maximizing fishery yield.

[9] On board observers are used in a small proportion (5%) of longline gear trips to monitor sea turtle encounters.

3 A model of regulated fishing behavior

This section presents a model of multiple-species fishing behavior under the regulations described above.

We assume that reef fish fishermen organize factors of production, e.g., fuel, bait, gear, and crew labor to search for and harvest multiple reef fish species. We use $i = 1, ..., M$ to index individual species or stocks. Inputs are purchased competitively and fish that is landed by the vessel operation is sold in competitive downstream markets at price denoted p_i for species i. We assume prices are fixed during in the short run, which we take as the time required to complete a fishing trip.

Harvest, h_i for species i, denotes the quantity of fish that is intercepted by the fishing gear, i.e., the quantity of fish that is caught and retreived to the deck of the vessel. Landings, l_i, may be less than harvest with the difference being the quantity that is discarded at sea. Thus $h_i = l_i + d_i$, where $d_i \geq 0$ denotes discard quantity of species i fish.

The per-trip profit maximization problem for a representative fisherman is:

$$\pi(p, w, x) = \max_{0 \leq l, 0 \leq d} \{p'l - c(h, w, x)\}, \tag{1}$$

where $c(h, w, x)$ is the harvest cost, $h = (h_1, ..., h_M)$ is the harvest vector, w denotes input prices and x is an M-vector of stock abundances. In addition to the technological constraints, embedded in the cost function, the maximization is subject to the regulations imposed by the fishery manager, which we discuss shortly.

We assume $c(h, w, x)$ is convex in h and increasing and concave in w. We assume the technology exhibits weak output disposability. This structural property captures the costly targeting aspect of multiple-species fishing wherein the fishermen may be required to search more, or modify their gear and fishing practices to avoid harvesting a particular species of fish. For example, selecting a harvest vector that includes a relatively small amount of a species that is relatively abundant in the region chosen for fishing will introduce added costs. Some fishing locations, dates and depths may have to be avoided to reduce encounters with the non-targeted species. Alternatively it may be necessary to modify gear and bait to attract and intercept the target while avoiding non-target species. Measures taken to avoid an unwanted species raises fishing costs.[10]

The total costs of harvesting h will therefore depend on the composition of the fish stock in the region of fishing. Suppose stock x_i is abundant in the region of fishing. Harvesting

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[10] The targeting ability of fishermen in multiple-species fisheries is well documented (Kirkley and Strand, 1988; Campbell and Nicholl, 1994; Branch and Hilborn 2008; Turner 1995, 1997; Singh and Weninger, 2009).

a vector h with $h_i = 0$ and $h_{-i} > 0$ can be more more costly than if a large quantity of species i fish where harvested. The added cost of maintaining $h_i = 0$ arises due to the costly avoidance measures that are required. The implication of the weak output disposability property is that, fixing $h_{-i} > 0$, the cost function can be non-monotonic in the harvest quantity h_i. Put another way, marginal harvesting costs will be negative for some species in some regions of M-dimensional output space. Letting $c_i(h, w, x) = \partial c(h, w, x)/\partial h_i$ denote marginal costs.

The weak output disposability property implies that $c_i(h, w, x) < 0$ is possible (likely) if at h, the share of h_i in the harvest bundle is small relative to the share of its stock abundance in the sea. As h_i increases, $c_i(h, w, x)$ will eventually become positive. Stock conditions, absolute and relative abundance of individual species can vary across space, within the fishing season, or over longer time periods as some stocks grow or decline due to natural mortality or aggregate fishing pressure. Stock conditions vary regionally and temporally which creates spatial-temporal variation in the targeting cost properties of the technology, and in the spatial-temporal harvesting behavior of fishermen.

Conditional on the region of fishing, fishermen select a harvest vector that maximizes profit. The chosen mix may differ from the mix of stocks in the sea. We assume that the costs that arise from avoidance behaviors increases with the *mismatch* between the harvest vector, h, and the stock abundance, x. If, on the other hand, a fisherman is willing to harvest a mix of species that is similar in composition to x, fewer costly avoidance measures are required. To formally capture this feature of the technology, we specify an empirical cost function that is increasing in the Euclidean distance between the harvest share vector and a stock share vector. A functional form for $c(h, w, x)$ that exhibits this property is presented in section 4. The next section explores the behavioral implications of the weak output disposability property in a regulated multi-species fishery.

3.1 Regulations and fishing behavior

We assume all fishermen strictly adhere to regulations - there is not cheating in our model. Let $J \subseteq M$ denote a subset of species that are managed with a species-specific landings constraint. Let $\bar{l}_i$ denote the per-trip maximum landing. Similarly, we use $K \subseteq M$ to denote the subset of species managed with a group maximum landings limit. The species-group limit regulation takes the form $\sum_{i \in K} l_i \leq \bar{l}_K$, where $\bar{l}_K$ is the per-trip maximum.

The Lagrangian function for the regulated profit maximization problem is,

$$L = \sum_i p_i l_i - c(h, w, x) + \sum_{i \in J} \lambda_i [\bar{l}_i - l_i] + \lambda[\bar{l}_K - \sum_{i \in K} l_i], \tag{2}$$

where λ_i are multiplies for the landings constraints.

To fix ideas, we first consider the case of no regulation. Ignoring the landings constraints in 2, the Kuhn-Tucker (KT) necessary conditions are (function arguments are dropped to reduce notation):

$$p_i - c_i \leq 0 \tag{3a}$$
$$l_i[p_i - c_i] = 0 \tag{3b}$$
$$-c_i \leq 0 \tag{3c}$$
$$d_i[-c_i] = 0 \tag{3d}$$
$$l_i, d_i \geq 0. \tag{3e}$$

These above conditions encompass four possibilities: $(l_i > 0,\ d_i = 0)$, $(l_i > 0,\ d_i > 0)$, $(l_i = 0,\ d_i = 0)$, and $(l_i = 0,\ d_i > 0)$. In the absence of regulation and with positive market prices, discarding fish at sea will never be part of a profit maximizing harvest strategy, and thus $(l_i = 0,\ d_i > 0)$ is not discussed further. The condition in equation (3b) is familiar; harvest is chosen to equate marginal revenue and marginal cost. From condition (3c) we see that marginal cost is non-negative. Therefore, $h_i = 0$ only if the technology exhibits strong output disposability. Summarizing, we have two behavioral regimes and associated necessary conditions:

Regime	Outcome	KT cond.
B1:	$l_i = 0,\ d_i = 0$	$p_i - c_i \leq 0$
B2:	$l_i > 0,\ d_i = 0$	$p_i - c_i = 0$

Next consider the implications of a species-specific fishery closure, i.e., a regulation landings of species i fish are prohibited. In this case, the maximum landings constraint can be ignored ($\lambda_i = 0$ for all closed species). The behavioral implications of a closure can be represented by setting $p_i = 0$. There are two harvest-discard possibilities to consider; both include $l_i = 0$, one with zero discards and one with positive discards:

Regime	Outcome	Necess. cond.
B1:	$l_i = 0,\ d_i = 0$	$-c_i < 0$
B2:	$l_i = 0,\ d_i > 0$	$-c_i = 0.$

$d_i = 0$ requires local strong output disposability. When discards are positive, condition (3d) profit maximization implies that marginal cost be equal to zero. Under local weak output disposability, it is likely costs will be lower with $h_i > 0$. However, since landings are prohibited, $d_i = h_i$, i.e., it is optimal to harvest a positive quantity of species i fish to forego costly avoidance measures and discard the harvest at sea since returning the fish to port generates no (legal) revenue and violates the closure regulation (see Singh and Weninger, 2009 for additional discussion).

We next consider the case of a maximum landings limit, i.e., $i \in J$. The KT necessary conditions are,

$$p_i - c_i - \lambda_i \leq 0 \tag{4a}$$
$$l_i[p_i - c_i - \lambda_i] = 0 \tag{4b}$$
$$-c_i \leq 0 \tag{4c}$$
$$d_i[-c_i] = 0 \tag{4d}$$
$$\lambda_i[\bar{l}_i - l_i] = 0 \tag{4e}$$
$$l_i,\ d_i\ \lambda_i \geq 0. \tag{4f}$$

The following behavioral regimes and necessary conditions apply:

Outcome	Necess. cond.	
B1:	$l_i = 0,\ d_i = 0$	$p_i - c_i < 0$
B2:	$0 < l_i < \bar{l}_i,\ d_i = 0$	$p_i - c_i = 0$
B3:	$l_i = \bar{l}_i,\ d_i = 0$	$p_i - c_i = \lambda_i$
B4:	$l_i = \bar{l}_i,\ d_i > 0$	$-c_i = 0.$

Again, regime B1 is possible only with strong output disposability. If the landings constraint is slack, as in B2, we have an interior solution with, $\lambda_i = 0$. From (4b) marginal profit must be zero, which combined with (4d), and assuming a positive price, implies $d_i = 0$. Under B3 and B4, the landings constraint binds, and thus $\lambda_i > 0$. If discards are zero (B3), the marginal profit is equal to the multiplier λ_i, which reflects the shadow cost of the constraint, $\bar{l}_i$. For regime B4, the landings limit binds and discards are positive. From condition (4d) we see that $-c_i = 0$ when $d_i > 0$. Case B4 requires zero marginal cost for species i, which suggests $l_i = \bar{l}_i$, and $d_i > 0$ is likely when the landings limit is small relative to harvests of other species.

The KT necessary conditions for a species regulated by a group landings limit ($i \in K$) include:

$$p_i - c_i - \lambda_K \leq 0 \tag{5a}$$
$$l_i[p_i - c_i - \lambda_K] = 0 \tag{5b}$$
$$-c_i \leq 0 \tag{5c}$$
$$d_i[-c_i] = 0 \tag{5d}$$
$$\lambda_K[\bar{l}_K - \sum_{i \in K} l_i] = 0 \tag{5e}$$
$$l_i,\ d_i,\ \lambda_K \geq 0. \tag{5f}$$

The group landings constraint may bind with $l_i = 0$. Additional harvest-discard regimes must be considered. Assume prices are strictly positive. Suppose initially that the group landings constraint is slack, such that $\lambda_K = 0$. With a positive price, $\sum_{i \in K} l_i < \bar{l}_K$ and $h_i > 0$, the combination $(l_i = 0, d_i > 0)$ or $(l_i > 0, /d_i > 0)$ cannot be part of a profit maximizing harvest strategy, which leaves the following regimes:

Regime	Outcome	Necess. cond.
B1:	$\sum_{i \in K} l_i < \bar{l}_K,\ l_i = 0,\ d_i = 0$	$p_i - c_i < 0$
B2:	$\sum_{i \in K} l_i < \bar{l}_K,\ l_i > 0,\ d_i = 0$	$p_i - c_i = 0$
B3:	$\sum_{i \in K} l_i = \bar{l}_K,\ l_i > 0,\ d_i = 0$	$p_i - c_i = \lambda_K$
B4:	$\sum_{i \in K} l_i = \bar{l}_K,\ l_i > 0,\ d_i > 0$	$p_i = \lambda_K$
B5:	$\sum_{i \in K} l_i = \bar{l}_K,\ l_i = 0,\ d_i = 0$	$p_i - c_i < \lambda_K$
B6:	$\sum_{i \in K} l_i = \bar{l}_K,\ l_i = 0,\ d_i > 0$	$p_i < \lambda_K$

Under regimes B1 and B5, $h_i = 0$, which implies local strong output disposability. If the technology exhibits local weak output disposability, marginal cost will be negative at $h_i = 0$, requiring $h_i = d_i > 0$ in order to minimize cost.

At an interior landings solution, as in B2, the group landing constraint is slack, $\lambda_K = 0$. Suppose the group landings constraint binds with positive landings of species i (B3-B4). If discards are zero, condition (5c) and (5d) imply non-negative marginal cost. From KT condition (5b), profit maximization requires h_i be chosen to equate marginal profit with λ_K.

Regime B4 includes a binding group landings constraint, positive landings and positive discards. From KT condition (5d), marginal cost is zero when $d_i > 0$. Substituting into (5b) obtains the necessary condition $p_i = \lambda_K$. In this knife-edge scenario, positive species i harvests arise jointly with the harvests of other species in the group. The price p_i is sufficiently high to warrant landing species i fish. This regime involves a form of high-grading behavior where the fisherman is indifferent between landing species i fish and discarding it to make room for other species in the group.

Regime B6 includes a binding group landings constraint, with $l_i = 0$ and $d_i > 0$. With $l_i = 0$ condition (5a) implies $p_i - c_i - \lambda_K < 0$. Substituting $-c_i = 0$ which holds when $d_i > 0$ obtains the condition $p_i < \lambda_K$. This regime describes a more standard high-grading scenario where, due to a low dockside price, species i fish is discarded to make room for more profitable species in the group.

A final observation is that a species-group landings constraint acts similarly to a vessel hold capacity constraint. Here the *group* landings constraint includes all harvested species. The KT necessary conditions (5a) - (5f) apply, with possible behavioral regimes B1-B6.

We now consider the behavioral implications on an individual transferable quota (ITQ) regulation. ITQs replace closures and landing limits with tradeable landings permits. Fisherman can legally land any quantity as long as they possess sufficient quota. If the quota binds at the fleet level, i.e., quota is scarce, a positive quota price will emerge that is equal to the marginal profit of landing an additional unit of species i fish. The necessary conditions for profit maximization are obtained by inserting the *net* price, the dockside price less the quota (lease) price, into the equation (2). Regime B1, zero harvests and landings for some species i, is possible under strong output disposability. If the net price is strictly positive and the fisherman owns quota, no discarding will occur and regime B2 ($i_i > 0, d_i = 0$) applies. If the quota binds stringently, the net price can be equal to zero. In this case, marginal costs must also be zero and discards will be positive, i.e., regime B4 applies with the landings constraint replaced by a quota holdings constraint.

4 Data and estimation

4.1 Data

Our data are from the National Marine Fisheries Service log book reporting system and a survey of annual operating expenses conducted by the Southeast Fisheries Science Center. The data period includes the 2005-10 calendar years. Regulations require vessel operators record per-trip harvest quantity by species, gear type used, primary region of fishing, and depth at which the bulk of the harvesting occurred. The logbook system also records the number of crew on board the vessel, quantity and type of gear used, and other trip characteristics. In 2003, a *Trip Expense and Payment Section* was added to the logbook form which collected information on trip revenue by species and trip expenses for fuel, bait, ice, and food. Beginning in 2005, expense and payment data collection became mandatory for a stratified sample of permitted reef fish vessels; 39.4% of the 2005-10 data record cost information. A second stratified sample of reef fish fishermen are required to record trip discard quantities by species; 17.5% of the 2005-10 trips record discard information. The data we use for our analysis consists of reef fish trips that have records of expense and discards; 7.72% of 2005-10 trips are included in our analysis for a total of 4,963 observations.

Preliminary analysis revealed data entries that were not representative of the median trip observation. Trips that recorded extreme costs per landed pound, less than \$0.04 per pound and in excess of \$2.50 per pound, were dropped. Trips that recorded less than 100 pounds landed across all species were removed. Trips taken in region 12, which corresponds to the New Orleans estuary were also dropped. Finally we deemed landings of more than 10,000 pounds of one particular species to be non-typical (the average landings of all species for vertical line gear is 1,854.61 pounds). Remaining data includes 3,558 vertical line gear trips and 304 longline trips.

Tractability requires that individual reef fish species be aggregated into output groups.

Groups are formed based on economic and regulatory importance or similarity of harvesting. There are four major harvested species in the reef fish fishery: h_1- red snapper; h_2- vermilion and other shallow water snappers; h_3- red grouper; and h_4- gag grouper. The remaining reef fish species are aggregated into output groups based on similarity of harvesting practice, e.g., fishing locations, depths, baits, and capture methods yielding three additional outputs: h_5- other shallow water groupers, h_6- deep water groupers and tilefishes, and h_7- all other reef fish species.[11] Descriptive statistics for trip-level costs, prices and harvest are reported in an appendix.

Stock abundance varies across space and time. Space is measured using the coarse geographical region in which the bulk of the each trip's catch is taken (see Figure 1). The measure (index) takes the value of 2 on trips taken in the Florida Keys and 21 for trips taken in waters off the southern Texas coast. Note that space is treated as a continuous variable in our model and much finer-scaled location information (e.g., latitude, longitude) could be incorporated if available. Our data lists the date that the trip's catch is landed at port. We specify a seasonal time index s which indicates the day of the year that landings are recorded, and a coarse index t which is set equal to the cumulative days since January 1, 2005. We impose the restriction that the seasonal effect on harvest cost on January 1 equal the effect on December 31 of each year.

Empirical implementation of our behavioral model is complicated by the fact that stock abundance is unobserved by the researcher at the relevant scale. Fisheries scientists rely on models that estimate total biomass for a fish species, the geographical boundaries of the species' habitat, preferred depths and, possibly, temporal migration patterns. The spatial, temporal and depth scale at which this information is available is coarse at best, or nonexistent. Our empirical approach is to estimate the stock composition, in fact the share of each species within as a latent variable. Details for this estimation are provided in section 4 below.

Table 1 reports the percentage of trips falling into key behavioral regimes. Rows 1-7 report trips taken under controlled access management and rows 8-12 report trips taken under ITQ management. The table further separates trips taken during regulatory open and closed periods.

The results in table 1 suggest reef fish fishermen have considerable control over the

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[11] Harvested quantities within each output category are aggregated linearly. The aggregation procedure assumes that optimal input choices and aggregate output levels can be chosen independently of the mix of species within each output category. The harvest technology is thus assumed to exhibit weak output separability. Linear aggregation implies a constant rate of transformation among species within each output group. These assumptions are consistent with fishing practices as described to us by reef fish fishermen. Nonetheless, it should be noted that output aggregation could bias the results that follow.

		B1	B2	B4	B6	B1	B2	B4	B6
Row	Species	Fishery open				Fishery closed			
1	Red Snap.	17.57	20.99	76.96	4.33	59.42	0.90	1.26	38.41
2	Verm. Snp.	25.31	59.91	13.84	0.94	-	-	-	-
3	Red Group.	40.06	19.13	44.80	2.06	78.92	3.20	0.87	17.01
4	Gag Group.	52.18	27.24	21.25	2.81	82.27	0.73	0.15	16.86
5	Oth. SWG	45.06	33.45	10.12	7.97	56.98	24.13	5.96	11.92
6	DWG/Tile.	73.83	25.08	1.46	0.34	91.46	3.88	0.93	3.73
7	Oth. Spec.	28.65	45.08	19.97	0.33	-	-	-	-
		With ITQs				Without ITQs			
8	Red Snap.	13.16	40.36	34.13	12.35	64.30	0.59	34.45	0.67
9	Red group.	12.67	36.11	50.29	0.93	88.36	7.40	1.68	2.56
10	Gag group.	28.02	38.43	24.88	8.66	87.28	4.69	1.23	6.81
11	Oth. SWG	27.83	47.42	10.28	6.82	69.75	23.55	2.57	3.35
12	DWG/Tile.	75.12	23.23	1.34	0.32	77.34	20.76	1.56	0.33

Table 1: Regulations and Targeting Behavior. Table reports percentage trips taken during 2005-10 in behavioral regimes, B1 ($l_i = d_i = 0$), B2 ($l_i > 0, d_i = 0$), B4 ($l_i > 0, d_i > 0$), and B6 ($l_i = 0, d_i > 0$).

mix of species that are intercepted by their gear, and modify their targeting behavior in response to the regulations they face. For example, consider red snapper under the controlled access regulation (row 1). When the red snapper fishery is open, 17.57% of trips avoid red snapper altogether. When the red snapper fishery is closed, 59.43% of trips avoid red snapper. Avoiding red snapper under a closure appears feasible, consistent with the property of local strong output disposability.

When the red snapper fishery is open 4.33% of trips include zero landings but positive discards (regime B6). These discards can be attributed to the minimum size restrictions which prohibits landings of red snapper less than 15 inches in length. Notice that when red snapper is closed, the regime B6 trips are more frequent at 38.41%. Under ITQ management (row 8), we see that reef fish fishermen who do not hold quota avoid intercepting red snapper; 64.30% of trips report no red snapper landings or discards (regime 1). We also see that trips with positive harvests but no landings are rare under ITQ management at 0.67%, considerably lower than under controlled access.

Harvesting patterns are similar for the other reef fish species. In sum, table 1 provides strong evidence that fishermen are able avoid species that are closed for fishing or for which they do not own quota. Evidence further suggests that avoidance is costly because discards of species that cannot be legally landed occur regularly in the data.

	Vessel, Crew, Trip Revenue and Cost							
	Vertical Line trips				Longline trips			
	Mean	Std.	Min.	Max.	Mean	Std.	Min.	Max.
Vessel length (feet)	37.59	8.88	22	67	44.63	6.56	31	69
Crew	2.61	1.10	1	21	3.10	1.17	1	8
Days/trip	4.12	2.74	1	17	9.54	3.23	1	18
Landings ('000 lbs.)	2.03	1.97	0.13	13.92	3.77	1.96	0.22	9.94
Discards ('000 lbs.)	0.29	0.63	0.00	8.71	1.02	1.56	0.00	10.52
Revenue ('000 $)	5.15	5.57	0.07	46.61	12.03	6.44	0.51	30.13
Variable exp. ('000 $)	0.83	0.66	0.10	6.42	2.47	0.96	0.37	7.17
Labor exp.s ('000 $)	1.63	1.71	0.02	12.09	3.18	1.73	0.14	8.10
	Harvest shares							
	Vertical Line trips				Longline trips			
	Mean	Std.	Min.	Max.	Mean	Std.	Min.	Max.
Red snapper	0.25	0.30	0.00	1.00	0.03	0.07	0.00	0.54
Vermilion snapper	0.29	0.33	0.00	1.00	0.01	0.04	0.00	0.43
Red grouper	0.22	0.32	0.00	1.00	0.45	0.41	0.00	1.00
Gag grouper	0.07	0.14	0.00	0.99	0.05	0.09	0.00	0.44
Other s.w. grouper	0.03	0.09	0.00	1.00	0.04	0.10	0.00	1.00
D.W. grouper/tilefish	0.02	0.08	0.00	1.00	0.32	0.40	0.00	1.00
All other species	0.13	0.17	0.00	0.99	0.10	0.17	0.00	0.86

Table 2: Data Descriptive Statistics. Data include 3,558 vertical line gear trips by 229 vessels, and 304 longline gear trips by 29 vessels.

Table 2 reports descriptive statistics for vessel length and crew size, trip revenue, costs and shares of harvested species. The data are separated by gear type and include 3,558 vertical line trips (92.1 %) and 304 (7.9 %) longline gear trips.

The average length of a vertical line gear boat is 37.59 feet. Longline trip boats are 7.04 feet longer on average. In general longline trips use larger crews, spend more days at sea, and have higher per-trip landings, discards, revenues, and expenses. The percentage of harvests that are discarded at sea for longline gear trips is also larger at 21.3 % versus 14.3 % for vertical line.

Average harvest shares across trips reveal the importance of the various reef fish species. On vertical line gear trips, the largest harvest share species are vermilion snapper, 29%, red snapper, 25%, red grouper, 22% and all other reef fish species, 13%. For vertical line trips, red grouper makes up the largest share of harvest at 41% with deep water groupers second at 32% and all other reef fish species accounting for 10% of the average trip harvest.

4.2 Estimation

The model can be estimated from observation of the variable cost equation and the M KT necessary conditions for profit maximization. We append an additive error to each of these conditions. Errors are is assumed to be normally distributed with zero mean and finite variance. Let ε_0 denote the cost equation error; $\varepsilon_i,\ i = 1, \ldots, M$ will denote the error term for the KT necessary conditions. The variance terms are denoted $\sigma_j^2\ j = 0, 1, \ldots, M$. We assume $E[\varepsilon_j \varepsilon_j'] = 0$, for all $j \neq j'$. The independence assumption is necessary given unobserved stock conditions, discussed below, and simplifies the estimation considerably.

As with many commercial fisheries, crew in the GOM reef fish fishery are paid a share of the trip revenues.[12] We subtract the labor costs $(1 - \eta) \sum_i p_i l_i$ from the trip profit in equation (1). The residual revenue to the skipper of the vessel is $\eta \sum_i p_i l_i$. Necessary conditions for profit maximization are adjusted accordingly.

With these assumptions, the estimating equations take the form,

$$\begin{gathered}
c - \bar{c}(h, \theta) = \varepsilon_0 \\
\eta p_1^e - \bar{c}_1(h, \theta) = \varepsilon_1 \\
\vdots \\
\eta p_M^e - \bar{c}_M(h, \theta) = \varepsilon_M,
\end{gathered}$$

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[12] Some vessel operators deduct a portion of trip expenses before calculating the crew share. Crew shares can vary considerably depending on the experience of crew members, ownership structure of the vessel, i.e., owner-operated versus hired skippers, and idiosyncratically across fishermen. Our data do not allow use to identify the precise remuneration scheme that is used on each vessel operation.

where $\overline{c}(h, \theta)$ is the empirical cost function with parameter vector θ.

We next derive the likelihood function for the model. The behavioral regimes presented above can be organized to three categories: (1) $h_i = 0$, (2) $0 < h_i \leq \overline{l}_i$, and (3) $h_i \geq \overline{l}_i$. In addition, the fishery may be open or closed, or if an ITQ program is in place, the vessel may or may not own quota. If the fishery is open or the fisherman holds quota, landings are permitted and the *effective* price at the dock is the prevailing market price. When the fishery is closed, or not quota is available, the effective price is zero. Within category (3), discards may be zero, in which case, the effective price is again the prevailing market price. If $h_i > \overline{l}_i$ and discards are positive, marginal harvests yield no additional revenue and therefore the effective price is zero.

We use p_i^e to denote the effective price for species i fish. Let y denote the observed data for a representative trip: $y = (c, h_1, \ldots, h_M)$. Define an indicator variable $I(h_i > 0) = 1$ if the harvest of species i is positive and zero otherwise. Define a second indicator variable $\overline{I}(h_i > \overline{l}_i) = 1$ if the harvest of species i fish exceeds the maximum landings limit or the vessel hold capacity, and zero otherwise.

The likelihood of observing y is,

$$\begin{aligned} \ell(\theta|y) &= \phi\left(\frac{c - \overline{c}}{\sigma_0}\right) \times \\ &\left\{ \prod_{i=1}^{M} \begin{pmatrix} [[1 - I(h_i > 0)]\Phi(\frac{-\eta p_i^e + c_i}{\sigma_i}) \\ +[I(h_i > 0)][1 - \overline{I}(h_i > \overline{l}_i)]\phi(\frac{\eta p_i^e - c_i}{\sigma_i}) \\ +[I(h_i > 0)][\overline{I}(h_i > \overline{l}_i)]\Phi(\frac{\eta p_i^e - c_i}{\sigma_i}) \end{pmatrix} \right\} \times \det|J(y)|, \end{aligned}$$

where $J(y)$ denotes the Jacobian of the transformation from the vector of shocks $(\varepsilon_0, \varepsilon_1, \ldots, \varepsilon_M)$, to the data vector $y = (c, h_1, \ldots, h_M)$.

The Jacobian matrix is therefore,

$$J(y) = \begin{vmatrix} 1 & -\overline{c}_1 & \cdots & -\overline{c}_M \\ 0 & -\overline{c}_{11} & \cdots & -\overline{c}_{1M} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & -\overline{c}_{M1} & \cdots & -\overline{c}_{MM} \end{vmatrix}. \tag{3}$$

Letting $n = 1, ..., N$ index individual fishing trips, the likelihood of observing the parameters θ given the full sample data $Y = \{y_n\}_{n=1}^N$ is,

$$L(\theta|Y) = \prod_{n=1}^{N} \ell(\theta|y_n). \tag{4}$$

4.2.1 Functional forms

The functional form for the harvest cost function is adopted from Singh and Weninger (2009):

$$\bar{c}(h, w, z|\gamma, \alpha) = \alpha_0 + \underbrace{\left[1 + \frac{\gamma}{2}\sum_i [s_i(h) - \varphi_i(x)]^2\right]}_{A} \times \underbrace{\exp\left[\sum_i \alpha_i h_i + \beta_k k\right]}_{B}. \tag{5}$$

The first right-hand term, A, reflects the cost of the targeting efforts made on the fishing trip; $s_i(h) = h_i / \sum_i h_i$ denotes the harvest share of species i. The term $\varphi_i(x)$ denotes a corresponding stock abundance share for species i. As discussed earlier, if a fisherman chooses a harvest vector such that $s_i(h) = \varphi_i(x)$ for all i, avoidance/targeting efforts are not required. In this case, $A = 1$ and trip costs are determined exclusively by the second term, B, which measures the non-target or extraction component of the full harvest cost. Note that the magnitude of A increases with the Euclidean distance between harvest share vector and the zero-target-cost share $\varphi(x) = (\varphi_1(x), ..., \varphi_M(x))$. The extraction cost component B depends on the quantity of harvested fish, plus additional conditioning variables, k. The elements of k are discussed in results section below.

We assume the composition of the fish stock varies by location, date, and depth. Let z_n summarize data on the location, date and depth of fishing trip n. We approximate $\varphi(x)$ as,

$$\varphi_{n,i}(z, \delta_i) = \frac{\exp(\phi(z_n, \delta_i))}{\sum_{i=1}^{M} \exp(\phi(z_n, \delta_i))}, \tag{6}$$

where δ_i is vector of parameters. The specification in equation (6) ensures that each share is contained in the interval $[0, 1]$ and that shares sum to 1 as required. The functional form for $\phi(z, \delta_i)$ is specified as a Chebychev polynomial function (Miranda and Fackler, 2002). Details are presented in 5.

5 Results

We report estimates of α and γ in an appendix. The Chebychev polynomial coefficients are difficult to interpret individually and, to save space, are not reported. We report the fitted zero-target-costs shares below. Most parameters are estimated with small standard error.[13] The R-squared statistic for the cost function equation is 62.9%, suggesting a good

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[13] A test of the null hypothesis that each parameter is equal to zero is rejected at the 99% confidence interval in all but 3 cases. Two of the δ parameters are statistically different from zero at the 95% level, one δ parameter is statistically indistinguishable from zero. Regulations in the reef fish fishery force wide variation in absolute harvest levels, and relative harvest mix which undoubtedly aides in parameter identification.

fit for incomplete panel data.

The model parameters are not directly interpretable. Economic effects of interest can be calculated from the model. Confidence intervals for these effects can be obtained with bootstrap methods. To conserve space we focus on point estimates and discuss a subset of results that illustrate the key properties of the technology.

Estimates of the variance terms associated with the Kuhn-Tucker necessary conditions, $\sigma_1, \ldots, \sigma_7$, are considerably larger than the cost equation variance. This reflects data scaling, costs and harvest quantities were scaled to thousands of dollars and pounds, respectively, to improve condition of the model.

We find that reef fish fishermen are able to target a particularly mix of species and incur modest cost increases to do so. The targeting component A of equation (5) is calculated for each trip and averaged across gear types. The result for vertical line gear trips (n=3,254) is 1.086, which suggests that, on average, 8.6% of vertical line trip costs can be attributed to the targeting efforts of fishermen. For longline gear trips (n=304), we find that 5.5% of trip costs derive from fishermen's targeting efforts. Keep in mind that variable costs on longline trip are almost three time larger than vertical line trips, averaging \$2,472 per trip versus \$833 per trip and thus absolute targeting costs in our sample for longline gear trips are estimated at \$135.96 per trip compared to \$71.64 per trip for vertical line gear trips.

The structural properties of the fitted cost function explains changes in fleet size that have taken place in the western region of the fishery, and suggests potential for additional fleet restructuring under the new grouper-tilefish quota management program (introduced in 2010). We calculate the cost elasticity for both gear types. Results suggest that a 10% increase in the per-trip harvest, holding the mix of harvested species fixed, raises trip variable costs an average of 5.14% on vertical line gear trips. A 10% increase in the harvest on longline gear trips raises variable costs by an average of 4.19%. These findings suggest reef fish fishermen in our data operated in a region of increasing returns to scale during the 2005-10 data period and that variable costs could be reduced if the catch were consolidated onto fewer trips. This is not surprising given the focus of the regulations in the fishery, particularly the temporal closure policies and per-trip landings limits. Quota management programs encourage fishermen to consolidate quota and exploit available economies of scale. Our results suggest further fleet downsizing in response to the recently introduced grouper-tilefish quota program are likely.[14]

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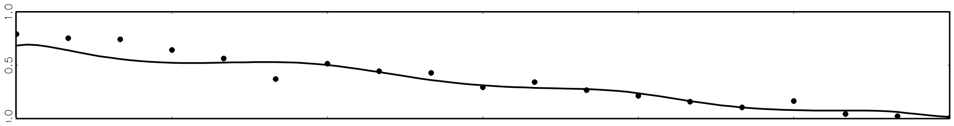
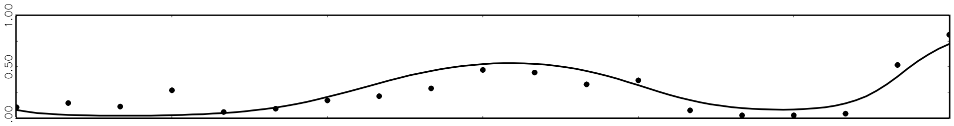
[14] Evidence of fleet downsizing caused by introduction of the red snapper quota program is apparent in the logbook data. The number of trips taken in the western region of the fishery, where red snapper is most prevalent, fell from 3,289 to 1,585 in the first year of the red snapper quota program, 2007. The average catch per trip has increased from 1,872.42 pounds in 2006 to 3,954.06 pounds in 2010, with a 58% increase in 2007, the first year of the program. The number of participating vessels in the western regions

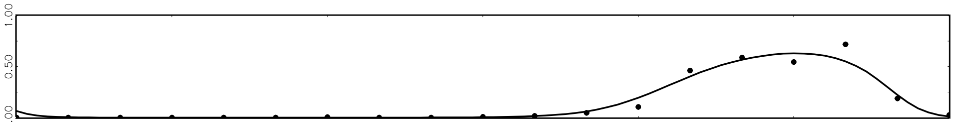
(a) Red snapper



(b) Vermilian and other snappers



(c) Red grouper



(d) Gag grouper

(e) DWG/tilefishes

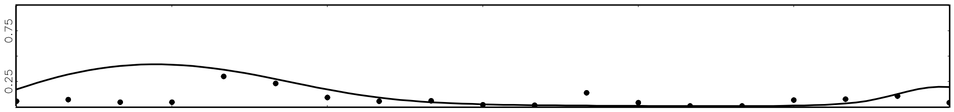


Figure 2: $\phi_i(z|\widehat{\delta})$ fitted values across Gulf regions (major target species)

We next consider the targeting properties of the estimated harvest technology. To illustrate, Figure 2 plots the fitted values for the zero-target-cost share vectors, $\phi_i(z|\widehat{\delta})$, or ϕ_i's for short, across space (solid lines). Values for five major harvested species are reported.[15] Results in the figure assume a representative fishing trip taken mid-year in 2009 at 150 feet depth, which is the median depth in our sample. For comparison, we also report the average observed catch shares in our data (solid circles). The left-hand of the graph corresponds to region 21 in waters off southern Texas. The right-hand side corresponds to region 1 in the Florida keys (see figure 1).

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has fallen as quota are consolidated onto few vessels. An estimate of the fleet structure projected under quota management is possible with additional information on vessel fixed operating costs. Such an analysis is beyond the scope the current paper.

[15] The estimated values of ϕ_5, other shallow water groupers averages 0.028 across the Gulf regions and shows very little spatial variation. Similarly, the estimate of ϕ_7 is 0.125 also with little spatial variation. To avoid clutter these results are not reported.

In panel (a) we see that the zero-target-cost harvest share for red snapper is high in the west, roughly 80% of the trip catch in region 21, and falls to almost 0% of trip catch in the eastern region of the fishery. The average red snapper harvest share in our sample data varies around the fitted ϕ_1 value.

Panel (b) in Figure 2 shows the vermilian snapper value, ϕ_2, is low in the western region, rises to roughly 40% in central regions, falls in regions 3-7 and rises sharply to over 80% in the east. The sharp rise in Florida Keys (regions 1-3) is explained by our decision to combine vermilian with other snapper species. Vermilian snapper habitat is not spatially disjoint as shown in panel (b) but is most prevalent in central Gulf regions (8-13). Average catch shares in our sample data also vary around the fitted ϕ_2 value.

Red and gag grouper zero-target-costs shares, ϕ_3 and ϕ_4, are reported in panels (c) and (d) of figure 2. The results indicate that grouper species are most prevalent in waters off of the Florida coast, regions 2-7. Sample average harvest shares indicate that reef fish fishermen tend to incur costs to target red grouper. The sample average gag grouper harvest share closely follows the fitted value for ϕ_4.

The results for deep water groupers and tilefish (panel (e) in Figure 2) indicate fitted values for ϕ_7 between 5%-20% in the western region and values close to zero in the eastern regions of the fishery.

Table 3 reports estimates of variable cost, ray average variable costs and marginal costs for the five main target species. The results are reported for two trip types, one taken in the eastern region 5 and the other taken in western region 15. Both trips are taken mid-year 2008 (roughly the mid-point of our data) in 150 feet of water. We vary the size of the harvest vector holding shares constant at the sample mean for vertical line gear trips.[16] Total trip pounds is varied from 1,000 to 6,000 which captures the range observed in our sample.

The results for the western Gulf region trip show trip costs rising from \$870 to \$1,820, and ray average variable costs falling from \$0.87 to \$0.30 per pound as the harvest increases. Falling ray average variable costs is consistent with the cost elasticity calculations above and increasing returns to size in our sample data. Turning to the species-specific marginal cost estimates we see that $\widehat{c}_1$ (red snapper marginal cost) is negative at small harvest quantities. Red snapper marginal cost increases and become positive, but remains small, at higher harvest levels. This result highlights the weak output disposability property of the reef fish targeting technology. Recall from figure 2, that the zero-target-cost

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[16] Average harvest shares in our sample are: 0.25 (red snapper); 0.29 (vermilian snapper); 0.22 (red grouper); 0.07 (gag grouper); 0.03 (other shallow water groupers); 0.02 (deep water groupers and tilefish); 0.13 (all other species). The 10% (90%) per-trip harvest quantity on vertical line trips is 280 (4,790) pounds.

			Western Region Trip				
Pounds/trip	Cost	AVC	$\widehat{c}_1$	$\widehat{c}_2$	$\widehat{c}_3$	$\widehat{c}_4$	$\widehat{c}_6$
1,000	\$620	\$0.62	-\$0.53	\$0.79	\$0.48	\$0.15	-\$0.38
2,000	780	0.39	-0.19	0.51	0.38	0.16	0.08
3,000	950	0.32	-0.07	0.43	0.36	0.17	0.24
4,000	1,130	0.28	-0.01	0.39	0.35	0.18	0.34
5,000	1,320	0.26	0.03	0.38	0.35	0.19	0.41
6,000	1,510	0.25	0.06	0.37	0.36	0.19	0.46
			Eastern Region Trip				
Pounds/trip	Cost	AVC	$\widehat{c}_1$	$\widehat{c}_2$	$\widehat{c}_3$	$\widehat{c}_4$	$\widehat{c}_6$
1,000	\$870	\$0.87	\$0.53	\$0.70	-\$1.40	-\$0.33	\$0.27
2,000	1,050	0.52	0.37	0.48	-0.59	-0.08	0.43
3,000	1,230	0.41	0.32	0.41	-0.31	0.01	0.51
4,000	1,420	0.35	0.30	0.38	-0.17	0.05	0.55
5,000	1,620	0.32	0.29	0.37	-0.08	0.08	0.60
6,000	1,820	0.30	0.19	0.36	-0.01	0.11	0.63

Table 3: Targeting Cost Across Space. Cost estimates are for a median vessel using vertical line gear, mid-year 2010, in 150 feet of water. Harvest shares are fixed at sample average values for vertical line trips.

share for red snapper in the west is in the range of 50%-80%. Results in table 3 maintain red snapper harvest share at 25% of trip catch which, at low harvest quantities, results in negative marginal costs. As the size of the harvest vector increases marginal extraction costs, which are increasing, dominate the targeting cost effect and marginal costs turn positive.

The deep water grouper and tilefish species group also exhibits the weak output disposability property and negative marginal costs at low harvest quantities. Marginal costs for vermilian snapper, red and gag groupers are positive throughout the range of harvests considered in table 3.

Turning to the eastern trip results, we see that the marginal cost for red snapper is positive and much larger at all harvest vectors considered. This confirms that the weak output disposability property is a spatially local phenomenon driven by local stock conditions. Red snapper marginal costs are positive in the eastern region, consistent with the relatively small estimated value for $\widehat{\phi}_1$ in figure 2. Weak output disposability is apparent for red and gag grouper in the eastern region of the fishery. Form figure 2 we see that the zero-target-cost harvest share for red grouper is as high as 40% whereas the red grouper share in table 3 is held at 22% of trip catch. Similarly, the zero-target-cost harvest share for gag grouper is roughly 10% in region 5; the gag grouper share is held at 7% in table 3.

Investigations of the longline gear technology yields similar costly targeting properties which vary across regions of the fishery.

Summarizing, negative marginal cost for red snapper and deep water groupers and tilefish in the west, and for red and gag grouper in the east, suggest that fishermen on trips taken during closures, or fishermen who face tight landings limits, have strong incentive to discard fish at sea. The fitted model finds that fishermen can lower their costs by intercepting and discarding some species rather than undertaking costly measures to avoid them. The next section presents results from simulations to further demonstrate the implications of the technology, and the weak output disposability property, for targeting and discarding behavior.

6 Policy analysis

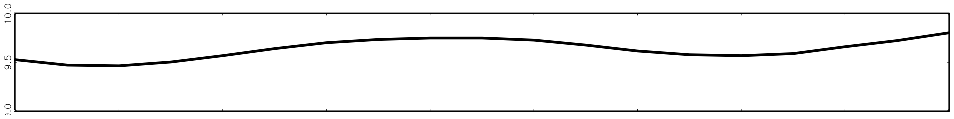
This section reports results from simulations using the fitted cost model. We programmed an optimization routine to calculate the per-trip variable profit maximizing harvest vector, separated by landings and discards, under the various regulations experienced by fishermen in our sample. We consider a vertical line gear trip taken mid-year in 2009 in 150 feet of water. Trip landings are constrained at 5,000 total pounds to reflect the hold capacity constraint on a typical vessel. There is however no limit imposed on the harvest, and we will see that in some cases profit maximization involves discarding fish at sea. We report trip variable profits which include the revenues less operating expenses and payments to the crew, calculated as the sample mean crew share times trip revenue. Prices are set in the range observed in the 2009 fishing season, with some adjustment to prevent dominant prices dictating the targeting activity of our representative fisherman.

6.1 Closures, trip limits and IFQ regulations

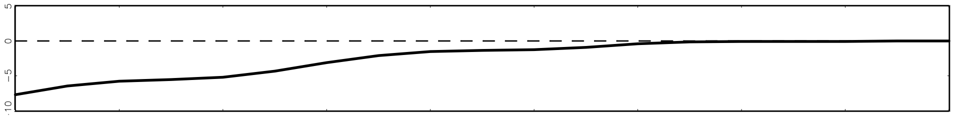
Figure 3 reports variable profits under five management scenarios. Panel (a) reports baseline variable profits where no regulations are imposed on harvesting activity. Trip variable profit average \$9,634 across regions with slight regional variation, which results from changes in relative stock abundance across space. Lower trip profit in the west, for example, is due to a relatively low red snapper price chosen for the simulation. That is, higher prices species, e.g., shallow water groupers, are less prevalent and more considerably more costly to harvests in the west which causes the reduced trip profit.

The results in panels (b)-(e) report percentage change in trip variable profit from the baseline, under four types of regulation. The dashed line demarcates zero profit change

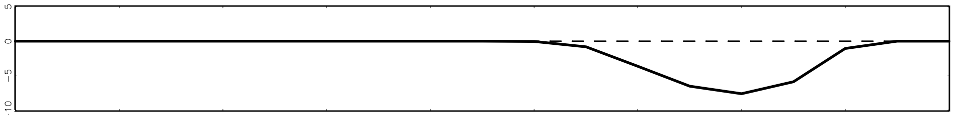
(a) Trip Profit ('000 $)



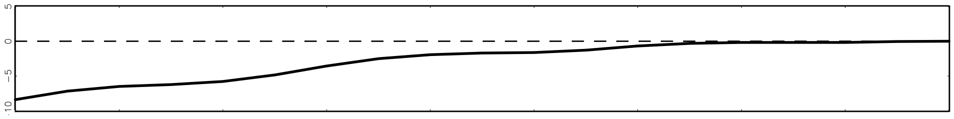
(b) 200 Lb. Red Snapper Trip Limit



(d) Red, Gag, SW Grouper Closure



(c) 25% Red Snapper Price Drop



(e) 25% Grouper Price Decline

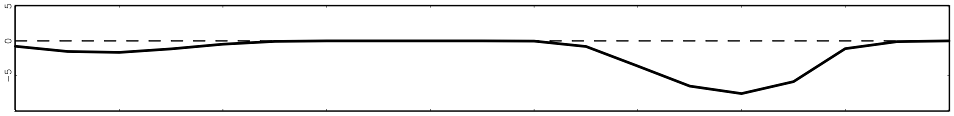


Figure 3: Prices, Regulations and Fishing Behavior

and we see that in each case regulations lower or have not effect on profits as required.

The results in panel (b) show the effect of a 200 pound red snapper landings limit. The average profit decline across the fishery is 2.42%. The profit decline ranges between 4%-7% in the western region and indicates no profit decline in the east. This result is driven by differences the relative abundance across regions of the fishery.

Additional results from simulation show the implications of landings limits for targeting behavior and discarding under local weak output disposability. Not surprisingly, the 200 red snapper landings limit causes a targeting shift toward other species, particular vermilian snapper in the west region of the fishery. Our model also predicts large red snapper discards under a 200 pound landings cap, also in the western region. Red snapper discards range between 250-1,000 pounds, more than landings in regions 13-21. Recall that the zero-target cost share for red snapper is high in the west, whereas a 200 pound landings limit amounts to only 4% of a 5,000 pound trip harvest.

Panel (c) in figure 3 simulates the effect of a shallow water grouper closure. This regulation is constructed by setting the red, gag and other shallow water grouper prices to zero. The variable profit decline is estimated between 3%-8% of the baseline in waters off northern Florida (regions 3-8) where shallow water groupers are relatively abundant. The model predicts discards of red grouper in these same regions. This finding is again explained by the weak output disposability property for groupers in the eastern region of the fishery.

Panels (d) and (e) simulate the effects of red snapper and grouper price decline of 25% from baseline prices. These scenarios are intended to capture the effects of introducing a quota management program for these species, while maintain no regulation for remaining species.[17]. When quota is tradable a quota rental price will emerge and this value must be deducted from the dockside price. Panels (d) and (e) are intended to capture the effect of a modest quote rental price set to 25% of dockside prices.

For reasons that are now well understood, profit declines caused by a red snapper net price drop are largest in the western region. Not apparent in the figure, however, is that the red snapper price decline causes a large change in targeting behavior on western trips. Lower red snapper price cause fishermen to target other reef fish species. The model predict a 26.5% increase in vermilian snapper harvests and landings above baseline levels. The model also predicts discards of red snapper at low prices. This behavior is an example of high grading, although in our simulation discards are motivated by the vessel hold capacity constraint rather than a red snapper quota constraint.

Panel (e) of figure 3 reports results for a 25% reduction in the price for all groupers and tilefish. Variable profit declines are largest in the eastern region where these species are most prevalent. We again find substitution toward higher priced species, in this scenario, vermilian snapper and the miscellaneous species group. Lastly, the results indicate discards of lower priced species, red grouper, which again is driven by the hold capacity constraint on total trip landings.

The results reported in Figure 3 represent a small number of scenarios of interest to regulators. We also simulated behavioral effects of changes in fuel prices, fishing in different seasons, years and depths, and examined harvest and discard behavior for longline fishing gear. These simulations further demonstrate the power of our model as a policy evaluation tool. Results are not reported here to save space.

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[17] This is how the quota management was introduced in the Gulf reef fish fishery: red snapper in 2007, groupers and tilefish in 2010. Remaining reef fish species continue to be managed under controlled access regulation

6.2 Sea-turtle bycatch policy

This section examines the behavioral implications of sea turtle bycatch management policies for longline gear fishermen. Amendment 32 to the reef fish management plan imposed depth closures, limits on the number of hooks onboard a vessel and reductions in the size of the longline fleet. We examine each of these regulations in seriatim.

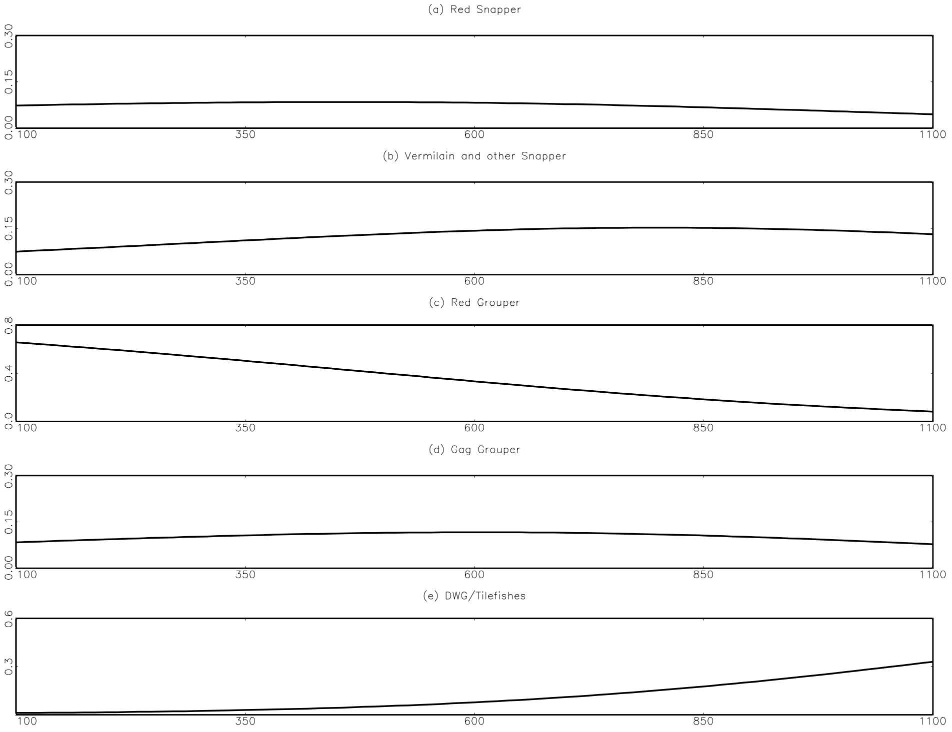

Figure 4: Fitted Zero-Target-Cost Harvest Shares.

Pushing vessels into deeper waters will affect targeting behavior if the composition of the stock varies with depth. Figure 4 reports fitted zero-target-cost shares over the range of fishing depths observed in our sample. We see that for snappers, and gag grouper, the fitted ϕ_i's vary modestly with depth. For red grouper and deepwater grouper and tilefish, zero-target-cost shares show considerable sensitivity to fishing depth. True to their name, the deepwater grouper fitted value, ϕ_6, increase from zero in shallow water to over 30% of the harvest at depths near 1,000 feet.

To demonstrate the implications of depth regulation we conducted additional variable profit maximization simulations across for rips taken between 50-800 feet of water. Prices

	All Trips			All Landings			Red Group. Landings		
Year	V. L.	L. L.	Total	V. L.	L. L.	Total	V. L.	L. L.	Total
2005	10,154	2,028	12,182	10,604	7,508	18,113	1,346	3,085	4,430
2006	9,749	2,128	11,877	10,429	7,482	17,910	1,346	3,085	4,430
2007	7,136	1,362	8498	9,389	4,968	14,357	1,368	2,991	4,359
2008	7,191	1,385	8,576	9,809	5,338	15,147	1,531	1,938	3,469
2009	7,940	793	8,733	11,462	3,214	14,676	1,857	2,772	4,629
2010	5,612	513	6,125	8,557	2,331	10,887	2,367	1,084	3,451

Table 4: Vertical and Longline Gear Effort and Landings, 2005-10. Landings are reported in thousands of pounds.

were selected to reflect the mix of species harvested on a typical longline trip in our data. The results show steady changes in the mix of targeted stocks as the depth of fishing increases. Per trip profits fall as fishing depths increase although these results must be interpreted cautiously as they are sensitive to prices. Consistent with the results in figure 4, red snapper, red grouper, and gag grouper shares fall with fishing depth, although the change in gag grouper share is slight. The predicted share of deep water grouper and tilefish in the total catch increases substantially with depth of fishing. The magnitude of the targeting change varies across regions, suggesting depth regulations can have important, and spatially heterogeneous implications for targeting behavior of longline fishermen.

A second bycatch management measure we consider is a limit on the number of hooks carried on board a vessel. Our data do not contain hooks data but do provide information on the average longline length (longline-gear trips only). We re-estimate our model with this additional explanatory variable and find that increased longline length lowers trips costs (the effect is small but statistically significant at the 99% confidence level). To assess the effect of the regulation, we compare sample predicted costs at observed longline lengths with costs evaluated at shorter line lengths. If we truncate longline length at the sample median value, costs are predicted to increase by 2.17%. If we truncate longline length at the 25'th percentile value on the sample, the model predicts a variable cost increase of 5.95% on longline gear trips. These results can be viewed as illustrative only because the relationship between longline length and hooks is a choice variable for fishermen. Evidence suggests, however, harvest costs are increased by the hook limit regulation.

The third bycatch measure implemented under Amendment 31 is a reduction in the use of longline gear in the fishery. Analysis of the full logbook data offers evidence of the effect of this regulation. We report (table 4) the number of trips, total pounds harvested, and total pounds of red grouper harvested per year and by gear type during the 2005-10 seasons. Red grouper is highlighted as it is the main target species for longline gear fishermen (the average share is 45% of trip catch).

	Vertical Line Gear			Longline Gear		
Pounds/Year	RAVC	AFC	RAC	RAVC	AFC	RAC
30,000	$0.32	$0.89	$1.21	$0.22	1.07	1.29
40,000	0.32	0.67	0.99	0.22	0.81	1.03
50,000	0.32	0.53	0.85	0.22	0.64	0.86
60,000	-	-	-	0.22	0.54	0.76
70,000	-	-	-	0.22	0.46	0.66
80,000	-	-	-	0.22	0.40	0.62

Table 5: Eastern Region Average Cost Estimates. RAVC-denote ray average variable cost. AFC - denotes average fixed cost. RAVC - denotes ray average variable costs.

The number of longline gear trips fell from 1,385 to 793 in the first full year of the bycatch management regulation, 2009, while vertical line gear trips increased. Total trips increased slightly between 2008 and 2009. It is reasonable to surmise that fishermen whose longline gear license was revoked under Amendment 31 substituted toward vertical line fishing.

Total landings by the two gear types declined slightly in 2009. Landings on vertical line gear trips increased from 9.809 million pounds in 2008 to 11.462 million pounds in 2009. Longline harvest (all species) fell by 43% between 2008 and 2009, from 5.338 million pounds to 3.214 million pounds. The effect of the regulation on red grouper landings by longline gear fishermen is even more apparent. In 2008 longline gear boats landed 59.9% of all red grouper. The longline landings share of red grouper fell to 31.4% in 2009.

Table 4 reveals that Amendment 31 reduced the amount of longline fishing effort and likely caused an increase in effort and landings with vertical line gear. Whether the regulation decreased total effort and landings is difficult to know; landings fell from 15.147 million pounds in 2008 to 14.676 million pounds in 2009.[18]

We supplement our trip-level model with information on annual operating expenses to provide further insight onto the costs of removing longline gear from the reef fish fishery (see Appendix B). Table 5 reports ray average variable cost and average fixed cost for a median vertical line and longline vessel over a range of annual total landings. Logbook data indicate that annual landings vary between 30,000 and 50,000 pounds for a full time vessel operation using vertical line gear. Landings for Longline gear boats is higher at 80,000 pounds annually. Vertical line annual harvests exceeding 50,000 pounds are deemed

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[18] The significant drop in total catch to 10.887 million pounds in 2010 is likely the results of the Deepwater Horizon oil spill which disrupted harvesting operations in a large portion of the fishing ground

infeasible as they are rarely observed in the logbook data.[19] Ray average variable costs are calculated at the sample average harvest mix for eastern regions trips. We assume the trip is taken midyear 2009, the first full year of the turtle bycatch regulation. Labor expenditures are a fraction of revenues and therefore do not change across gear types. Labor expenses are not included in the cost calculations.

The results show that ray average variable costs for longline fishermen is slightly lower than for vertical line fishermen. However, because longline gear vessels land significantly more fish per year, and fixed operating expenses do not vary by gear type, average fixed costs and average total costs (excluding labor) are lower for longline gear fishermen. The difference for a fully utilized vessel is estimated at \$0.23 per pound.

Simple back of the envelope calculations shed further light on the costs of removing longline gear from the the fishery. Consider a scenario in which the 2009 landings are harvested under the 2008 fleet structure, i.e, with 64.5% harvested by vertical line gear and 35.5% by longline gear (rather than the 78.8%, 21.2% split observed in 2009). The 0.23\$ per pound cost saving amounts to a foregone \$483,000 cost saving in 2009. Carrying out the same calculation for 2010 yields a cost savings estimate of \$340,000; a smaller amount due to the smaller landings in 2010.

7 Conclusion

Fishery managers regularly employ spatial and temporal closures or depth restrictions to control harvests in multiple-species fisheries. These regulations affect all aspects of fishing behavior including harvest patterns, discards, and fishing profits. We introduce and estimate a structural model of a costly targeting technology using data from the GOM reef fish fishery. The model generates a system of Tobit-type equations which are estimated with non-linear maximum likelihood. The results yield a vector of target-cost-minimizing harvest shares which describe the profit opportunities for fishermen across continuous measures of space, time and depth.

The fitted model characterizes harvesting and targeting costs across space, time and depth in the Gulf reef fish fishery. Our results show how closure policies and landing limits provide incentives to discard fish at sea in regions of he fishery. Closures, landings limits and depth restrictions affect the targeting strategies of reef fish fishermen is complex ways

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[19] Landings data reveal considerable variation in annual landings across vessels, and gear types. Annual landings for longline gear fishermen are considerably larger than for vertical line gear fishermen. The 90'th percentile landings value for vertical line vessel ranges between 36,000-44,000 pounds per year in 2005-10. The 90'th percentile value for longline vessels annual landings ranges between 80,000-86,000 pounds per year.

that are linked to relative abundance of reef fish stocks over space, time and depth. Our model also predicts discard behavior that results from measured local weak output disposability. Simulations of behavioral responses to prices and regulations across regional, date and depth dimensions are presented.

Our model overcomes several problems that plague discrete choice models of spatial fishing behavior. Because our unit of analysis is a multiple-species harvest vector in a regulated fishery, our model predicts much more than a probability of choosing a fishing location. Our predictions of harvests and discard across continuous measures of time, space and depth provide crucial insights that yield important insights for improving regulations in the Gulf reef fish fishery. Application of the model to other multiple-species fisheries will prove similar insights.

8 References

Abbott J. K. and J. E. Wilen, Dissecting the tragedy: A spatial model of behavior in the commons. *Journal of Environmental Economics and Management*, **62** (2011): 386-401.

Berman, M., Modeling Spatial Choice in Ocean Fisheries. *Marine Resource Economics*, **21** (2007): 375-394.

Bockstael, N. E. and J. J. Opaluch, Discrete modeling of supply response under uncertainty-the case of the fishery. *Journal of Environmental Economics and Management*, **10** (1983): 125-137.

Branch, T. A., and Ray Hilborn, Matching catches to quotas in a multispecies trawl fishery: targeting and avoidance behavior under individual transferable quotas, *Canadian Journal of Fisheries and Aquatic Sciences* **65** (2008): 1435-1446.

Brodziak, J., and J. Link, Ecosystem-Based Fisheries Management: What is it and how can we do it? *Bulletin of Marine Science*, **70** (2002) 589-611.

Campbell, H. F., and R. B., Nicholl, Can purse seiners target yellowfin tuna? *Land Economics*, **70** (1994): 345-353.

Curtis, R. E. and K. E. McConnell, Incorporating Information And Expectations In Fisherman's Spatial Decisions, *Marine Resource Economics*, **19** (2004): 131-144.

Eales, J. and J. E. Wilen, An examination of fishing location choices in the pink shrimp fishery. *Marine Resource Economics*, **2** (1986): 331-351.

Haab, T. C., M. Hamilton and K. E. McConnell, Small boat fishing in Hawaii: A random utility model of ramp and ocean destinations, *Marine Resource Economics*, **23** (2008):

137-151.

Haynie, A. and D. Layton, An Expected Profit Model for Monetizing Fishing Location Choices. *Journal of Environmental Economics and Management* **59** (2010): 165-176.

Herrera, G. E., Benefits of Spatial Regulation in a Multispecies System. *Marine Resource Economics*, **21** (2006): 63-79.

Kirkley, J. E., and I. E. Strand, The technology and management of multi-species fisheries. *Applied Economics*, **20** (1988): 1279-1292.

Pikitch, E. K., C. Santora, E. A. Babcock, A. Bakun, R. Bonfil, D. O. Conover, P. Dayton, P. Doukakis, D. Fluharty, B. Heneman, E. D. Houde, J. Link, P. A. livingston, M. Mangel, M. K. McAllister, J. Pope, K. J. Sainsbury, Ecosystem-based fisheries management. *Science* **305** (2004): 346-347.

Miranda, M. J., and P. L. Fackler, Applied Computational Economics and Finance. Massachusetts Institute of Technology Press, 2002.

Mistiaen, J. A. and I. E. Strand, Location choice of commercial fishermen with heterogeneous risk preferences. *American Journal of Agricultural Economics*, **82** (2000): 1184-1190.

Singh, R. and Q. Weninger, Bio-Economies of scope and the discard problem in multiple-species fisheries. *Journal of Environmental Economics and Management*, **58** (2009): 72-92.

Smith, M. D., Spatial Search and Fishing Location Choice: Methodological Challenges of Empirical Modeling. *American Journal of Agricultural Economics*, **82** (2000): 1198–1206.

Smith, M. D., Two Econometric Approaches for Predicting the Spatial Behavior of Renewable Resource Harvesters. *Land Economics*, **78** (2002): 522-538.

Turner, M. A., Economics without Free-Disposal: The problem of Quota-induced Discarding in Heterogeneous Fisheries. Mimeo, University of Toronto, 1995.

Turner, M. A., Quota-Induced Discarding in Heterogeneous Fisheries. *Journal of Environmental Economics and Management* **33** (1997): 186-195.

U.S. Commission on Ocean Policy, Preliminary Report of the U.S. Commission on Ocean Policy, Governor's Draft., U.S. Commission on Ocean Policy, Washington, DC, April, 2004.

Wales, T. J., and A. D. Woodland, Estimation of Consumer Demand Systems with Binding Non-negativity constraints. *Journal of Econometrics*, **21** (1983): 263-285.

Weninger, Q. and J. Waters, Economic benefits of management reform in the northern Gulf of Mexico reef fish fishery. *Journal of Environmental Economics and Management*, **46** (2003): 207-30.

Wilen, J. E., Spatial management in fisheries. *Marine Resource Economics*, **19** (2004): 7-19.

Worm, B., R. Hilborn, J. K. Baum, T. A. Branch, J. S. Collie, C. Costello, M. J. Fogarty, E. A. Fulton, J. A. Hutchings, S. Jennings, O. P. Jensen, H. K. Lotze, P. M. Mace, T. R. McClanahan, C. Minto, S. R. Palumbi, A. M. Parma, D. Ricard, A. A. Rosenberg, R. Watson and D. Zeller, Rebuilding Global Fisheries. *Science*, **325** (2009): 578-585.

9 Appendix A

This appendix derives marginal costs and the Jacobian transformation matrix for the likelihood function. The marginal harvesting cost for species i fish is,

$$\frac{\partial \bar{c}(h,w,z|\theta)}{\partial h_i} = B\frac{\partial A}{\partial h_i} + A\frac{\partial B}{\partial h_i}.$$

Carrying out the derivations obtains:

$$\begin{aligned}
\frac{\partial A}{\partial h_i} &= \frac{\gamma}{\overline{h}}\left[(s_i-\varphi_i)(1-s_i) - \textstyle\sum_{j\neq i}(s_j-\varphi_j)s_j\right] \\
&= \frac{\gamma}{\overline{h}}\left[(s_i-\varphi_i) - \textstyle\sum_{j=1}^{M}s_j^2 - \sum_{j=1}^{M}\varphi_j s_j\right] \\
\frac{\partial B}{\partial h_i} &= \alpha_{1,i} + \alpha_{2,i}h_i,
\end{aligned}$$

where $\overline{h} = \sum_i h_i$. Function arguments are dropped to ease notation.
The matrix of second derivatives is derived as

$$\begin{aligned}
\frac{\partial^2 \bar{c}(h,w,z|\theta)}{\partial h_i \partial h_j} &= \frac{\partial}{\partial h_j}\left\{B\frac{\partial A}{\partial h_i} + A\frac{\partial B}{\partial h_i}\right\} \\
&= B\frac{\partial^2 A}{\partial h_i \partial h_j} + \frac{\partial B}{\partial h_j}\frac{\partial A}{\partial h_i} + \frac{\partial A}{\partial h_j}\frac{\partial B}{\partial h_i} + A\frac{\partial^2 B}{\partial h_i \partial h_j}.
\end{aligned}$$

The terms A, B, $\partial A/\partial h_i$ and $\partial B/\partial h_i$, are presented above. Terms to be evaluated include, $\partial^2 A/\partial h_i \partial h_j$ and $\partial^2 B/\partial h_i \partial h_j$. Carrying out the derivations for the case of $j = i$ obtains:

Variable	Parm.	Std. err.	Prob.
Constant	-0.693	0.104	0.000
Owner operator	-0.109	0.018	0.000
Crew size	0.149	0.036	0.000
Vessel Length	-0.001	0.003	0.645
Crew × Length	-0.003	0.001	0.000
Longline gear	-0.270	0.024	0.000

Table 6: Crew Share Model Parameter Estimates. 16,376 obs. are available for analysis.

$$
\begin{aligned}
\frac{\partial^2 A}{\partial h_i^2} &= \frac{\partial}{\partial h_i}\left\{\frac{\gamma}{\overline{h}}\left[(s_i-\varphi_i)-\textstyle\sum_{j=1}^{M} s_j^2-\sum_{j=1}^{M}\varphi_j s_j\right]\right\} \\
&= -\frac{\gamma}{\overline{h}^2}\left[(s_i-\varphi_i)-\textstyle\sum_{j=1}^{M} s_j^2-\sum_{j=1}^{M}\varphi_j s_j\right] \\
&+ \frac{\gamma}{\overline{h}}\left[\frac{\bar{h}-h_i}{\overline{h}^2}-2s_i\frac{\bar{h}-h_i}{\overline{h}^2}-2\textstyle\sum_{k\neq i} s_k\left(\frac{-h_k}{\overline{h}^2}\right)+\varphi_i\frac{\bar{h}-h_i}{\overline{h}^2}+\sum_{k\neq i}\phi_k\left(\frac{-h_k}{\overline{h}^2}\right)\right] \\
&= \frac{\gamma}{\overline{h}^2}\left[1-4s_i-2\varphi_i+3\textstyle\sum_k s_k^2-2\sum_k\varphi_k s_k\right]. \\
\frac{\partial^2 B}{\partial h_i^2} &= \alpha_{2,i}.
\end{aligned}
$$

When $j \neq i$ we find:

$$
\begin{aligned}
\frac{\partial^2 A}{\partial h_i \partial h_j} &= -\frac{\gamma}{\overline{h}^2}\left[(s_i-\varphi_i)-\textstyle\sum_k (s_k-\varphi_k)s_k\right] \\
&+ \frac{\gamma}{\overline{h}}\left[\frac{-h_i}{\bar{h}}-2s_j\frac{\bar{h}-h_j}{\bar{h}}-2\textstyle\sum_{k\neq j} s_k\left(\frac{-h_k}{\bar{h}}\right)+\varphi_j\frac{\bar{h}-h_j}{\bar{h}}+\sum_{k\neq j}\phi_k\left(\frac{-h_k}{\bar{h}}\right)\right] \\
&= \frac{\gamma}{\bar{h}^2}\left(-2\left(s_i+s_j\right)+\left(\phi_i+\phi_j\right)+3\textstyle\sum_k s_k^2-2\sum_k\phi_k s_k\right). \\
\frac{\partial^2 B}{\partial h_i \partial h_j} &= 0.
\end{aligned}
$$

10 Appendix B

This appendix reports parameters estimates and additional results used in our analysis.

Table 6 reports the results for a crew share model estimated from the full logbook data

Variable	Std. err.	Prob.	
Constant	-3.412	0.899	0.000
ln(Vessel Length)	1.796	0.233	0.000
ln(Horse Power)	0.369	0.102	0.000
Proportion of days fished	0.288	0.055	0.000

Table 7: Fixed Operating Expenses Parameter Estimates. Dependent variable is log of annual operating expenses. The model is estimated with ordinary leases squares with 178 observations. The model R-square statistic is 0.40. The F-statistic value is 38.615.

set. We specified the following equation:

$$\mathrm{CP}_t = \frac{1}{1 + exp(-z_t\theta)},$$

where CP_t is the crew payment on trip t and z_t denotes explanatory variables for trip: a constant term; *Owner operator*, a 0-1 indicator variable equal to unity if the vessel skipper is also the owner of the vessel; crew size; vessel length and a 0-1 indicator variable set to unity if the trip used longline gear. The model is estimated with non-linear least squares regression with 16,376 observations.

Data are from a survey of annual operating expenses conducted by the Southeast Fisheries Science Center. Fixed operating expenses include expenditures on tackle, vessel repair and maintenance, boat dockage fees, insurance, office expenses, and other annual expenses. Least squares regression was used to fit 178 observations for the 2005-09 fishing seasons to vessel characteristics. The model R-squared is 0.40. As shown above annual expenses increase with vessel length, horse power and total days fishing during a season. Additional regression showed that gear type and the year of fishing had no affect on fixed expenses.