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Cap-and-trade Bycatch Management with Costly Avoidance and Stock Uncertainty

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Abstract

Regulations to reduce bycatch of non-marketed marine species often impose gear restrictions, reductions in harvest of the target species, and/or spatial and temporal closures of the fishing ground. These regulations can exact significant social costs in commercial fisheries. We evaluate performance of a cap-and-trade bycatch management policy. Harvest of a target fish species, costly avoidance of the bycatch species, and harvesting efficiency are examined in a stochastic production environment with and without at-sea observability of bycatch, and with and without trade in harvest quotas and bycatch caps. Our results suggest that precise implementation of a socially optimal management plan is possible only if bycatch is observable and trade in fish quotas and bycatch cap is frictionless. Conditions exist in which quota/permit trading raises bycatch relative to a no-trade environment. The results offer useful guidance for designing cap-and-trade bycatch management programs.

Disciplines

Economics

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ABSTRACT

Regulations to reduce bycatch of non-marketed marine species often impose gear restrictions, reductions in harvest of the target species, and/or spatial and temporal closures of the fishing ground. These regulations can exact significant social costs in commercial fisheries. We evaluate performance of a cap-and-trade bycatch management policy. Harvest of a target fish species, costly avoidance of the bycatch species, and harvesting efficiency are examined in a stochastic production environment with and without at-sea observability of bycatch, and with and without trade in harvest quotas and bycatch caps. Our results suggest that precise implementation of a socially optimal management plan is possible only if bycatch is observable and trade in fish quotas and bycatch cap is frictionless. Conditions exist in which quota/permit trading raises bycatch relative to a no-trade environment. The results offer useful guidance for designing cap-and-trade bycatch management programs.

Key words: Cap-and-trade bycatch management, costly bycatch avoidance, uncertainty.

JEL Code: Q2.

INTRODUCTION

National standard 9 of the Magnuson-Stevens Fisheries Management and Conservation Act requires that US Fisheries Management Plans minimize, to the extent practicable, bycatch and bycatch mortality. Examination of US fisheries suggest, however, that significant bycatch problems remain. A recent National Bycatch Report estimates that 1,887 marine mammals, 11,772 endangered sea turtles, and 7,769 sea birds were intercepted by fishing gear in 2005, the base year of the study (NMFS 2011). Unintended bycatch and discard of non-target fish species is estimated at 1.22 billion pounds, or 17% of the total 2005 US catch. An approach often used by resource managers to reduce bycatch of non-marketed, but socially valuable, marine species is to curtail fishing or regulate fishing practices. Alternatives that allow the benefits from commercial and recreational fishing to continue, while controlling unintended bycatch, are clearly preferred.

This article studies the implications of controlling non-marketed bycatch with a system of tradeable bycatch permits. Under such a cap-and-trade bycatch regulation, the fishery manager issues a fixed number of permits, each of which grants its owner the right to intercept a unit of

the bycatch stock. Permit prices provide incentives for fishermen to avoid bycatch. Providing incentives to avoid bycatch offers an alternative to command-and-control regulations, which seek to reduce bycatch directly through costly spatial, temporal, and depth fishing closures; reductions in fishing effort; lowering of target stock harvest; and/or gear restrictions.

Our model features two key elements of the bycatch problem. First, fishermen employ a technology that yields conditionally uncertain harvest of the target and bycatch species. Randomness arises from unobserved absolute and relative abundance of the target and bycatch stocks in the sea. Second, we assume fishermen can exert partial control over the mix of target and bycatch species encountered by their gear; bycatch avoidance is a choice variable in our model. A weak output disposable harvest technology is proposed under which reductions in bycatch involve reductions in the harvest of the saleable target species. The model thus allows us to investigate the endogenous bycatch-to-target harvesting decisions that arise in equilibrium under a quota-based regulation. While these features have been introduced separately in earlier literature, combining both into a single framework builds new insights for the design of quota-based bycatch management programs.

We derive and compare equilibrium harvests, landings, discards of the target and bycatch species, permit prices, and input costs under varying program designs including a scenario where at-sea harvesting operations are fully observed by the fishery manager, and another where at-sea actions are unobserved. The latter case describes most fisheries in the US and worldwide due to the high cost of placing observers on fishing vessels. While observability is a must for implementing bycatch cap-and-trade, our analysis of the unobservable bycatch case provides a baseline for comparison with non-quota-based management instruments, such as effort reductions, area or seasonal closures, and gear modifications, which can be implementable without observers.

We also examine the implications of permit trading restrictions, which may arise due to transactions costs; e.g., thin bycatch cap markets or regulatory prohibition. We show that management performance generally deteriorates in the absence of trade. Without permit trade, the cost of landing a given quantity of the target stock is higher, although bycatch may fall below the target set by the manager. The intuition for the lower bycatch result is the following. In the absence of post-harvest quota trade, any harvest overage of the target fish stock must be discarded, while harvest uncertainty causes some fishermen to land less than their quota. In the aggregate, there is a larger input employment to land the same amount of fish. Costs rise and profitability declines. The larger input allocation provides added maneuvering *slack* to further reduce bycatch. A reduction in bycatch in the no trade case, by no means, should be interpreted as an argument against trade. Trade allows aggregate target quota and bycatch caps to be met. Therefore, if these targets are optimally chosen, the equilibrium outcome under trade in quotas and bycatch permits is more efficient.

As one would expect, our model also predicts that an observer program, which can monitor and enforce bycatch caps at sea, commands fishermen to employ inputs capable of harvesting their target-stock quota while meeting bycatch limits. Placing observers on boats has its own costs. As a result, while bycatch can be brought down to the desired level, harvesting costs will rise. An observer program to cap bycatch at a socially optimal level has to thus balance bycatch reduction benefits with its increased monitoring costs.

Cap-and-trade management is an alternative to non-quota-based regulations that attempt to reduce bycatch through: (1) reductions in fishing effort and/or target stock harvest; (2) closure policies that limit access to the target stock at chosen times, depths, or in regions of the

fishing ground where the bycatch stock is believed to be concentrated; and (3) fishing gear modification. These regulations are popular in fisheries, possibly due to relatively low administrative costs of implementation, for example, by avoiding costly onboard observers. Empirical evidence of the effects and costs of non-quota-based regulations in the Gulf of Mexico longline reef fish fishery, which we provide as motivation for our study, suggests significant social costs in terms of forgone harvest and fishing profits. While data limitations do not permit an exhaustive cost-benefit analysis of competing bycatch management approaches, the evidence we provide suggests that quota-based bycatch management warrants serious consideration by managers.

The remainder of the article is organized as follows. The next section briefly reviews the market-based bycatch management literature. We then present an abbreviated case study of the Gulf of Mexico longline reef fish fishery to highlight the costs of non-quota-based regulations and motivate need for alternative (quota-based) bycatch management approaches. We introduce our model and derive our results. Conclusions and closing comments appear in the final section of the article. A supplemental online Appendix contains proofs of key derivations, empirical examples, analysis under alternate model assumptions, and other ancillary empirical results.

RELATED LITERATURE

Efforts to reduce bycatch and discards of fish, birds, and sea mammals have spawned a large literature in the fisheries sciences and economics.[1] Bycatch management policy has generally followed two somewhat independent paths. One focuses on modifying fishing gear to improve gear selectivity; i.e., designing gear to lower the quantity of bycatch intercepted per unit of harvested target stock. Examples include turtle excluder devices on shrimp trawl nets and circle hooks (as opposed to traditional J-hooks), which tend to snag fewer sea turtles and cause less damage when turtles are hooked. Gilman et. al. (2006) summarizes the state of knowledge regarding sea turtle avoidance technologies. A second path, one followed herein, seeks to design regulations that provide fishermen with incentives to undertake costly bycatch avoidance.

Fishermen make many production decisions that can influence the mix of species intercepted by their gear; e.g., choice of fishing time, fishing depth and location, gear and bait combinations, net mesh sizes, duration of soak times for baited hooks, and use of sonar equipment, which can increase awareness of species vulnerable to capture (see Branch and Hilborn (2008) for empirical evidence). Bycatch avoidance is privately costly, and, therefore, providing incentives to incur avoidance costs can be an effective management tool (Bisack and Sutinen (2006), Segerson (2011), Mukherjee and Segerson (2011), and Pascoe et al., (2010)). Economic incentives for bycatch avoidance in cap-and-trade management programs, as we show, depend crucially on fish quota and bycatch permit prices. A key novelty of our approach is that we investigate an explicit harvest-bycatch technology that, within an equilibrium framework, allows us to study the properties of endogenously determined fish quota and harvest bycatch permit

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1. We do not attempt a full review of this literature. In addition to Gilman et al. (2006), see Lewison and Crowder (2004), Pascoe et al. (2010), and references therein. Economists (e.g., Arnason (1994), Boyce (1996), Turner (1995, 1997), and more recently Singh and Weninger (2009)) have examined economic trade-offs implicit in multiple-species quota management programs and the associated bycatch problem. See Hutton et al. (2010) for a review.

prices and their role in shaping fishermen's harvesting and bycatch avoidance behavior. As a result, our framework enables a quantitative evaluation of the ecological and economic outcomes expected under a target/bycacth species quota/cap regulation.

Our article most closely relates to recent work by Segerson (2011) and Holland (2010).[2] Segerson (2011) presents a model of costly bycatch avoidance to study social efficiency under various bycatch management policies, including taxes on the harvest of target and bycatch stocks, limits on allocated effort, and penalties or fines levied when a bycatch limit is exceeded. In her model, the harvest of the target stock is deterministic, and bycatch encounters are random. Segerson (2011) finds that taxes, fines, and caps placed on the bycatch stock at the individual fisherman level can lead to socially efficient bycatch avoidance, whereas similar measures imposed on target stock generally do not achieve efficient outcomes. To induce efficient bycatch avoidance, Segerson (2011) suggests an industry-wide bycatch quota with a proportional penalty/reward that is paid by/to all members when the group limit exceeds/falls below the management target. Segerson (2011) does not evaluate a cap-and-trade bycatch policy at the industry level and does not consider the implications of unobservable bycatch. Our work contributes to the bycatch literature in these two respects.

Holland (2010) studies the impacts of individual bycatch quotas in a model of fishing uncertainty, with a focus on the role of risk aversion in bycatch avoidance behaviors. Holland (2010) simulates bycatch, quota prices, and fishing profit distributions numerically under competing assumptions for risk preferences, randomness in production, and quota pooling arrangements adopted by fishermen. Holland (2010) argues that quota pooling arrangements used in the British Columbia groundfish trawl fishery reduce risk exposure and inefficiencies that would otherwise arise due to thin quota markets. Holland (2010) assumes for simplicity that bycatch encounters are purely random, acknowledging however that in reality fishermen affect bycatch by *changing when, where and how they fish, and the gear they use*.[3] Our model extends the work of Holland (2010) by incorporating endogenous bycatch avoidance in a quota/permit market equilibrium framework.

Quota-based bycatch policies have received increasing attention from managers and researchers and warrant further analysis (Fisheries Leadership and Sustainability Forum 2009, Abbott and Wilen 2009, and Holland 2010). Our contribution to the bycatch literature is manifold. We focus on the role of markets in implementing aggregate target species and bycatch limits in a setting of production uncertainty and endogenous bycatch avoidance. Importantly, we study equilibrium outcomes including factor input allocation, harvest, avoidance efforts of fishermen, and bycatch outcomes under target/bycatch quota-management. Finally, since unobservability is a fact of life in most fisheries and quota/permit tradeability is often limited by market thinness or through regulatory restriction, we contrast equilibrium outcomes under these two phenomena. Last, our comparisons with non-quota-based regula-

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2. Earlier work by Boyce (1996) develops a stylized model of the fisheries bycatch problem to address issues related to the allocation of a fixed bycatch allowance across multiple users and conditions under which individual transferable bycatch quotas can replicate socially optimal outcomes. In the Boyce (1996) model, the quantity of bycatch intercepted by fishermen is given exogenously as a fixed (perhaps increasing) proportion of harvest; endogenous bycatch avoidance is not considered.

3. A few studies have attempted to measure the cost of sea turtle bycatch management regulations. Curtis and Hicks (2000) estimate the cost of closing portions of Hawaii's pelagic longline fishing ground. Chakravorty and Nemoto (2000), Huang and Leung (2007), and Pradhan and Leung (2008) apply various empirical techniques to estimate the cost of reducing sea turtle bycatch in the same fishery.

tions offer crucial insight for regulators and industry faced, under the Magnuson-Stevens Fisheries Management and Conservation Act, with the task of reducing bycatch.

BYCATCH MANAGEMENT IN THE GULF OF MEXICO COMMERCIAL REEF FISH FISHERY

The Gulf of Mexico commercial reef fish fishery is a complex of mid-column and bottom-dwelling species consisting of snappers, groupers, tilefish, amberjacks, triggerfishes, grunts, porgies, and a host of others. Fishermen also harvest coastal pelagic species such as mackerel, dolphin, shark and tuna. Total fishery landings ranged between 13.053–16.645 million pounds annually, between 2005–09. Annual dockside revenue varied between $36.884–$43.227 million during the same period.[4]

Two main gear types are employed in the commercial reef fish fishery. Vertical line gear is the most common, followed by longline gear (fish traps, nets, and trolling gear are also used). Longline fishing involves deploying a long cable with as many as 2,000 smaller ganion lines, each containing a baited hook, to the desired fishing depth. The gear is soaked from anywhere between 2–10 hours. It is then retrieved with a hydraulic winch. Captured reef fish are removed from the hooks, eviscerated, and placed on ice for transport back to port.[5]

Loggerhead (*Caretta caretta*) is the main turtle species intercepted by longline fishermen, although gear interactions with Kemp's Ridleys (*Lepidochelys kempii*) and leatherback turtles (*Dermochelys coriacea*) may also occur. Turtles can become entangled in the longline ganion or hooked as they pursue the same feed used as reef fish bait. Entangled turtles may drown or be seriously injured and die. Turtle encounters with vertical line gear are virtually non-existent due to the very short soak time; once a boat is *on fish*, baited hooks can be lowered and retrieved quickly with little opportunity to attract and entangle turtles.

An onboard observer study conducted by the National Marine Fisheries Service from July 2006–2008 recorded turtle encounters on 17.6% of longline trips, and on 1.9% of sampled sets (see NMFS 2009). Extrapolation to total longline effort allocated during the study period predicts that there were 861 sea turtle encounters (95% confidence interval at 384–1,934) during the 20-month period. The estimated turtle take exceeds permissible levels under the US Endangered Species Act, requiring the NMFS to take regulatory action.[6]

In May 2008, the Gulf of Mexico Fisheries Management Council enacted three emergency measures to reduce sea turtle bycatch. Longline fishermen were prohibited from setting gear shoreward of a line approximating the 35 fathom contour eastward of the 85 degree, 30-minute longitude, across most of the Florida Gulf Coast. Second, longline fishermen were permitted to carry no more than 1,000 hooks onboard their vessel, of which 750 could be rigged for fishing. Hook limits are intended to limit the length of the longline, which effectively reduces soak time, a factor thought to be positively related to sea turtle encounters and mortality. Lastly,

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4. In 2010, commercial fishing in the Gulf of Mexico was impacted by the Deepwater Horizon oil spill disaster, which led to spatial closures and significant disruptions to commercial fishing activity. We do not report data for 2010 as it likely does not reflect *normal* fishing activity. Our data do not include a complete record on 2011 fishing activity. All dollar values are reported in 2011 dollars.

5. Fishing with vertical line gear involves lowering multiple baited hooks on vertical main lines off the side of the vessel. Turtle encounters are not considered a problem with vertical line gear.

6. Sea turtles are listed as endangered under the Endangered Species ACT (ESA). By law, the National Marine Fisheries Service must adopt fisheries regulations that are deemed not a threat to the existence of sea turtles. Encounters during legal commercial fishing activities at or below levels that satisfy this requirement are permissible under ESA law.

managers limited the number of vessels that were permitted to use longline gear. Amendment 31 was passed in May 26, 2010, making made the emergency rules permanent.

Amendment 31 does not include provisions for onboard observers. The location of a fishing vessel is tracked electronically with satellite-based global positioning technology which enforces depth restrictions at relatively low cost. Likewise, the number of hooks onboard and vessel permits can be monitored at port, thus avoiding the need and expense of onboard observers. Examination of logbook records collected by the National Marine Fisheries Service suggests that Amendment 31 regulations have affected fishing practices and raised harvesting costs in the Gulf of Mexico reef fish fishery.

IMPLICATIONS AND COST OF AMENDMENT 31 REGULATIONS

Table 1 reports annual fishing effort, landings, and revenue for the Gulf longline fleet during the 2006–09 fishing seasons. We report landings and revenues for all reef fish species combined, and for the longline fleet's main target species, red grouper.[7] Recall that longline bycatch management regulations began in May 2008. The first full year of the regulation was 2009.

Table 1 reports that 19 fewer vessels fished with longline gear in 2009 than in 2008. This decline is more pronounced if we consider *dedicated* longline gear boats. If we measure participants as vessels that used longline gear on the majority of their annual trips, the longline fleet size dropped from an average of 117 vessels in 2005–08, to 73 in 2009. Total longline gear trips declined from 1,385 in 2008 to 793 in 2009, a 42% drop. Landings and revenues also declined sharply in 2009. The decline is most pronounced for red grouper, where landings fell 39% and revenues fell 38% between the 2008 and 2009 fishing seasons.

Logbook data provide evidence that reef fish fishermen switched gear types in response to Amendment 31 regulations. The number of vertical line fishing trips increased by 749 in 2009, a 10% increase over 2008. Landings by vertical line gear (all species) increased by 17%, and vertical line landings of red grouper increased by 21% between 2008 and 2009. Total landings for both gear types fell 4.4% to 13.306 million pounds, and total revenue declined by $4.53 million, or 11.1%, in 2009.

Table 2 reports summary statistics for fishing costs. Not all reef fishing trips record cost information, which is why the number of trip observations is smaller than in table 1.[8]

For longline gear, sample average cost per landed pound varies between $1.53-$1.83 in 2005–09. A small increase in the average cost per pound is indicated in 2009 when bycatch regulations took hold. The average cost per landed pound on vertical line gear trips is higher, with a range of $2.44-$2.68. Averaging across years, vertical line gear trips incur roughly $0.87 higher cost per landed pound than longline gear trips. If we compare median values, vertical line gear costs are, on average, $0.70 more per landed pound.

Information on revenues and costs reported in table 2 suggest that regulations that reduce longline gear fishing in the Gulf reef fish fishery are indeed costly. Reef fish fishermen are able to switch gear types, which offsets the losses from reductions in longline fishing. However, cost comparisons across gear types suggest harvesting with vertical line is more costly. A few simple calculations demonstrate.

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7. The majority of longline fishing takes place off the western Florida coast where red grouper is a prominent species.

8. Trip costs include: (1) expenses for fuel, bait, ice, and other miscellaneous expenses (from logbook data), (2) payments to captain and crew labor, which we calculate as the estimated crew share times the trip revenue, and (3) fixed operating expenses. Details for crew share calculations and fixed operating expenses are reported in the online Appendix.

Table 1. Longline Gear Effort, Landings, and Revenue, 2006–10

	Effort			Landings ('000 lbs.)		Revenue ('000 $)	
Year	Trips	Vessels	DAS	All Spec.	Red Grp.	All Spec.	Red Grp.
2005	2,028	170	12,908	7,508	3,085	$16,303	$8,974
2006	2,128	145	14,343	7,482	2,991	16,268	9,461
2007	1,362	134	12,068	4,968	1,938	13,835	6,456
2008	1,385	124	12,405	5,338	2,772	15,172	8,473
2009	793	105	7,690	3,214	1,084	8,713	3,242

Table 2. Harvest Costs per Landed Pound (all reef fish species)

	Longline Gear				Vertical Line Gear			
	Trips	Ave.	Std.	Med.	Trips	Ave.	Std.	Med.
2005	1,495	1.53	0.93	1.23	9,039	2.53	1.52	2.04
2006	1,409	1.74	0.97	1.47	8,570	2.63	1.55	2.14
2007	1,175	1.83	0.97	1.50	6,029	2.68	1.60	2.16
2008	1,209	1.66	1.02	1.33	6,086	2.51	1.51	2.03
2009	689	1.70	1.14	1.36	6,639	2.44	1.44	2.01

Total landed pounds by both gear types during 2005–2010 has remained fairly constant at roughly 13.6 million pounds per year. The average share of landings on longline vessels between 2006–08 was 0.415. The longline gear landings share dropped to 0.242 in 2009. Assume the longline share of reef fish landings would have remained at 0.415 in 2009 had longline effort restrictions not been imposed. Using the 2009 sample average cost per landed pound from table 2, the fleet aggregate costs would have been $1.70 million less. It should be noted that the data-generating process underlying table 2 included depth restrictions and trip hook limits. The $1.70 million cost saving can, therefore, be viewed as a lower bound.

THE MODEL

The harvest environment we have in mind is a single fishing season in which the stock size of the target and bycatch species are given. Due to random fluctuations in the marine environment; e.g., changing weather, water temperatures, currents, and the distribution of feed, the relative mix of the target and bycatch species varies.

We assume the number of fishermen is predetermined and large. To simplify our analysis, we assume a continuum of ex ante identical fishermen with a unit mass operate in the fishery.[9] The continuum assumption allows us to apply the law of large numbers, and scaling by unit mass lets expected outcomes equal actual aggregate outcomes.

There are two stocks: a target species stock and a bycatch stock. For concreteness, the target species will be fish and the bycatch will be sea turtles. Fish have consumptive use value

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9. The assumption of ex ante homogenous fishermen is not necessary for the key results derived in this article. Allowing for heterogenous fishermen will unnecessarily complicate the model and add few new insights. In an online Appendix, we analyze the effect of area closures with heterogenous fishermen, where managers, as well as fishermen, have perfect location-specific knowledge of the stock mix. We show that our results are qualitatively invariant to whether agents are ex ante or ex post heterogenous.

and fetch a positive unit price at the dock. Sea turtles have non-use value only. Harvesting operations are conducted within a single production period.

Individual fishing quotas grant their owners a right to harvest a specified quantity of the target species during a fixed calendar period. Bycatch permits legalize turtle encounters. In our model, the production period and fishing season coincide.[10]

Measures can be taken to avoid bycatch, but these measures utilize resources. For example, shorter soak times and fishing at night, which has been shown to reduce sea turtle encounters with longline fishing likely requires additional labor. Sea turtle interceptions with longline fishing gear is affected by the type of hooks used, the type of bait, the depth and location of fishing, the length of time baited hooks are soaked in the water, and day versus night fishing (Gilman et al. 2006). We model the cost of bycatch avoidance as reduced harvest and landings of fish for a given input allocation.[11] To be precise, we assume fishermen choose a variable, c, which determines the point along a target-bycatch transformation frontier at which production takes place. In particular, reducing bycatch by a proportion c from its *natural* baseline level reduces fish harvest by the proportion $a(c)$. The avoidance-augmented technology is expressed as:

$$\{h_f, h_t\} = \{z_f(1 - a(c))\phi^{1-\beta}, z_t(1 - c)(1 - \phi)^{1-\beta}\}n^{\beta}. \tag{1}$$

We assume an increasing and strictly convex product transformation between the target and bycatch species. In our framework, the marginal foregone fish harvest that results from a marginal reduction in bycatch increases with additional avoidance. Formally, we assume $a(0) = 0$; $a(1) \in (0, 1)$; $a', a'' \geq 0$ with strict inequality for $c > 0$; and $a'(0) = 0$, $a'(1) = \infty$. Thus, $a(c) < c$ for all c. These assumptions ensure the profit maximization problem is strictly concave in c. We allow $c \in [0, 1]$. Thus, a sufficiently high avoidance effort eliminates bycatch completely, while still yielding a positive quantity of harvest.[12]

Figure 1 depicts the avoidance augmented technology. Maximum harvests of the target and bycatch species for a common n is denoted A, B, and C in the figure for ϕ at a low, medium, and high values. All three harvest outcomes correspond to the case where no effort/input is spent on bycatch avoidance; i.e., $c = 0$. If the fisherman chooses maximum avoidance; i.e., $c = 1$, bycatch is eliminated, but harvest of the target species is reduced to a fraction of its maximum value.

Harvesting uncertainty is introduced as follows. We assume that when input n is chosen, a fisherman knows only the distribution of relative stock abundance, ϕ. Once at sea, actual realization of ϕ occurs, as fishing reveals stock conditions *under the boat* so to speak. Fishermen then choose avoidance c to intercept their preferred quantities of fish and bycatch.

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10. An alternate interpretation of our model is that the fishing season is divided into a finite number of production periods. The analysis that follows would then apply to the final period in which the target species quota and bycatch permits bind, and aggregate quotas/permits denote remaining, unfished quota/bycatch permits. Backward induction could then be used to analyze avoidance behavior, quota prices, etc., in periods leading up to the final period. A formal analysis of the multiple production period case is not attempted here.

11. Segerson (2011) presents a model that is dual to ours; fishermen choose a costly action that lowers the probability of intercepting sea turtles. In her model, increased avoidance raises costs and reduces the quantity of fish that is harvested per gear set.

12. The technology could alternatively be parameterized as null-joint in outputs, where zero bycatch is feasible only with zero harvest of the target species.
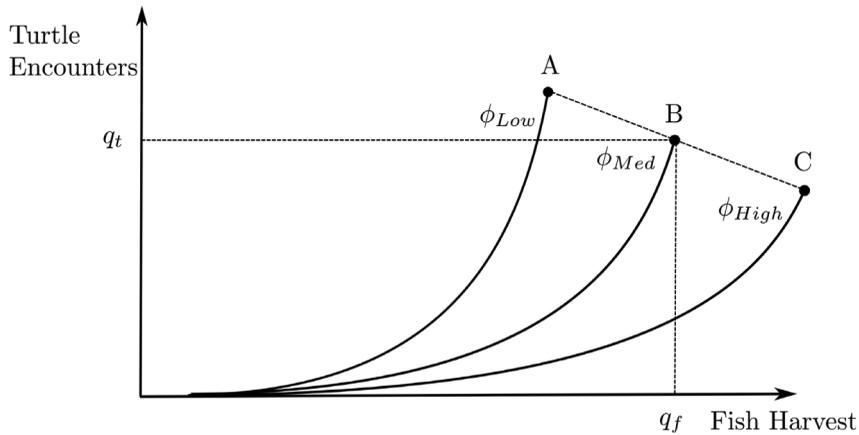
Figure 1. Relative Stock Abundance and Harvesting Technology
   Note: The figure depicts the avoidance augmented technology under the assumption $a(c) = \frac{1-\sqrt{1-c^2}}{2}$; ϕ takes a low (ϕ_{LOW}), medium (ϕ_{MED}) and high (ϕ_{HIGH}) value.

Our assumptions for uncertainty result in a choice problem that is solved in two stages. In the first stage, input bundle n is chosen based on the known distribution of ϕ. We call this the *planning* stage. The second stage, *operations*, begins once ϕ and the harvest possibilities are realized. It is clear from (1) that a higher ϕ rotates the fish-bycatch frontier clockwise (see figure 1). In what follows, we let $G(\phi)$ and $g(\phi)$ denote the cumulative and probability distribution functions of ϕ, respectively, with a support $[(\phi_{(\min)}, \phi_{(\max)}]$, with $0 \leq \phi_{(\min)} < \phi_{(\max)} \leq 1$, and $x^e \equiv E\{x\} \equiv \int x\, g\,(\phi)\, d\phi$ denotes the expected value of a variable x. We use $H(n, \phi) = \{h_f(n, \phi),\, h_t(n, \phi)\}$ to denote the harvest-bycatch possibilities frontier (HBPF). For a given $H(n, \phi)$, input price, dockside fish price, and regulations limiting harvest and bycatch, fishermen choose n in the planning stage to maximize expected profits (denoted by π^e) and c in the operations stage to obtain their desired harvest/bycatch mix on the HBPF.

A few words about the model set up are warranted. Uncertainty in relative abundance generates a stock-mix realization in which some lucky fishermen realize a high target to by-catch stock mix; unlucky fishermen realize the opposite. This generates a natural environment for trade in fish quotas and bycatch caps: the lucky ones will wish to buy more fish quotas, while the unlucky will seek more turtle permits. Having a single parameter, ϕ, as opposed to two separate stock uncertainty parameters simplifies the analysis. Uncertainty is idiosyncratic in our model. Uncertainty in the aggregate stock levels is important for setting fishery-wide targets and quantitative evaluation of alternative regulatory regimes; however, here our focus is on bycatch avoidance behavior under quota- and non-quota based regulations. Aggregate uncertainty in quota managed fisheries is examined in Singh and Weninger (2012).

Alternate assumptions could be made regarding the timing of input choices and realization of uncertainty. In an online Appendix we assume stock conditions ϕ are revealed before the input bundle is chosen. This case is equivalent to assuming that inputs are perfectly reversible. Our model assumes the planning stage input choice is irreversible. As an example, a fisherman organizes crew, bait, fuel, etc., based on expectation of stock conditions. The challenge is to organize the committed input bundle to optimize trip revenue. While the full irreversibility

assumption may be somewhat extreme, it captures the essence of input choice under uncertain production. Nonetheless, we take care throughout our analysis to indicate where results can change when the irreversibility assumption is relaxed.

A second scenario models the production decision as a one-shot event in which n and c are both chosen prior to the random harvest/bycatch realization (e.g., Segerson 2007). Our model features endogenous bycatch avoidance combined with harvest uncertainty. A one-shot model would require that we take a stand on the proportion of bycatch caused by pure randomness versus the proportion caused by avoidance actions, and the results would depend on this choice (Abbott 2007). Adding pure randomness to catch outcomes would require specification of penalties in the event of quota overages. This would introduce behavioral incentives different from those that arise from buying and selling quota in a decentralized quota- and bycatch-cap fishery. It is the latter incentives that are of interest in this article. For this reason, there is no unintended bycatch in the operations stage of our model. In effect, we assume that all bycatch can be avoided at a sufficiently high cost. This assumption may be reasonable for longline gear where fishermen have several options to avoid turtles (Gilman et al. 2006).

Finally, we assume the fishery manager has accounted for the social costs/benefits when setting the target fish stock quota and quantity of turtle bycatch permits. In fact, these choices depend on harvesting costs, which we show vary with the form of regulation. Determination of the jointly socially optimal fish quota and turtle bycatch cap is reserved for future work.

CAP-AND-TRADE BYCATCH MANAGEMENT

We now consider the implications of our costly bycatch avoidance model in a fishery that is managed with individual quotas for the target fish stock and permits for turtle bycatch, denoted in the model as q_f and q_t, respectively. Corresponding quota/cap prices are denoted by r_f and r_t. We begin with a case where at-sea fishing activity is unobserved by the manager. This scenario approximates a regulation with no effective controls on harvest of the bycatch stock and, thus, no incentive to undertake costly bycatch avoidance. Analysis of the case where at-sea fishing activity is observable is discussed later. In each case, we contrast scenarios where quota is and is not tradeable.

QUOTA-BASED MANAGEMENT WITHOUT AT-SEA OBSERVABILITY

Assume dockside landings are monitored but at-sea fishing operations are unobserved by the regulator. We assume the fishermen's objective is to maximize private fishing profits. Fishermen harvest no more than their quotas, even if it is feasible to do so. Furthermore, while sea turtle bycatch is socially undesirable, and fishermen will take necessary measures to avoid it, minimizing bycatch remains a secondary objective.[13] Thus if in the operations stage the realized HBPF permits full utilization of quotas, we assume fishermen choose a $\{h_f, h_t\}$ pair that obtains the lowest turtle bycatch. For example, suppose a fisherman realizes the HBPF depicted in figure 2. If his quota and bycatch cap is $\{q_f, q_t\}$, harvest will be at point A, and both fish quota and turtle bycatch cap will be met. On the other hand, if his quota is $\{q_f', q_t\}$

13. Sea turtle bycatch management policies exist because sea turtles have non-consumptive social value. Fishermen's non-consumptive values have been ignored to simplify our analysis.
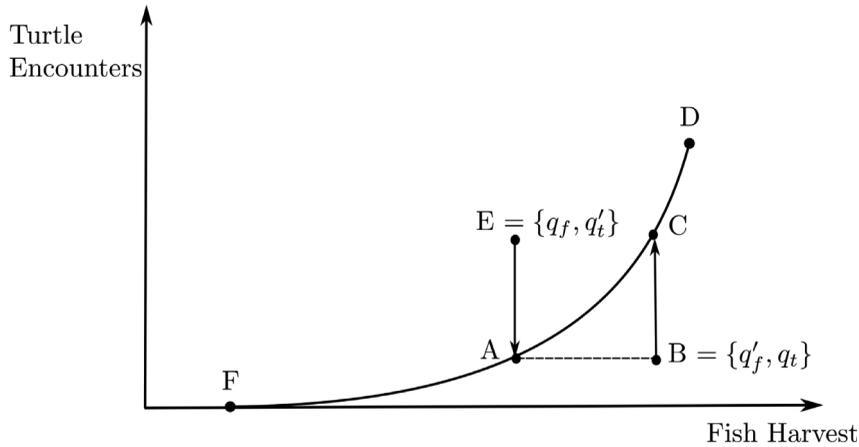
Figure 2. Harvest Choices for Different Fish Quotas and Bycatch Caps

at point B, he will harvest q_f' and ignore (and violate) his turtle bycatch cap by harvesting at point C because the bycatch overage is unobservable.

FISH HARVEST AND BYCATCH UNDER TRADE IN QUOTAS

Suppose fish quotas are traded in fully functional quota markets. We focus on fish quotas that have a positive price; i.e., $r_f > 0$. This requires that all the quota supplied, q_f, is bought and the quota binds in equilibrium. Since quotas can be traded both before and after the HBPF is realized, by invoking arbitrage we assume that the same price prevails in both sub-periods.

At the planning stage, a fisherman anticipates his operations stage choices, contingent on the realized random stock, to be rationally optimal. With this sequence in mind, we can solve for the equilibrium fish harvests and turtle bycatch by applying backward induction.

The operations stage. Without at-sea observability of fishermen's actions, any cap on sea turtle bycatch is meaningless. Effectively, the price of turtle bycatch is zero, and a fisherman's optimal choice will be to maximize revenues from fish harvest. Let the dockside price of fish be p_f. As long as the quota price satisfies $r_f < p_f$, a fisherman will not incur any avoidance costs and choose $c = 0$ to maximize fish harvest.[14] This is shown as point D in figure 2.

Suppose fish quota bought by all ex-ante identical fisherman is q_f, as shown in figure 1. Then a fisherman with a realization of ϕ_{Med} simply harvests at point B with $z_f(\phi_{Med})^{1-\beta}n^{\beta} = q_f$, and does not enter the quota market. The fisherman with ϕ_{High}, on the other hand, can harvest more than his quota, and as $r_f < p_f$, will buy additional quota from a fisherman with realization such as ϕ_{Low}; e.g., at point A. The equilibrium quota price, r_f, by arbitrage, equals its market price at the planning stage.

The planning stage. At the planning stage, fishermen choose inputs n, keeping in mind their optimal operational responses to all possible realizations of ϕ. They know their harvest

14. With no aggregate uncertainty, $r_f \in (0, p_f)$ holds. Under aggregate uncertainty ex ante and ex post quota prices will be different. Also, if ex post harvest turns out to be sufficiently high, there may be an excess demand for quotas driving $r_f = p_f$. In such cases, discard will also occur.

will be a pair given by (1), i.e., the frontier points represented by $A - B - C$ in figure 1. The problem then is to choose n and q_f to maximize *expected* profit:

$$\pi^e = (p_f - r_f)E[\phi^{1-\beta}] \cdot z_f \ n^\beta - w \ n,$$

where w is the per-unit price of the input, and E is the expectations operator.[15] An interior choice of n solves:

$$\beta(p_f - r_f)E[\phi^{1-\beta}] \cdot z_f \ n^{\beta-1} = w. \tag{2}$$

Thus, inputs are employed to equate the value of their marginal product, left-hand side, with their marginal factor cost, right-hand side. In equilibrium, r_f is determined from the above and the quota market clearing condition:

$$E[\phi^{1-\beta}] \cdot z_f \ n^\beta = q_f. \tag{3}$$

Notice that the assumption of unit mass, ex ante homogeneity, and i.i.d. realizations of ϕ across fishermen, equates the expected with the aggregate harvest, left-hand side. The first two assumptions also imply that the aggregate quota in the market equals that held by an individual. To economize on notation, this feature will be repeatedly exploited in the rest of the article.

By combining (2) and (3), the quota price can be expressed as:

$$r_f = p_f \left(1 - \frac{wn}{\beta p_f q_f} \right).$$

The quota price can be interpreted as per-unit market earnings, net of its utilization costs. The term $\frac{wn}{\beta p_f q_f}$ is the ratio of cost of inputs in its share of dockside market earnings. If fishermen are not quota constrained, this share equals unity and no rents accrue to the holder of quota rights. If constrained, a lower constrained-optimal input employment implies that its share of dockside earnings exceeds its costs, and the rents are positive.

Turtle bycatch. Bycatch is governed by fishermen's choices as dictated by (2) and (3). The aggregate bycatch is:

$$h_t^e = \frac{z_t}{z_f} \underbrace{\frac{E[(1-\phi)^{1-\beta}]}{E[\phi^{1-\beta}]}}_{\equiv \tau} q_f = \tau \ q_f. \tag{4}$$

The higher the fish quota, the higher is the quantity of inputs employed, which leads to a higher bycatch of turtles. Bycatch also depends on the mean relative abundance of fish in the water. A higher average ϕ implies that the expectation term is lower. A higher average relative abundance of fish naturally leads to a lower bycatch.

---

15. For completeness, the profit function should be written as:

$$\Pi = E(p_f \ \phi^{1-\beta} \cdot z_f \ n^\beta + r'_f(q_f - \phi^{1-\beta} \cdot z_f \ n_\beta)) - w \ n - r_f q_f,$$

where r_f and r'_f denote quota prices in the pre- and post-harvest markets. This essentially yields the arbitrage condition $r_f = r'_f$ and allows profit to be expressed as above.

Thus, in a fishery with unobservable bycatch and tradable fish quotas, sea turtle bycatch is directly determined by the aggregate fish quota. In order to restrict sea turtle encounter/mortality to a desired level, the manager has a single regulatory instrument available, q_f. The social cost of reducing bycatch mortality in this setting is the foregone net profits from harvesting the target stock.

FISH HARVEST AND BYCATCH WITHOUT TRADE IN QUOTAS

While fishermen are assumed ex ante homogeneous, a rationale for trade exists as fishermen's harvest possibilities diverge in the operations stage when stock conditions are realized. Without trade, however, a fisherman cannot purchase additional quota to land any harvests that exceed quotas purchased in the planning stage. We refer to figure 1 again for illustration. Let the fish quota holding of all fishermen be q_f. Then, all fishermen with harvest realizations ϕ_{Low} will land their maximum possible harvest, whereas a fisherman realizing ϕ_{High} will hold excess quota; $q_f > z_f \phi^{1-\beta} n^\beta$. These fishermen are landings constrained. We next compute equilibrium fish harvest and sea turtle bycatch when no quota trading occurs in the operations stage.

The operations stage.   In the absence of operations-stage quota trades, fish harvest (and landings) will follow:

$$
hf = \begin{cases} z_f \phi^{1-\beta} n^\beta, & \text{if } \phi < \overline{\phi} \equiv \left(\dfrac{q_f}{z_f n^\beta} \right)^{\frac{1}{1-\beta}} \\[3mm] q_f, & \text{if } \phi \geq \overline{\phi} \end{cases} \tag{5}
$$

The planning stage.   Given operations-stage harvests in (5), the problem at the planning stage is to maximize expected profit:

$$
\pi^e = p_f \left[\int_{\phi_{min}}^{\overline{\phi}} z_f \phi^{1-\beta} n^\beta dG(\phi) + q_f \int_{\overline{\phi}}^{\phi_{max}} dG(\phi) \right] - wn.
$$

The first integrand represents harvests that fall below quota, while the second integrand captures stock realizations where landings are constrained by quota. The optimal input choice equates the marginal input cost with its marginal value product:

$$
\beta\, p_f \int_{\phi_{min}}^{\overline{\phi}} z_f \phi^{1-\beta} n^{\beta-1} dG(\phi) = w. \tag{6}
$$

Comparing necessary conditions (6) and (2) indicates two differences. First, the marginal value of an incremental harvest under quota trade is $p_f - r_f$, since each unharvested unit can be traded in the quota market at price r_f, whereas marginal value is p_f in the absence of quota trade. Second, a marginal unit of harvest (at its maximum feasible) is useless if $\phi > \overline{\phi}$, since without quota trade the overage cannot be landed. Hence, the expectation under (6) is truncated at $\overline{\phi}$

Expected fish harvest.   With non-tradable quotas, aggregate fish harvest falls below the aggregate quota since some quota is unutilized. Expected fish harvest follows from (5):

$$
h_f^e = q_f(1 - G(\overline{\phi})) + \int_{\phi_{min}}^{\overline{\phi}} z_f \phi^{1-\beta} n^\beta dG(\phi) < q_f, \tag{7}
$$

where n is determined from (6). The first term denotes the constrained harvest, q_f, weighted by the probability of being quota constrained. The second term accounts for all harvests that fall below the quota, which also explains the last inequality.

Turtle bycatch.   For relatively high fish abundance realizations, such that $\phi > \overline{\phi}$, fishermen are quota constrained and harvest below the maximum feasible (e.g., in figure 2, points below and left of D, such as C or A). In this case, the ex ante input allocation is ex post excessive in the sense that the fish harvest capacity, $z_f \phi^{1-\beta} n^{\beta}$ exceeds the quota holding. Without opportunity to acquire additional fish quota, the shadow price of unused input is effectively zero. Under our assumption of no unnecessary turtle bycatch, some turtle avoidance occurs. As fish harvest equals q_f, the choice of c at the operations stage is trivially determined from:

$$q_f = z_f(1 - a(c))\phi^{1-\beta} n^{\beta}. \tag{8}$$

Aggregate bycatch then follows as (see the online Appendix):

$$h_t^e = z_t n^{\beta} \left[\int_{\overline{\phi}}^{\phi_{\max}} (1 - c(\phi))(1 - \phi)^{1-\beta} dG(\phi) + \int_{\phi_{min}}^{\overline{\phi}} (1 - \phi)^{1-\beta} dG(\phi) \right], \tag{9}$$

where $c(\phi)$ solves (8). The first bracketed term denotes bycatch with avoidance: these are the fishermen who are quota constrained and can afford to reduce bycatch. The second term captures those unconstrained fishermen who put all their inputs toward harvesting fish. In all the numerical illustrations that follow, we assume $a(c) = \frac{1 - \sqrt{1 - c^2}}{2}$, which in the present case implies $c(\phi) = \sqrt{1 - (\frac{2q_f}{z_f \phi^{1-\beta} n^{\beta}} - 1)^2}$ (see the online Appendix).

Recall that sea turtle bycatch under quota trade equals $z_t n^{\beta} E[(1 - \phi)^{1-\beta}]$. Since $c(\phi)$ is positive, the term within square brackets in (9) is less than this amount. If, in addition, n here is lower than its quantity under quota trade (see (2) and (3)), bycatch is lower. Otherwise, whether bycatch is higher or lower with quota trading is ambiguous.

A normative comparison of bycatch under the two environments is complicated by the fact that fish harvest is lower without quota trade. A meaningful comparison, therefore, requires that aggregate fish harvest and landing be kept the same under the two trading environments. One can then examine whether trade leads to a lower or a higher turtle bycatch. To land the same amount of fish with no quota trade, aggregate (and expected) harvest must be higher, as some fishermen harvest below their fish quota and divert inputs to reduce sea turtle bycatch. Therefore, input employed must be larger. We confirm this insight with a numerical example.

Figure 3 reports the percentage increase in input cost and the percentage reduction in sea turtle bycatch under no quota trade relative to their values under trade holding fish landings constant across the two scenarios. As evident, bycatch is lower without trade in quotas. As discussed earlier, when quotas cannot be traded, fishermen employ a higher input quantity to obtain the same expected fish landing. As evident, this raises input costs. Then, however, fishermen who encounter high fish abundance cannot direct all inputs to fish harvest, as this would exceed their quota. Unutilized inputs are directed to bycatch avoidance, and bycatch is lower.

As is also evident, the increase in input cost and decrease in bycatch diminish as landings increase. The reason is simple. A higher landing target requires a higher quota allocation,
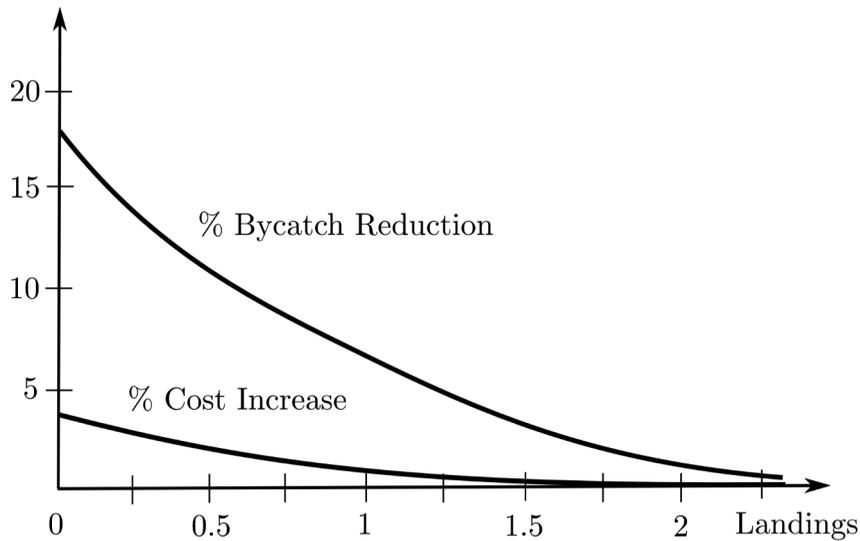
Figure 3. Cost Increase and Bycatch Reduction Under No Trade
Note: Results assume ϕ uniformly distributed on [0.7, 0.9] with $w = p_f = 1$, $z_f = 0.1$, $\beta = 0.6$ and $q_f = 1$.

which due to diminishing returns, implies a lower likelihood of a binding target-species quota constraint. Trade becomes less relevant as the quota allocation moves towards its nonbinding threshold, and the outcomes under two environments converge.

One key lesson drawn by comparing harvest and bycatch under trade vis-à-vis no trade is that under the latter, effort is expended to avoid bycatch, whereas under the former all effort is directed towards harvesting fish. Trade raises the shadow cost of bycatch avoidance. It is then for the manager to evaluate whether cost increases justify bycatch reduction. Prima facie, however, there may be a rationale for restricting trade when bycatch is unobservable.

It is instructive to examine the conditions under which this result will and will not hold. First, as noted above, when the input allocation is higher under the no-trade case and irreversible, the opportunity cost of diverting unutilized n toward bycatch avoidance is zero. Bycatch is lowered due to a good Samaritan effect where, all else equal, fishermen choose to avoid turtles. If quota is tradable, the opportunity cost of diverting n to bycatch avoidance is positive, determined as the productive value of the input in the harvest of fish that can be landed by purchasing additional quota.

The assumption that the planning-stage input allocation is irreversible is crucial for this result. If, alternatively, unutilized inputs can be costlessly saved for future fishing endeavors, maximization of fishing profits requires $c = 0$, and the harvest/bycatch ratio for a fisherman is increasing in the ϕ realization, as given by $(\frac{1}{\phi} - 1)^{1-\beta}$. In this case, sea turtle bycatch is unambiguously higher when quota cannot be traded relative to when it can be traded in the operations stage. Without trade, all fishermen harvest their fish quotas. With trade, high (low) ϕ fishermen buy (sell) fish quotas and harvest more (less) than q_f. Since under trade a relatively larger quantity of fish is harvested by high ϕ fishermen who incur lower bycatch per unit of target harvest, total bycatch is lower.

QUOTA-BASED MANAGEMENT WITH AT-SEA OBSERVABILITY

We now turn to the case where sea turtle bycatch is monitored at sea. We assume the penalties for violations are sufficiently high and fishermen, as a result, obey their bycatch cap by taking all necessary avoidance measures.

If sea turtle caps are sufficiently high, they do not bind in equilibrium. The choice problem, as under the unobservable case studied above, is completely guided by fish harvests. On the other hand, if the cap is sufficiently low but fish quotas are sufficiently high, the choice problem is governed primarily by the turtle bycatch cap. Fish harvest management then becomes trivial. Therefore, we focus here on the more interesting case where both fish quotas and bycatch caps bind in the aggregate.

As above, we alternately study scenarios where fish quotas and bycatch permits are and are not traded in the operations stage.

FISH HARVEST AND BYCATCH UNDER TRADE IN QUOTAS

We continue to assume that arbitrage equalizes quota/cap prices across the planning and operations stage since there is no aggregate uncertainty.

The operations stage. The fisherman's problem is to maximize profits by balancing fish harvest with turtle bycatch:

$$\pi(\phi) = \max_c \left\{ \left(\underbrace{(p_f - r_f)\, z_f \phi^{1-\beta}(1-a(c))}_{h_f(\phi)} - r_t \underbrace{z_t(1-\phi)^{1-\beta}(1-c)}_{h_t(\phi)} \right) n^\beta - w\, n + r_f q_f + r_t q_t \right\}. \tag{10}$$

With at-sea observability, bycatch must be matched with permit holdings which trade at price r_t. An optimal and interior choice of c, contingent on ϕ, is then:

$$a'(c) = \frac{r_t}{p_f - r_f} \frac{z_t}{z_f} \left(\frac{1}{\phi} - 1 \right)^{1-\beta}. \tag{11}$$

Under our assumption $\phi \in (0, 1)$ the term within brackets is finite. Also, for positive harvests to take place, $r_f < p_f$. Finally, for all $q_t > 0$, the equilibrium bycatch price $r_t < \infty$. Thus, $a'(c)$ is finite, and it is positive when $r_t > 0$.

Recall that $a'' > 0$, which implies that c is increasing in r_t, r_f, and decreasing in p_f.[16] Thus, the higher the bycatch permit price, the higher the bycatch avoidance. Conversely, the higher the marginal revenue from fish harvest, the lower the bycatch avoidance. When $r_t > 0$, we have $c > 0$ for all $\phi < 1$. Thus, no fisherman harvests (or lands) his maximum feasible harvest of fish.

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16. For example, when $a(c) = \frac{1-\sqrt{1-c^2}}{2}$, the above gets:

$$\tilde{c}(\phi) = \sqrt{\frac{1}{1 + 4\left(\frac{r_t z_t}{(p_f - r_t)z_f}\left(\frac{1-\phi}{\phi}\right)^{1-\beta}\right)^{-2}}}.$$

Figure 1 illustrates the optimum harvest and bycatch combinations at points A, B, and C for ϕ realizations of ϕ_{Low}, ϕ_{Med}, and ϕ_{High}, respectively, when the quota held by all fishermen is at $\{q_f, q_t\}$. Equation (11) also indicates that c is decreasing in ϕ. Thus, a fisherman who encounters a relatively high concentration of fish directs little effort to avoid sea turtles. The opposite is the case for fishermen who encounter a relatively high concentration of turtles. The above logic also implies that fishermen with relatively higher fish encounters will buy additional fish quotas and sell turtle bycatch permits, while those with lower fish encounters will do the opposite.

The planning stage. We have assumed that all quotas are binding; i.e., no quota or bycatch permit goes unutilized. As harvest and bycatch cannot exceed their respective limits, it must be the case that:

$$h_f^e = q_f = n^\beta z_f E_\phi \left\{ \phi^{1-\beta}[1 - a(\tilde{c}(\phi))] \right\};$$

(12a)

$$h_t^e = q_t = n^\beta z_t E_\phi \left\{ (1-\phi)^{1-\beta}(1 - \tilde{c}(\phi)) \right\},$$

(12b)

where $\tilde{c}(.) : \phi \to (0, 1)$ is implicitly defined by (11).

The optimal input choice is obtained by maximizing the expected profit:

$$\pi^e = \underbrace{E_\phi \left[\begin{array}{c} (p_f - r_f)z_f \ \phi^{1-\beta}[1 - a(\tilde{c}(\phi))] \\ -r_t z_t (1-\phi)^{1-\beta}(1 - \tilde{c}(\phi)) \end{array} \right]}_{=(p_f - r_f)q_f - r_t q_t} \cdot n^\beta - w \, n,$$

which calls for an input quantity that satisfies:

$$wn = \beta[(p_f - r_f)q_f - r_t q_t].$$

(13)

Input payments (left-hand side) equal their share (β) in revenues, as is standard with Cobb-Douglas production functions.

It is worth reiterating that r_f and r_t are endogenously determined. Thus, equations (12a), (12b), and (13) jointly determine n, r_f, and r_t.

Fish discards and turtle bycatch. As evident from (12a), there are no fish discards. Furthermore, turtle bycatch in (12b) is exactly as planned by the manager. Those fishermen who exceed their individual bycatch cap trade from others; in aggregate, sea turtle bycatch exactly matches the cap q_t. This result is noteworthy. Recall that bycatch permit sales and purchases determine its equilibrium price at the operations stage. These prices are known in advance (and also prevail) at the planning stage because there is no aggregate uncertainty. These prices, in turn, determine input employment, which in equilibrium has to be consistent with demand (purchases) and supply (sales) of bycatch permits at the operations stage.

It is worth comparing the costs and benefits with and without at-sea observability. We have shown that trade in fish quotas ensures that fish landings exactly match their quota, whether bycatch is observable or not. However, when bycatch is unobservable, its quantity is proportional to the fish quota. The manager cannot set fish quotas and turtle caps independently, whereas under observability this will be the case. From (12a) and (12b) we see that the quantity of bycatch per unit of fish harvest will be greater when at-sea behavior is unobserved:

$$\frac{h_t^e}{h_f^e} = \frac{E_\phi\{(1-\phi)^{1-\beta}(1-\tilde{c}(\phi))\}}{E_\phi\{\phi^{1-\beta}[1-a(\tilde{c}(\phi))]\}}\frac{z_t}{z_f} < \frac{E_\phi\{(1-\phi)^{1-\beta}\}}{E_\phi\{\phi^{1-\beta}\}}\frac{z_t}{z_f} = \tau,$$

where τ is as in (4). A lower observable bycatch requires fishermen to incur avoidance costs, and $\tilde{c}(\phi) > 0$ for all ϕ. The inequality follows from the assumption that $a(c) < c$ for all c.

While an observer program can implement a particular bycatch quantity, the cost of landing the same fish quantity without observability is larger by a factor $(E_\phi\{\phi^{1-\beta}\}/E_\phi\{\phi^{1-\beta}[1-a(\tilde{c})(\phi)]\})^{\frac{1}{\beta}}$. The cost of deputing observers on boats must factor into the policy choice. The bottom line once again is that bycatch reduction comes at a cost.

FISH HARVEST AND BYCATCH WITHOUT TRADE IN
QUOTAS OR BYCATCH PERMITS

Now suppose that fishermen cannot trade fish quota or bycatch permits and, due to ob-servability, their harvest/bycatch cannot exceed their quotas/permits.

The operations stage. The quantity of input and location of ex-post HBPFs will depend on the fish quota and bycatch cap $\{q_f, q_t\}$ relative to prices. If the marginal return to the input is high; i.e., $\{q_f, q_t\}$ are sufficiently small for given p/w, fishermen will have chosen a relatively large n in the planning stage. In this case, quotas and bycatch permits will likely lie in the interior of realized HBPFs. Point A in figure with quota/permits $\{q_f, q_t\}$ represents this case. On the other hand, if quota/permit caps are sufficiently large for given p/w, the HBPF may fall out-side the envelope of zero-avoidance points. This allows for a quota/cap point like B with quota/permits $\{q'_f, q'_t\}$ in figure 4.

Below, we present the case where quota/permits are at point like A in figure 4. A detailed analysis of equilibrium for points such as B is provided in an online Appendix.

As evident, if a fisherman holding $\{q_f, q_t\}$ in figure realizes $\hat{\phi}$, he precisely meets his targets by harvesting at point A. If his realized ϕ is above, say at $\bar{\phi}$, he can meet his fish target and also
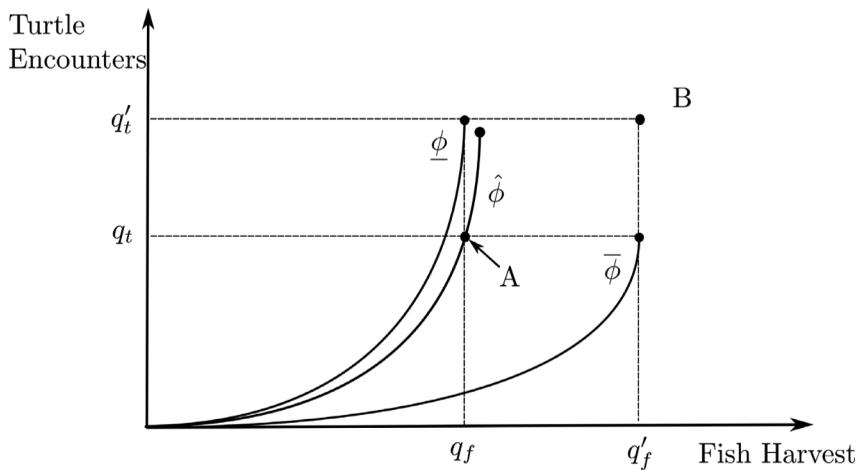

Figure 4. Observable Harvests and Bycatch Under No Quota Trade

observe his bycatch cap by catching fewer turtles than q_t. On the other hand, if his $\phi = \underline{\phi}$, he can not fully utilize his fish quota, since doing so will violate his bycatch cap. He must sacrifice fish harvest by diverting effort to bycatch avoidance. This argument leads to the following harvesting rules that implicitly determine a fisherman's avoidance efforts, c:

$$h_f = z_f(1 - a(c))\phi^{1-\beta}n^{\beta} = q_f \quad \text{for all } \phi \geq \hat{\phi}; \tag{14a}$$

$$h_t = z_t(1 - c)(1 - \phi)^{1-\beta}n^{\beta} = q_t \quad \text{for all } \phi \leq \hat{\phi}. \tag{14b}$$

Thus, while (14a) determines c as a function of ϕ, n, and q_f, (14b) determines c as a function of ϕ, n, and q_t. Let these functions be denoted as $\hat{c}_f(\phi, q_f, n)$ and $\hat{c}_t(\phi, q_t, n)$, respectively. This, in turn, obtains:

$$h_t = \hat{h}_t(q_f, \phi, n) \equiv z_t(1 - \hat{c}_f(\phi, q_f, n))(1 - \phi)^{1-\beta}n^{\beta}, \quad \phi \geq \hat{\phi}; \tag{15a}$$

$$h_f = \hat{h}_f(q_t, \phi, n) \equiv z_f(1 - a(\hat{c}_t(\phi, q_t, n)))\phi^{1-\beta}n^{\beta}, \quad \phi \leq \hat{\phi}. \tag{15b}$$

Thus, (14a)–(15b) completely characterize harvests and bycatches when $\{q_f, q_t\}$ is sufficiently tight.

The planning stage. Using (15a) and (15b), the expected (and aggregate) fish harvest and sea turtle bycatch are derived as:

$$h_f^e = q_f(1 - G(\hat{\phi})) + \int_{\phi_{\min}}^{\hat{\phi}} \hat{h}_f(q_t, \phi, n)dG(\phi); \tag{16a}$$

$$h_t^e = q_t G(\hat{\phi}) + \int_{\hat{\phi}}^{\phi_{\max}} \hat{h}_t(q_f, \phi, n)dG(\phi). \tag{16b}$$

Since quotas/caps cannot be traded, the optimal choice of input simply maximizes $p_f h_f^e - wn$, where h_f^e as expressed by (16a) internalizes the harvest/bycatch quota/cap constraints (see the online Appendix):

$$w = \beta p_f \int_{\phi_{\min}}^{\hat{\phi}} z_f \underbrace{\left(1 - a(\hat{c}t(\phi, q_t, n)) - (1 - \hat{c}t(\phi, q_t, n))a'(\hat{c}t(\phi, q_t, n))\right)}_{<1} \phi^{1-\beta}n^{\beta-1}dG(\phi). \tag{17}$$

It is instructive to compare the above with its counterpart under unobservable bycatch, equation (6). Under both cases, landing is observable and fishermen do not harvest more than their fish quotas. Landing is quota-constrained when relative fish abundance exceeds a threshold. Suppose the thresholds turn out to be identical under both cases. Then by (17) inputs employed under observability must be less than those under no observability. This is intuitive: a marginal unit of input not only increases harvest but also bycatch, and the latter is costly under observability. This discourages input employment. Expected/aggregate harvest under observability is lower as a result.

Recall that with unobservable at-sea behavior, equilibrium bycatch is lower with no trade *vis-à-vis* trade, although the reduction comes at a higher cost. Does a similar contrast exist when bycatch is observable? We examine this through a numerical example.
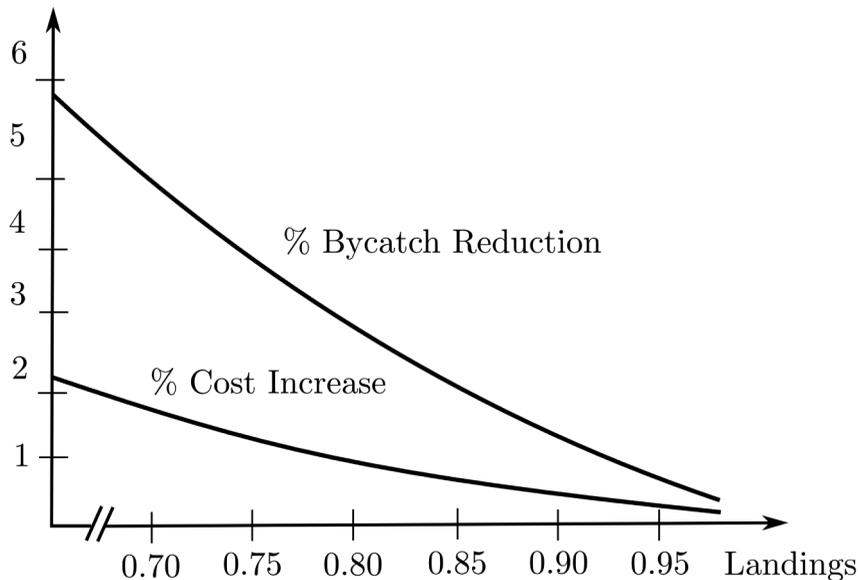
Figure 5. Cost Increase and Bycatch Reduction without Trade and at-sea Observability

Note: Results assume ϕ uniformly distributed on [0.7, 0.9] with $w = p_f = 1$, $z_f = 2$, $z_t = 0.1$, $\beta = 0.6$, and $q_f = 1$.

Observable bycatch without quota trade. Without trade in quotas and bycatch caps, the equilibrium is governed by (14a)–(17). We solve for the equilibrium and contrast costs and bycatch for varying landings targets under the two environments. The results are reported in figure 5.

Qualitatively, figure 5 is similar to that exhibited in figure 3, which reported outcomes with no at-sea observability. Without trade, fishermen employ higher input quantities to land the same quantity of fish, which raises costs. With more inputs and a lower opportunity cost of allocating the inputs to avoidance under no trade, bycatch is smaller. As quotas/landings become larger for given prices, the role of trade diminishes and the differences in outcomes diminishes.

It bears emphasis that under observability and quota/bycatch cap trade, any $\{q_f, q_t\}$ chosen by the manager is implementable. This is not possible in the absence of trade. The upshot here is that trade in quotas and caps welfare dominates the absence of trade, when bycatch is observable.

Once again, the result that bycatch is relatively lower without quota trade hinges on the assumption of input irreversibility. In an online Appendix, we show that with input reversibility, quota trade instead leads to a lower bycatch. The intuition is similar to the unobservability case. With reversibility, $c = 0$ and a fisherman's bycatch/harvest ratio depends on $\left(\frac{1}{\phi} - 1\right)^{1-\beta}$. With trade, a relatively higher harvest is reaped by fishermen with high ϕ realizations by purchasing additional quotas. Since these fishermen inflict a lower sea turtle mortality, bycatch/harvest in the aggregate is lower under trade.

CONCLUSION

This article develops a framework to study the design and performance of quota-based management approaches in fisheries experiencing socially harmful bycatch of non-market species.

Our model combines endogenous and costly bycatch avoidance and randomness in harvests of both the target and bycatch stocks. We incorporate our technology within a standard optimizing framework to study fishing behavior and management performance with observable and unobservable at-sea fishing activities, and with and without quota and bycatch permit trades. Empirical evidence from the Gulf of Mexico longline reef fish fishery is presented to motivate our analysis and add context.

Our results suggest that, with trade in fish quotas and bycatch caps, but without at-sea observability, fishermen do not incur the cost of avoiding bycatch while conducting target-stock fishing operations. Trading in bycatch permits is irrelevant. With trade in fish quotas, bycatch can be controlled by the regulator only by reducing the fish quota and foregoing harvest of target fish stock.

Bycatch observability introduces an incentive to undertake costly avoidance efforts, through the introduction of a bycatch permit user cost. A bycatch management scheme with both observability and frictionless quota/cap trading allows fishermen to match aggregate harvests with aggregate quota/cap for both the target and bycatch species, at lowest cost. Costs increase when quota/cap is not freely traded. This is because fishermen allocate more inputs to guard against target-stock harvest underages, while at the same time revenue in the fishery is lost without trade, as some fish stock quota remains unfished.

Overall, our results hold that efficient target stock/bycatch outcomes emerge under quota/cap management when regulators are able to observe at-sea fishing activity and if trades of target stock quota and bycatch permits are frictionless. Trading frictions can be overcome with modern communications technology. Achieving at-sea observability at reasonable cost appears possible with recent advances in electronic video monitoring technology. Our assessment of the costs associated with non-quota-based regulation under Amendment 31 suggest tradable bycatch caps should be given serious consideration in the Gulf of Mexico longline reef fish fishery and in other fisheries facing similar bycatch problems.

The costs of non-quota-based bycatch regulations emerge as foregone harvests of valued target stocks and/or higher harvesting costs. These costs can be substantial as evidence suggests in the Gulf of Mexico longline reef fish fishery. If sea turtle encounters are proportional to longline fishing effort, licence reductions under Amendment 31 appear to address the goal of reducing turtle bycatch. Assuming the 17.6% encounter rate is accurate and is unaffected by changes in fishing behavior, post Amendment 31, roughly 104 fewer turtle encounters occurred in 2009 (see table 1). Data limitations do not allow an assessment of the cost of attaining the same turtle bycatch reduction under a tradable bycatch cap program. While empirical evidence suggests Amendment 31 regulations are costly in terms of foregone harvest and increased fishing costs, an important advantage they offer is that at-sea fishing activity need not be monitored. The cost of placing an observer onboard a longline reef fish vessel is estimated at $1,500 per day before administrative costs (Perruso 2012).[17] Since quota-based bycatch management would require 100% observer coverage, the price tag for a longline fleet observer program would exceed $1.86 million per year based on the 2008 days at sea.

Recent developments in electronic video monitoring technology, on the other hand, can provide a viable alternative for implementing 100% observability (Lara-Lopez, Davis, and Stan-

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17. L. Perruso (larry.perruso@noaa.gov), interview by Q. Weninger, September 2012.

ley 2010). The cost of electronic equipment may be as low as $30 per vessel fishing day. Additional costs are incurred to review video footage collected by onboard cameras. These costs could be kept in check through a system of fisherman self-reporting and random auditing (Stanley et al., 2011). That is, fines for misreporting bycatch coupled with random audits would likely be sufficient to ensure effective monitoring and thus implementation of a cap-and-trade bycatch management program.

Comparing the costs of restricting bycatch below a particular target under quota- and non-quota-based regulation can be difficult. With sufficient data, a structural model of a target-stock/sea turtle bycatch technology could provide a more complete picture of the cost of reducing bycatch under alternate regulations. Extensions of our model to consider multiple fish and bycatch species and/or multiple production periods could provide additional insights for the design of cap-and-trade bycatch policies. Our article provides a useful starting point for further investigation.

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