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Adjusting technical efficiency to reflect discarding: The case of the U.S. Georges Bank multi-species otter trawl fishery

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Abstract

Discarding undesirable catch is recognized as a major problem confronting fishery managers. It is widely perceived by managers, however, that reductions in discards can only be accomplished via reductions in good or desirable outputs and technical efficiency. Yet there appear to be few studies which actually examine the relationship between discard reduction and technical efficiency. In this paper, we present an alternative concept of technical efficiency, which explicitly recognizes that measures of technical efficiency should be adjusted for discard levels. This is because traditional measures of efficiency do not consider the resources used in order to discard. We also offer a framework based on data envelopment analysis for assessing efficiency in the presence of undesirable outputs. We examine the relationship between vessel efficiency and regulatory discards in the U.S. Georges Bank multi-species otter trawl fishery on a tow-level basis. We then examine differences between efficient and inefficient tows, and extend our results to the trip level. Further examination of trip-level results then yield insights into the potential impact of trip-limit regulations. Results show that in order to reduce discards, vessels are limited in the amount they can increase their total output, and that trip-limit regulations may have unintended consequences.
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Keywords: Efficiency; Data envelopment analysis; Discards

1. Introduction

Discarding in commercial fishing operations worldwide is a problem which has received much attention. In 1994, the United Nations Food and Agriculture Organization published an assessment of worldwide levels of discards (Alverson et al., 1994). A subsequent report by FAO indicated that annual discards were approximately 20.0 million metric tonnes (mt) per year (FAO, 1998). This was followed by a 2004 assessment that suggested discards had declined to approximately 7.3 million mt a year (Kelleher, 2005). Some of the reasons for the decline were greater utilization of catch for aquaculture and human consumption, adoption of more selective fishing technologies, a decline in fishing intensity for some species, management actions, and more progressive attitudes by individuals on the need to solve discarding problems.

Regardless of the actual level of discards, concern remains about discards in the world's fisheries. The United Nations Food and Agriculture Organization (FAO) Code of Conduct for Responsible Fisheries, Section 8.4.5, states that nations should encourage the development and implementation of technologies and operational methods which reduce discards (FAO, 1995). It further states that "The use of fishing gear and practices that lead to the discarding of catch should be discouraged, and the use of fishing gear and practices that increase survival rates of escaping fish should be promoted." The United States National Oceanic and Atmospheric Administration's (NOAA), National Marine Fisheries Service (NMFS) has developed bycatch plans for their

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managed fisheries to explicitly reduce discards (NOAA, 2005).

One major concern of reducing discards, however, is determining how a reduction in discards achieved through management and regulation or gear modifications affects the technical efficiency (TE) of vessels operating in a fishery. TE is a measure of how well a producing unit is utilizing its inputs (e.g., days at sea and crew) to produce outputs (e.g., fish). The focus of our work is to include both the landings and discards of the same species when measuring TE. Failure to do so could result in vessels being deemed more efficient because they would have higher output levels for a given level of inputs. This unfortunately ignores the potential costs of disposing of discards because resources must be used to discard catch. In other words, the traditional notion of TE does not directly incorporate the resources used disposing of undesirable outputs, and thus overstates TE.

In this paper, we present a measure of TE which recognizes the need to reduce undesirable outputs, while simultaneously permitting the expansion of desired outputs. We provide a measure of TE which explicitly credits fishing operations for reducing the production of undesirable outputs (i.e., recognizes that some fishing operations with lower output levels, higher input levels, but lower levels of undesirable outputs may be more efficient than operations with higher output levels, lower inputs levels, and higher levels of undesirable outputs). Our measure of efficiency and method for estimating TE are based on work done by Färe et al. (1996), Chung et al. (1997), and Chambers et al. (1998), which offers a measure and framework for estimating TE in the presence of undesirable outputs. We then compare efficient and inefficient tows to determine if operational differences such as area fished, tow speed, depth, and time of year are correlated with differences in efficiency. The analysis is then extended to the trip level to determine if there are differences in landings and discards if all tows were efficient. Further extensions examine the implications of imposing trip limits as a regulatory measure.

The methods extend data envelopment analysis (DEA), which is a non-parametric mathematical programming technique for estimating technical efficiency. DEA constructs a "best practice frontier" which maps out the greatest output (least input) for a given level of input (output) based on observed outputs and inputs of decision-making units (DMUs; e.g., vessels). It is particularly well suited for firms which produce multiple products, such as fishing vessels which harvest a variety of species. DEA results give managers information on what each vessel should be able to produce given their physical configuration and use of variable inputs such as crew and fuel. Several studies in recent years have used DEA models to study fishing vessel production (Weninger, 2001; Tingley et al., 2003; Walden et al., 2003; Kirkley et al., 2004). Larson et al. (1996) provide an alternative non-parametric approach for examining bycatch in multi-species fisheries.

This study applies a DEA model based on a directional distance function which permits the determination of the maximal proportionate expansion of desirable outputs and contraction of undesirable outputs. It offers a particularly useful approach for assessing TE in fisheries, which involves the inadvertent capture of non-marketable species and products. The approach is applied to the U.S. Georges Bank

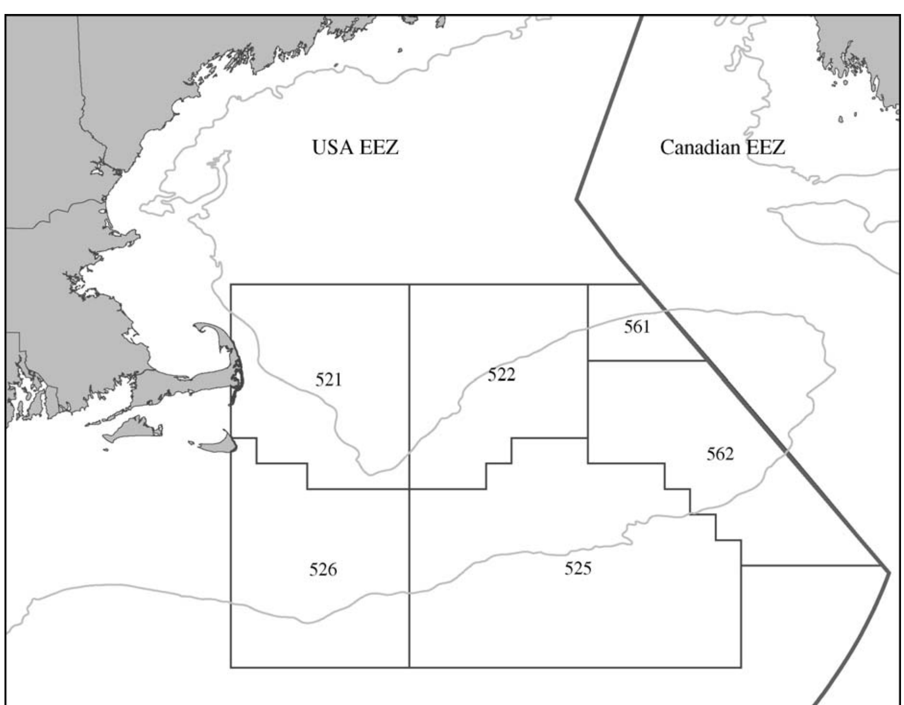

Fig. 1. The Georges Bank fishing area and associated statistical areas.

multi-species otter trawl fishery. Georges Bank is a large productive fishing ground situated in the northwest Atlantic, adjacent to the northeastern United States and stretching into Canadian waters (Fig. 1). Vessels fishing on Georges Bank harvest a wide variety of finfish species, but also harvest non-marketable or restricted species. Discards (by weight) are often quite large and occur because of regulatory limits (e.g., trip limits) and market conditions. Vessels in the fishery typically land 10 or more species, which may include cod (*Gadus morhua*), haddock (*Melanogrammus* aeglefinus), yellowtail flounder (*Limanda ferruginea*), pollock (*Pollachius virens*), winter flounder (*Pseudopleuronectes americanus*), witch flounder (*Glyptocephalus cynoglossus*), windowpane flounder (*Scophthalmus aquosus*), American plaice (*Hippoglossoides platessoides*), white hake (*Urophycis tenuis*), redfish (*Sebastes* spp.), and monkfish (*Lophius americanus*). All species are subject to size restrictions, and trip limits are imposed on cod—10,000 pounds per trip. Our estimation and analysis of TE considers undesirable outputs due to trip limits, minimum size restrictions, and non-marketability for various reasons such as being too small. There may be other species which are discarded because they have no markets or cannot be landed because of current laws, but they are not considered here. Some examples of these species are turtles, marine mammals, and birds.

2. Methods

The origins of the model used to study the Georges Bank otter trawl fishery are found in Chung et al. (1997). We assume a technology such that good and bad (undesirable outputs or discards in this study) outputs are jointly produced. Good outputs are denoted by $y \in R^M_+$, bad outputs by $u \in R^K_+$, and inputs by $x \in R^N_+$. The technology can be described using output sets as: $P(x) = \{(y, u): x \text{ can produce } (y, u)\}$ (i.e., inputs used produce both good and bad outputs). The output set is assumed to be closed and bounded, and inputs are freely disposable.

Färe and Grosskopf (2004a) note that $P(x)$ is an environmental output set if outputs are weakly disposable, and good and bad outputs are null-joint. Weak disposability explicitly recognizes that disposability of undesirable outputs is not without cost, as the firm is forced to reallocate resources from producing good outputs to reducing bad outputs. The traditional notion of TE assumes strong disposability, or the notion that disposing of undesirable outputs has zero opportunity costs. Weak disposability of outputs (Shephard, 1970) is formally defined by the condition that if $(y, u) \in P(x)$ and $0 \leq \theta \leq 1$, this implies $(\theta y, \theta u) \in P(x)$. This means that a proportional contraction of good and bad outputs is feasible, and that it is costly to reduce bad outputs. The null-joint property means that if good outputs are produced, bad outputs are also produced as part of the production process (i.e., if $u = 0$, then $y = 0$). This is a typical result in fishing operations, where there is usually some form of discards. More formally, good and bad outputs are null-joint if $(y, u) \in P(x)$ and $u = 0$ implies $y = 0$. Conversely, in terms of fishing operations, if one catches desirable fish there will be some level of discards. This is particularly true when regulations are in place which limit the output of one or more species, and vessels then discard when the trip limit is reached for the regulated species.

Given there are $j = 1, \ldots, J$ observations of inputs and outputs (x^j, y^j, u^j), the output set can be written as follows:

$$P(x) = \left\{ (y, u) : \sum_{j=1}^{J} z_j y_{jm} \geq y_m, \quad m = 1, \ldots, M, \right.$$
$$\sum_{j=1}^{J} z_j u_{jk} = u_k, \quad k = 1, \ldots, K,$$
$$\sum_{j=1}^{J} z_j x_{jn} \leq x_n, \quad n = 1, \ldots, N,$$
$$\left. z_j \geq 0, \quad j = 1, \ldots, J \right\}.$$

where $z_j, j = 1, \ldots, J$ are the intensity variables which map out the efficient frontier. Observations which are on the frontier are considered efficient, while those not on the frontier are projected to the frontier based on a convex combination of efficient observations.

The above model imposes constant returns to scale on the technology, which allows weak disposability to be modeled as a strict equality on the bad output constraint and as an inequality on the good output (Färe and Grosskopf, 2004a). Variable returns to scale may be imposed on the technology by restricting the sum of the intensity variables to equal 1.0 and adding more constraints (Färe and Grosskopf, 2004b).

Null-jointness is imposed on the production model by imposing the following restrictions on the bad outputs:

$$\sum_{k=1}^{K} u_{kj} > 0, \quad j = 1, \ldots, J,$$

$$\sum_{j=1}^{J} u_{kj} > 0, \quad k = 1, \ldots, K.$$

The first restriction says that each DMU produces at least one bad output, while the second states that each bad output is produced by at least one DMU. In the case of Georges Bank otter trawl fishery, these conditions imply that there are discards for each species landed and that each vessel discards at least one species.

Given the above environmental DEA technology, it is necessary to formalize the model to evaluate the performance of individual decision-making units. We use the approach of the directional output distance function, $\vec{D}_o$, rather than the traditional radial expansion used in many DEA models. This allows an expansion of good outputs and contraction of bad outputs. Let $g=(g_y, -g_u)$ be a direction vector. Efficiency in the g-direction is then estimated for each DMU as the solution to the following linear programming problem:

$$\vec{D}_o(x^{j'}, y^{j'}, u^{j'}; g) = \max_{\beta,z} \beta$$

s.t.

$$\sum_{j=1}^{J} z_j y_{jm} \geq y_{j'm} + \beta g_m, \quad m = 1, \ldots, M,$$

$$\sum_{j=1}^{J} z_j u_{jk} = u_{j'k} - \beta g_k, \quad k = 1, \ldots, K,$$

$$\sum_{j=1}^{J} z_j x_{jn} \leq x_{j'n} \quad n = 1, \ldots, N,$$

$$z_j \geq 0, \quad j = 1, \ldots, J.$$

The model is run once for each observation, and values for β and z are returned. Efficiency is indicated when $\vec{D}_o(x^{j'}, y^{j'}, u^{j'}; g) = 0$, and inefficiency when there are positive values of $\vec{D}_o(x^{j'}, y^{j'}, u^{j'}; g)$. The efficiency scores, βs, indicate the proportion by which good outputs and bad outputs can be, respectively, expanded and contracted relative to efficient levels of outputs. Setting the directional vector $g=(y^j, u^j)$ (i.e., the direction of the observed data) provides symmetry with the traditional Shephard distance function, the Shephard output distance function being a special case of the directional distance function (Chung et al., 1997).

If the g_y vector is set to the observed good output, and the g_u vector to the negative of the observed bad output, the following model is produced:

$$\vec{D}_o(x^{j'}, y^{j'}, u^{j'}; g) = \max_{\beta,z} \beta$$

s.t.

$$\sum_{j=1}^{J} z_j y_{jm} \geq (1+\beta) y_{j'm}, \quad m = 1, \ldots, M,$$

$$\sum_{j=1}^{J} z_j u_{jk} = (1-\beta) u_{j'k}, \quad k = 1, \ldots, K,$$

$$\sum_{j=1}^{J} z_j x_{jn} \leq x_{j'n} \quad n = 1, \ldots, N,$$

$$z_j \geq 0, \quad j = 1, \ldots, J,$$

where β is a measure of technical efficiency and represents the potential proportionate change in good and bad outputs. Because good outputs are being expanded and bad outputs contracted proportionally to one another (i.e., β is the same for both), and the directional vector is set to the observed outputs, β is bounded between 0 and 1. Since the bad outputs can never fall below 0, the possible expansion of the good outputs is limited to twice the observed amount.

The above model was used to examine tow-by-tow efficiency of U.S. Georges Bank otter trawl fishing vessels using data collected by at-sea fisheries observers from trips taken during 2003. The analysis was restricted to vessels fishing on Georges Bank, and within this region there are numerous choices of fishing location. However, location on Georges Bank was not included in the above model, but was subsequently incorporated into the statistical analysis of the results. The underlying stock conditions were also considered fixed since only one year of data was used, and stock conditions were not likely to vary significantly during the year.

Otter trawl vessels catch a variety of finfish species, which for this paper were restricted to cod, haddock, yellowtail flounder, pollock, winter flounder, witch flounder, windowpane flounder, American plaice, white hake, redfish, and monkfish. The estimation and analysis of TE, however, were based on selected groupings of species rather than each individual species. The construction of groupings of outputs or aggregates was necessary to facilitate the construction of good and bad outputs, and to ensure null-jointness for all observations. Outputs included in the analysis were cod, haddock, yellowtail flounder, monkfish, other roundfish (pollock, white hake, and redfish), and other flatfish (winter flounder, witch flounder, windowpane flounder, and American plaice).

Each output group was then further stratified into "good" outputs, which were the landings, and "bad" outputs, which were the discards. Inputs used in the analysis were horsepower, vessel length, gross tonnage, crew size, and tow duration. With the exception of tow duration, the other inputs do not change once a trip begins. Tow duration is one factor which can change, but it was not allowed to vary in the model. An alternative formulation would have been to allow the model to also contract the tow duration in order for the observation to be technically efficient. However, for this analysis we wanted to determine if technically efficient tows were associated with lower tow duration rather than with the optimal tow duration.

The data set contained 1286 tows from 57 vessels over 81 trips. Vessels averaged 77 ft in length, 145 gross registered tonnes, had engine horsepower of 674, fished with a crew of 4, and towed their gear on average 225 min (Table 1). Retained catch per tow of each species averaged between 92 and 372 pounds (whole weight), while average discards per species per tow ranged between 1.2 and 27.8 pounds. However, there was a large amount of variability in the data as indicated by the high standard deviations (Table 1).

To formally test whether or not there were significant differences in the outputs and inputs between efficient and inefficient tows, non-parametric Kruskal–Wallis tests were conducted. The Kruskal–Wallis test, or H test, is a generalization of the Wilcoxon, or U test, and is used to determine whether samples come from identical populations (Freund and Walpole, 1980), although in practice it is often used to test for the differences among population means (Kruskal and Wallis, 1952). Each input and output was tested separately, with a null hypothesis (H0) that the inputs and outputs from

Table 1
Selected statistics for the U.S. Georges Bank otter trawl fleet observed from fishery observer trips (81) taken in 2003

	Number of vessels	Minimum	Mean	Maximum	Standard deviation
Vessel characteristics					
Length	57	44	77	106	9.0
Gross registered tonnes	57	22	145	201	35.0
Horsepower	57	300	674	1380	210.7
Crew	57	2	4.3	5.0	0.8
	Number of tows				
Inputs					
Tow time (min)	1286	7	225	422	84
Outputs (pounds)					
Monkfish	1286	0	254	1650	364
Cod	1286	0	290	2600	407
Haddock	1286	0	141	3000	335
Yellowtail flounder	1286	0	112	2400	289
Other flounder	1286	0	372	3000	445
Other roundfish	1286	0	92	1300	190
Discards (pounds)					
Monkfish	1286	0	25.6	210	42.1
Cod	1286	0	6.3	240	20.5
Haddock	1286	0	3.2	75	9.4
Yellowtail flounder	1286	0	3.5	130	12.7
Other flounder	1286	0	27.8	280	39.6
Other roundfish	1286	0	1.2	30	4.7

the efficient tows come from a similar population as from the inefficient tows, and an alternative hypothesis (H1) that the two populations are different.

3. Results

Of the 1286 observed tows, 308 (24%) were deemed to be efficient as shown by a beta (β) score of 0 (Table 2). A β score of 0 indicates that the vessel cannot increase good outputs and decrease bad outputs. β-Values ranged from 0 to 1, with an average score of 0.48, a median score of 0.51, and a standard deviation of 0.37. This indicates that on average, if production was technically efficient, good outputs could be expanded by 48% and bad outputs could be reduced by 48%.

Table 2
Descriptive statistics for β returned from the directional distance function model

	β
Minimum	0.00
Mean	0.48
Standard deviation	0.37
Maximum	1
Percentiles	
10	0.00
20	0.00
30	0.14
40	0.33
50	0.51
60	0.68
70	0.82
80	0.89
90	0.95

For efficient tows, the mean gross registered tonnes, crew size, and tow times were either the same or slightly less than inefficient tows, while efficient tows were made by boats that were slightly longer, but by only a trivial amount (Table 3). Both the retained catch and discards were higher for efficient tows than inefficient tows. Results from the Kruskal–Wallis test revealed that efficient tows were associated with vessels with lower engine horsepower, and higher landings for all species except for the other flounder category, at a 0.05 significance level. Discards were significantly higher on efficient tows than on inefficient tows for haddock, and in the "other flounder" and "other roundfish" categories (Table 3). Efficient tows were therefore associated with higher levels of retained catch and higher discard levels for three different species groups. This indicates that reducing discards of these groups is going to be costly (i.e., a lower level of discards is only possible by reducing retained catch).

To investigate further why some tows were efficient and some were not, efficiency scores were regressed against explanatory variables not included in the directional distance function model. The dependent variable (efficiency) is censored on both the right and left side of the distribution of TE ($0 \leq TE \leq 1$); thus ordinary least squares is not an appropriate method for estimating the relationship between TE and the explanatory variables. Instead, a Tobit model, which uses maximum likelihood estimates, is preferred since it yields unbiased and more efficient estimates (Kennedy,

Table 3
Results of the Kruskal–Wallis test comparing efficient and inefficient tows

	Inefficient tows	Efficient tows	Chi-square value	Reject H0?[a]
Number	978	308		
Inputs				
Length	77.3	77.6	0.05	No
Gross registered tonnes	150	148.2	0.6	No
Horsepower	701	676	10.1	Yes
Crew	4.5	4.5	1.5	No
Tow duration (min)	225	223	0.13	No
Landings				
Monkfish	223.5	352.2	6.9	Yes
Cod	238.1	453.6	27.1	Yes
Haddock	85.7	314.8	59.3	Yes
Yellowtail flounder	74.9	231.6	14.5	Yes
Other flounder	334.4	492.9	2.0	No
Other roundfish	72.8	154.0	17.7	Yes
Discards				
Monkfish	22.7	35.1	0.003	No
Cod	4.7	11.3	2.2	No
Haddock	2.1	6.9	37.1	Yes
Yellowtail flounder	2.8	6.0	3.3	No
Other flounder	26.0	33.6	4.1	Yes
Other roundfish	0.8	2.4	13.5	Yes

[a] Critical value = 3.8, d.f. = 1.

2003). Efficiency scores from the directional distance model were transformed by subtracting them from 1 (i.e., $1-\beta$, where $0 \leq \beta \leq 1.0$). This means that efficient tows have a score of 1, while inefficient scores are less than 1. The specific functional relationship tested through the Tobit model was as follows:

$$\text{Efficiency} = f(\text{depth, tow speed, qtr2, qtr3, qtr4, area 522, area 525, area 526, area 561, area 562}),$$

where depth equals the depth of the tow; tow speed equals the speed of the tow; qtr2 = 1 if tow took place in April, May, or June, 0 otherwise; qtr3 = 1 if tow took place in July, August, or September, 0 otherwise; and qtr4 = 1 if tow took place in October, November, or December, 0 otherwise. Areas 522, 525, 526, 561, and 562 are specific statistical areas on Georges Bank which take the value 1 if the tow took place within the statistical area, and 0 otherwise. This was a fixed effects model. Quarter 1 and area 521 were not included in the model, and were therefore held constant.

Depth and tow speed were two factors which could vary with every tow, and perhaps account for the differences in efficiency scores. The Tobit model was estimated using the statistical package LIMDEP. Depth and fishing in area 562 were significantly different than 0.0 ($p < 0.05$), and positively correlated with more efficient tows (Table 4). Fishing during the third and fourth quarters was negatively associated with efficient tows, and the coefficients were significant at the 0.05 level. Fishing in area 525 was negatively associated with efficient tows, but the coefficient was not significant at the 0.05 level. Fishing activity during quarter 2 and fishing in areas 522, 526, and 561 were positively associated with efficient tows, but not at the 0.05 level.

Table 4
Results from the Tobit model used to investigate explanatory variables contribution to efficiency

Variable	Coefficient	Standard error	$P[Z] > z$	Significant at 0.05 level?
Intercept	0.270	0.142	0.057	No
Qtr2	0.057	0.038	0.133	No
Qtr3	−0.093	0.042	0.026	Yes
Qtr4	−0.088	0.040	0.027	Yes
Depth	0.002	0.0004	0.0004	Yes
Tow speed	0.066	0.043	0.124	No
Area 522	0.049	0.035	0.162	No
Area 525	−0.074	0.053	0.161	No
Area 526	0.029	0.066	0.659	No
Area 561	0.083	0.046	0.074	No
Area 562	0.130	0.050	0.009	Yes

Results from the tow-by-tow model were then aggregated to the trip level to determine whether these results held. The efficient level of landings per tow was calculated by multiplying landings by the sum $(1+\beta)$, where β was the score from the directional distance function model. The efficient level of discards per tow was calculated by multiplying discards by the difference between 1.0 and β (i.e., $1-\beta$). These numbers were then expanded to the trip level by multiplying the mean level of efficient landings and discards per tow by the total tows per trip. This yielded the estimated trip-level landings and discards if each tow was made efficiently, corresponding to the maximal expansion of good outputs and contraction of bad outputs. These results were then compared to estimated trip landings and discards, given the actual tow level data to test for any significant differences in good or bad outputs. Landings and discards per trip given observed tows were calculated by multiplying the mean values per tow by the total number of tows per trip.

Although estimated mean landings generated when all tows are efficient is higher and the mean discards lower than the estimated mean landings and discards per trip given observed tows, no significant differences were detected between the two groups at the 0.05 level by the Kruskal–Wallis test, with the exception of discards of the "other flounder" category (Table 5). This may indicate that most trips are a mixture of efficient and inefficient tows, and that for operational reasons (which are not being measured, such as the capacity of the crew to deal with the catch and conduct other operational duties) it is difficult for all tows to be efficient.

Regulatory measures implemented in 2004 as part of Amendment 13 limit trips to 10,000 pounds of cod. To explore the impact of this trip limit, Georges Bank otter trawl trips with estimated landings of more than 10,000 pounds of cod were compared to trips which would have landed more than 10,000 pounds if all tows were efficient. Twenty-seven trips had estimated cod landings greater than 10,000 pounds, but if all tows had been efficient, 34 trips would have landed more

Table 5
Results of the Kruskal–Wallis test comparing base data and output levels based on efficient tows at the trip level

	All trips	Trips with all tows efficient	Chi-squared statistic	Reject H0 at 0.05 level?[a]
Number of trips	81	81		
Landings				
Monkfish	7100	9036	1.23	No
Cod	8017	10494	2.21	No
Haddock	4126	4965	0.85	No
Yellowtail flounder	3382	4269	0.33	No
Other flounder	11186	14745	3.21	No
Other roundfish	3074	3732	0.67	No
Discards				
Monkfish	722	459	2.43	No
Cod	195	129	1.68	No
Haddock	89	65	1.22	No
Yellowtail flounder	90	53	0.59	No
Other flounder	749	404	10.71	Yes
Other roundfish	34	24	0.20	No

[a] Critical value = 3.8, d.f. = 1.

than 10,000 pounds of cod. However, there was little difference between mean landings per trip in the observed trips and trips where more than 10,000 pounds of cod would be landed if all tows were efficient (Table 6). Furthermore, based on the Kruskal–Wallis test, there were no significant differences between the two groups ($p < 0.05$). The average cod landings per trip under both conditions (base case and operating efficiently), respectively, is over 18,000 and 20,557 pounds (more than double the 10,000 pounds trip limit), which would require most vessels to discard half their cod catch. Given these results, the only way to reduce cod output would be to discard catch, change fishing practices to reduce all outputs, or switch fishing areas to locations with low cod biomass. If a vessel chooses to discard, they will spend more time sorting and discarding. If a vessel reduces all outputs, it is giving up potential revenue from other species. If it switches to another location, the change in the species mix may yield lower revenue, and the vessel may incur additional costs because of changes in steaming time.

4. Discussion

To evaluate the potential impacts of regulations on discards, the underlying production process for the regulated vessels needs to be understood. Using directional distance functions to examine vessel efficiency in the U.S. Georges Bank, multi-species otter trawl fishery facilitated the identification of possibilities for expansion and contraction of both good and bad outputs at a vessel, trip, and tow level. Such an approach is particularly relevant in multi-species fisheries where the production is characterized by a multi-output, multi-input technology. When there are discards as exist in most fisheries, directional distance functions reveal

Table 6
Kruskal–Wallis test results comparing 2003 observer trips with greater than 10,000 pounds of cod to results from the directional distance model for trips with greater than 10,000 pounds of cod

	Base data	Trips with all tows operating efficiently	Chi-squared statistic	Reject H0 at 0.05 level?[a]
Number of trips	27	34		
Landings				
Monkfish	6512	6554	0.007	No
Cod	18000	20557	1.38	No
Haddock	6353	6588	0.0005	No
Yellowtail flounder	5581	6287	0.28	No
Other flounder	12884	16642	1.86	No
Other roundfish	3404	3372	0.003	No
Discards				
Monkfish	735	439	2.8	No
Cod	316	184	1.8	No
Haddock	179	117	3.1	No
Yellowtail flounder	131	84	0.17	No
Other flounder	1017	496	2.8	No
Other roundfish	37	24	0.34	No

[a] Critical value = 3.8, d.f. = 1.

whether vessels can reduce discards by altering their production mix, or whether they will have to simply reduce landings, which is costly. This may simply force vessels to turn landings into discards, and fishing mortality of the regulated species may therefore not be reduced at all.

Results showed that on average, vessels could increase their landings and decrease their discards by 48%. Tows which had a β score of 0 were considered efficient and defined the frontier. These tows could not increase landings or decrease discards. The maximum β score returned was 1.0, which indicated that these tows could double their landings while eliminating their discards. Tows which were efficient had engines with lower horsepower and landed more of all species with the exception of the "other flounder" category. They also had higher discards of haddock, "other flounder," and "other roundfish."

In order to gain further insight into factors which may be influencing vessel efficiency which were not included in the DEA model, a regression of efficiency scores against external factors was carried out using a Tobit model. The data were transformed so that a score of 1 indicated efficiency, and results would show factors positively associated with efficient tows. Both depth and fishing in area 562 positively influenced efficiency, while fishing in calendar quarters 2 and 3 negatively influenced efficiency. It was surprising that with a large geographic area such as Georges Bank, more statistical areas did not end up being significant in the model. However, the results are telling us that fishing in every other area besides 562 is not different than fishing in area 521, which was considered fixed in the model. It is also telling us that fishing in the second quarter was not different than fishing in the first quarter, but that efficiency declined in quarters 3 and 4 compared to quarter 2. Quarters 1 and 2 would be considered a winter/spring time period, while quarters 3 and 4 are summer/fall. The negative coefficients on the summer/fall period may be due to fish migration, or may simply mean that more vessels are fishing in the summer/fall time period and there are congestion externalities taking place.

Results also indicated that efficient tows were associated with vessels with significantly lower horsepower. This does not mean that vessels should immediately switch to smaller engines, as this will be costly. Additionally, we have only examined technical efficiency and not economic efficiency, which compares profit from an actual output–input bundle with the maximum profit available (Ray, 2004). However, TE is a necessary condition for economic efficiency. It must also be remembered when interpreting these results that any bias in the sampling scheme has not been investigated. The vessels selected were larger and had greater horsepower than the average vessel which fished on Georges Bank. The vessels were chosen based on a port stratification, where a certain number of trips from each port to Georges Bank needed to be taken each month. Although the vessels were supposed to be chosen at random, safety concerns and scheduling conflicts may have prevented a truly random vessel selection. If observers were allowed to substitute trips on alternative vessels, they may have chosen bigger vessels for safety reasons or because the vessels provided more crew amenities.

Amendment 13 to the Northeast Multispecies FMP enacted trip limits on U.S. Georges Bank otter trawl vessels to reduce mortality on Georges Bank cod. Vessels were limited to 1000 pounds per day of cod or 10,000 pounds per trip. Results indicate that if all tows were efficient, the average cod landings would barely be above 10,000 per trip. However, there was a subset of these vessels that would land nearly double the trip limit if they operated all their tows efficiently. For these vessels, it will be costly to reduce their cod landings in terms of forgone catch of other species. They could reduce their cod landings by spending less time at sea, shifting their effort to areas where there is little cod, or perhaps by altering tow times. Adjusting tow time was not considered in the analysis in this paper, although extensions to the model can reveal the optimal tow time. Vessels could also simply convert their landings into discards once the vessel reaches the 10,000 pounds trip limit, which would decrease their technical efficiency. A more direct approach of limiting fishing time on Georges Bank or closing additional areas with high catch per unit effort would likely be more successful in reducing cod mortality than the trip limits.

5. Conclusion

Utilizing data collected by observers on selected fishing trips offers many possibilities for understanding the factors which influence technically efficient production by fishing vessels. We have used directional distance functions to model technical efficiency while accounting for discards on a tow-by-tow basis from data collected on sea-sampling trips in 2003. Combining these results with other variables in a subsequent statistical model can reveal factors or behavior influencing efficiency, which could not be explicitly included in the DEA model. This approach also holds promise for experimental gear work, where it could also be used to determine how changes in both retained catch and discards using the experimental gear alter technical efficiency. However, this further emphasizes the need for fisheries observer data to be drawn from a representative sample of vessels and for potential bias in the data to be explored. The data used to construct these models are quite detailed, and can usually only be obtained through a dedicated fishery observer program. Generally they are not available from vessel logbook records collected at the docks.

In order to say anything about the economic efficiency of vessels, cost data will need to be collected and models estimated that incorporate economic optimizing behavior, such as profit maximization. The directional distance function models can be expanded to incorporate economic optimizing behavior, and this makes it critical to collect additional data on sea-sampled trips. Such data would include input usage, such as fuel, ice, and water, and the prices paid for those inputs. Prices for the landings would also need to be collected for each trip. Extensions to the models presented here could also be developed with different assumptions about returns to scale. With a time series of data spanning several years, one could examine changes in productivity and technical change.

With growing emphasis on ecosystem management, discards in commercial fishing operations will continue to be an important topic. The models presented here give managers important information about the potential for vessels to increase landings while decreasing discards. Coupled with appropriate biological models, managers should have much better information to make decisions about discard reduction strategies. Again, we emphasize that this depends on the ability to collect data through trained at-sea observers.

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