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Selective Fishing and Shifting Production in Multispecies Fisheries

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Abstract

A limited ability to target or avoid individual stocks complicates successful output management in multispecies fisheries. For vessels in these fisheries, reducing harvest of one species often requires simultaneous reductions in harvest of other stocks. The extent to which multispecies allocation targets can be met may depend critically on harvesters' ability to substitute production across species. We introduce a measure of compositional control which captures the level of forgone production resulting from imperfect selectivity. This metric is then applied to data from the New England multispecies groundfish fishery and used to test for evidence of limited selectivity in the composition of individual vessel daily landings. Results indicate that increases in landings of one species generally require simultaneous increases in landings of other species—a finding which suggests difficulty in substituting production across groundfish species. Our measure is seen to vary widely through time as well as across vessels and species, and may be affected by both environmental conditions and incentives created through management. The model developed here should hold value for managers and researchers seeking to assess inter-stock economic tradeoffs in multispecies fisheries.

Keywords: multispecies fishery; fishing selectivity; production frontier; weak disposability

Introduction

Hard limits on allowable catch have been associated with decreased variability in exploitation levels (Essington 2010, Melnychuk et al. 2012) and may yield conservation benefits if properly designed and implemented (Hilborn et al. 2005, Grafton et al. 2006). In multispecies fisheries, non-selective harvest has long been recognized by fisheries scientists, managers, and economists as a major impediment to successful output management (Copes 1986, Squires et al. 1998, Sanchirico et al. 2006), leading to the frequent use of effort restrictions and technological standards to limit harvest pressure. Absent species-specific targeting or avoidance incentives, management via input controls has, in many cases, produced poor biological and economic outcomes (Hilborn et al. 2005). In the US, hard annual limits are now required for all federally managed species (MSRA 2006), forcing managers to consider a variety of output control measures in both single and multispecies fisheries.

In imperfectly selective multispecies fisheries, single or multispecies avoidance requires either additional fishing inputs or reductions in output of jointly harvested species (Turner 1997, Singh and Weninger 2009). Additional inputs (e.g., fuel, ice, labor, or gear) might enable a vessel to reach grounds where the avoided stock is less abundant or operate in a manner which decreases encounters. Reductions in harvest of target stocks, on the other hand, might be necessary if modifications in catch composition are too costly or are technologically infeasible. Though substantial compositional control can often be exercised via spatiotemporal harvest decisions (Branch and Hilborn 2008, Jannot and Holland 2013), magnitudes and margins of control may vary over space, time, and species (Abbott et al. 2015), and selectivity is generally thought to be bounded. Recognizing this, many multispecies fisheries managed with output controls utilize additional mechanisms intended to create flexibility in balancing catch with

70 quota, e.g., multispecies fisheries regulated with individual fishing quotas may allow quota
71 trading, carry-forward and carry-backward allowances, deemed value payments or species
72 equivalence conversions (Sanchirico et al. 2006). Multispecies output controls can nonetheless
73 incentivize discard of limiting stocks (Turner 1997) or lead to the underutilization of healthy
74 species (Kuriyama et al. 2016). Successful output management in multispecies fisheries therefore
75 requires both the presence of incentives and ability to target and avoid individual species, as well
76 as institutional mechanisms designed to facilitate flexibility in catch-quota balancing.

77 Utilizing the conceptual and analytical framework of production frontiers, we explore a
78 novel approach to analyzing imperfect compositional control and the production tradeoffs which
79 characterize many multispecies fisheries. Production frontier models have been applied
80 extensively in fisheries, however applications in non-selective or imperfectly selective
81 multispecies fisheries have generally focused on measuring technical efficiency and the effects
82 of capacity reduction measures (e.g., Dupont et al. 2002, Färe et al. 2006, 2011). Our approach
83 instead examines the technological tradeoffs in joint production of multiple species and may be
84 found useful in a wide variety of joint harvest, bycatch, as well as other multi-output production
85 scenarios. We apply the empirical tool to data from the New England multispecies groundfish
86 fishery following the implementation of catch share management and test for evidence of
87 imperfect control in the composition of individual vessel daily landings. Imperfect compositional
88 control is found to be common, implying reductions in landings of key groundfish species may
89 require simultaneous reductions in landings of other species. This result is economically
90 significant and suggests avoidance of limiting species may reduce landings, revenues, and profits
91 of quota-abundant species.

92

93 **Materials and methods**

94 **Fishery background**

95 From 1994 until 2010, the New England multispecies groundfish complex was managed through
96 limited entry and days-at-sea effort controls. Following this, and in response to national
97 legislation which requires strict annual mortality limits for all federally managed stocks (MSRA
98 2006), regional managers implemented a multispecies catch share program. On May 1st, 2010, 80
99 thousand metric tons (mt) of tradable quota for 14 stocks of nine groundfish species was
100 allocated to 17 self-identifying groups of harvesters, or sectors, representing a fleet of over 400
101 vessels. Sector members are considered jointly liable in maintaining harvests within group quota
102 limits and were encouraged to collectively manage group allocations. It was hoped that the
103 transition to rights-based output controls would incentivize targeting and avoidance behavior,
104 aligning individual, group, and management objectives, while also increasing fishery profits and
105 long-term economic viability (NEFMC 2009). Previous research cautioned against management
106 of individual groundfish stocks however, finding New England multispecies production to be
107 joint and non-separable (Squires 1987, Kirkley and Strand 1988).

108 During the first year of catch share management, harvesters in New England landed 30
109 thousand mt of multispecies groundfish—just 38% of the fleet's total allocation. Quota
110 utilization rates varied widely across stocks. For example, 94% of the Georges Bank yellowtail
111 flounder allocation was harvested, though the fleet utilized only 16% of its Georges Bank
112 haddock allocation. Limited compositional control and marginal profitability can drive slack
113 quota constraints in multispecies fisheries. In 2010, ex-vessel prices for most groundfish species
114 increased or remained constant while nominal revenues per unit effort also increased and average
115 trip costs showed little change (Kitts et al. 2011). While it remains uncertain what ultimately led

to the underutilization of groundfish allocations, an inability to shift production from constraining to non-constraining quota species could have caused vessels to forgo profitable trips in order to maintain harvests within legal limits.

Conceptual framework

A production frontier is the boundary of the set of output combinations producible with a specific technology and input level. When considering joint production of multiple outputs (e.g., vessels that harvest and land several different species of fish), the frontier identifies combinations of outputs that could be efficiently produced with a fixed amount of input; producing below the frontier is feasible but wastes inputs, and producing beyond the frontier is technologically infeasible. A multispecies output frontier depicting, for example, production of the New England groundfish species cod and haddock, would identify the maximum amounts of production (e.g., landings) for these species given a fixed level of inputs (e.g., a certain size vessel and crew). The slope of the frontier indicates the rate of transformation between outputs (e.g., cod which must be given up to produce more haddock). Typically, output frontiers exhibit a negative slope due to tradeoffs in production of different goods.

A production frontier with a non-positive slope maintains the commonly applied assumption of free, or strong, output disposability, where reducing an individual output can be accomplished without reduction in joint outputs or additional inputs (Figure 1a). This assumption if applied to a multispecies fishery suggests that harvesters have complete control over output composition, i.e., output of any species can be decreased without reducing joint outputs or requiring additional inputs (in our previous example this would imply cod production could be reduced independently of haddock). Free output disposal does not characterize many

multispecies fisheries where, due to imperfect selectivity, reducing output of one species requires either additional inputs or corresponding reductions in output of jointly produced species (Turner 1997, Singh and Weninger 2009). Multi-output production frontiers exhibiting costly compositional control can instead be characterized by costly, or weak, output disposability (Figure 1b), which allows for proportionate output contractions (Shephard 1970, Färe et al. 1994). In a multispecies fishery, weak output disposability corresponds to imperfect selectivity, where species avoidance may require additional inputs or reductions in joint outputs (e.g., reductions in haddock necessary to limit the harvest of cod).

A frontier measure of compositional control

A multispecies production technology can be defined for a set of inputs $x = (x_1, \dots, x_N) \in \mathbb{R}_+^N$ which produce a set of multispecies outputs $y = (y_1, \dots, y_M) \in \mathbb{R}_+^M$. Inputs may include, for example, vessel size, crew, or days spent fishing, while outputs might be harvests, landings, or revenues from several different species of fish. Specification of a production technology identifies how inputs are transformed into outputs as well as rates of substitution and transformation among individual inputs and outputs. For our purposes, we will consider two contrasting multispecies production technologies, one characterized by free targeting and avoidance and another where compositional control is a costly behavior (see Appendix for a specification of each technology).

Directional distance functions measure the extent of inefficiency for a particular observation of production inputs or outputs as the additive distance to the efficient production frontier (Chambers et al. 1996, Chung et al. 1997). When analyzing output frontiers, a distance of zero would indicate that the observation was on the efficient production frontier, producing

the maximum amount of output achievable with the observed level of inputs. A positive distance would instead indicate that the observation was inefficient and interior to the frontier, and could therefore achieve a higher level of output without increasing inputs. Two such functions, one for each of free and costly output disposal, are:

$$(1) \quad \bar{D}_O^F(x, y, g_y) = \max \{ \beta : y + \beta g_y \in P_F(x) \};$$

$$(2) \quad \bar{D}_O^C(x, y, g_y) = \max \{ \beta : y + \beta g_y \in P_C(x) \}.$$

In (1) and (2), β is a scalar output distance measure, $g_y \in \mathbb{R}_+^M$ is a vector defining the direction of output expansion, and $P_F(x)$ and $P_C(x)$ are free and costly output disposal technologies, respectively. Each function finds the maximum amount a particular multispecies output observation y could increase, in the direction g_y , while still remaining producible given the set of observed inputs x and the technological restrictions imposed by free or costly output disposability (Figure 2a,b). If $\beta = 0$, the observation is on the production frontier and multispecies outputs could not be increased (i.e., the observation is efficiently using inputs x to produce outputs y).

In Figure 2 panel c, the production frontier has some regions characterized by free output disposal, and other areas where it is costly. Four efficient multispecies production points are shown: A, B, C, and D; each uses similar inputs but produces differing amounts of species 1 and 2. At observation D, a large quantity of species 1 is produced without any corresponding production of species 2, indicating avoidance of species 2 (targeting of species 1) is not costly. Species 1 avoidance (species 2 targeting) is shown to be costly however (asymmetric costly

avoidance may reflect differences in species' range or habitat). Over the segment 0AB, reductions in species 1 require corresponding reductions in species 2. Similarly, increases in species 2 over this range require increases in species 1. When targeting and avoidance are costly behaviors, the free and costly output disposal efficient frontiers will diverge (Figure 2c), indicating the assumption of free output disposal is violated.

Differencing output distances (1) and (2) yields a measure of compositional control:

(3)
$$\phi(x, y, g_y) = \bar{D}_O^F(x, y, g_y) - \bar{D}_O^C(x, y, g_y) .$$

In (3), ϕ is equal to the difference in output distances to the free and costly output disposal efficient frontiers constructed for the production observation (x, y) in the direction g_y . This difference reveals the additional output which could have been efficiently produced if the underlying technology were not restricted by limited compositional control (e.g., the additional haddock possible under perfect haddock targeting, given inputs are used efficiently). In multispecies fisheries, large values of ϕ would suggest management via output controls may be challenging as a low allocation for one stock could constrain production of other stocks. This situation is illustrated in Figure 2c, where compositional control is shown to be costly at observation y in the species 2 direction (this can be seen by the separation in free and costly output disposal efficient frontiers). In this example, a small allocation of species 1 paired with a large allocation of species 2 might result in significant levels of uncaught species 2 allocation.

Measures similar to ϕ have been developed to investigate the impact of regulatory controls on firms emitting pollutants, where the difference between free and costly output disposal efficient frontiers is thought to capture the opportunity cost of a regulation which

restricts free pollution disposal (Färe et al. 2007). Our measure is more general in that it allows these costs to be defined in single or multi-output dimensions (e.g., compositional control can be analyzed with respect to one or several species). Exact interpretation of ϕ will depend upon definitions of inputs, outputs, and the directional vector. In what follows, equation (3) will be used to evaluate compositional control in landings of New England multispecies groundfish.

Data

We considered outputs to be daily landings by vessels of nine catch share regulated multispecies groundfish: Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), American plaice (*Hippoglossoides platessoides*), pollock (*Pollachius virens*), Acadian redfish (*Sebastes fasciatus*), white hake (*Urophycis tenuis*), winter flounder (*Pseudopleuronectes americanus*), witch flounder (*Glyptocephalus cynoglossus*), and yellowtail flounder (*Limanda ferruginea*) (Table 1). Vessel length, gross tons, and horsepower, obtained from federal fishing permit lists, were used as production inputs (Table 2). Data on gear and variable inputs (e.g., crew, fuel, number of tows) was not available. By considering only fixed factors in our technological specification, we are not capturing the effects on compositional control resulting from different choices of gear or variable inputs (e.g., if different gears or effort levels lead to different species compositions). As such, and because output levels are ultimately constrained by fixed factors (e.g., due to storage capacity), it was expected that our model would return conservative estimates of ϕ , which here corresponded to additional daily landings under efficient production and perfect targeting for a New England groundfish vessel of a certain size and horsepower.

Analysis was restricted to landings from vessels registered north of Cape Cod as this group relies heavily on catch share regulated groundfish (over two-thirds of annual revenues).

Additionally, only landings during the first five months of fishing year (FY) 2010 were considered (May 1st – September 30th). The final sample consisted of 3 731 daily groundfish landing observations from 179 sector vessels, which were found by aggregating dealer-reported ex-vessel transactions by day and vessel. Total landings amounted to 5.5 thousand mt worth US \$17.4 million. Landing amounts and frequencies were highly variable across species, though joint production was common. Over 90% of observations included landings from multiple species, of which more than half were landings of five species or more.

Computational methods

For a given multispecies daily landings observation k_0 , ϕ was found by solving the following linear programming routines:

$$\begin{aligned}
 \bar{D}_O^F(k_0; g_y) &= \max_{\beta, \lambda} \beta \\
 \text{s.t. } \sum_{k=1}^K \lambda_k x_{n,k} &\leq x_{n,k_0}, \quad n = 1, \dots, N \\
 \sum_{k=1}^K \lambda_k y_{m,k} &\geq y_{m,k_0} + \beta g_y, \quad m = 1, \dots, M \\
 \sum_{k=1}^K \lambda_k &= 1 \\
 \lambda_k &\geq 0, \quad k = 1, \dots, K;
 \end{aligned}$$

$$\begin{aligned}
 \bar{D}_O^C(k_0; g_y) &= \max_{\beta, \mu, \theta} \beta \\
 \text{s.t. } \sum_{k=1}^K \mu_k x_{n,k} &\leq \theta x_{n,k_0}, \quad n = 1, \dots, N \\
 \sum_{k=1}^K \mu_k y_{m,k} &= y_{m,k_0} + \beta g_y, \quad m = 1, \dots, M \\
 \sum_{k=1}^K \mu_k &= \theta \\
 \mu_k &\geq 0, \quad k = 1, \dots, K \\
 0 &\leq \theta \leq 1.
 \end{aligned}$$

Solutions to (4) and (5) find the additive output distance β which places k_0 along the efficient production frontier of each respective technology. Efficient frontiers are constructed empirically by comparing output levels across observations with similar inputs; those producing the most define the efficient frontier. This method is known as data envelopment analysis (Farrell 1957, Charnes et al. 1978) and uses intensity variables to place positive weight on those observations which meet technological constraints and define the efficient frontier. Technologies characterized by weak output disposability and variable returns to scale exhibit frontiers which are non-linear functions of the intensity variables λ_k (see Appendix). Fortunately, a change of intensity variables in (5), i.e. $\mu_k = \theta \lambda_k$, linearizes the problem, allowing standard linear programming methods to easily and efficiently find a solution (Zhou et al. 2008, Kuntz and Sülz 2011, Lozano and Gutiérrez 2011, Leleu 2013).

The primary difference between (4) and (5) is in their treatment of multispecies outputs y . In (4), each of the M output constraints indicates that species m output at k_0 is feasible if it is less than or equal to a convex combination of points defining the efficient frontier. This is the condition of free output disposal, permitting any level of output equal to or less than that along the efficient frontier. If considering a cod and haddock landings frontier, this constraint implies that cod landings could be reduced without any reduction in haddock, as well as vice versa. In (5), all outputs are treated as weakly disposable. This condition is introduced into the output constraints by requiring that output at k_0 be proportionate, across all outputs, to a convex combination of frontier observations. Assuming proportionate output reductions are feasible is akin to assuming the production process can be scaled down without affecting output composition (e.g., taking fewer tows on a trip).

When solving (4) and (5), every element of the directional vector g_y was set equal to zero except for a single element, which was set equal to one. Efficient frontiers were therefore approached in a single output direction. Through iterative adjustment of the directional vector, a ϕ was found for every groundfish species in all landings observations, resulting in the calculation of 33 579 ϕ values (9 species x 3 731 observations). These measures corresponded to the potential increase in species-specific landings under efficient production and perfect targeting. A large value indicated significant separation in the free and costly output disposal efficient frontiers and suggested a limited ability to increase landings of the individual species without corresponding increases in landings of other species. In instances where allocations are exhausted or nearly binding, this approach could produce values of ϕ which are legally infeasible. Such a situation might be handled by including additional constraints in (4) and (5) which reflect quota availability, or by redefining the directional vector. We used data from the first five months of a FY in which no allocations were exhausted. All returned values of ϕ were therefore assumed to be legally feasible.

Linear programming problems were solved in R (R Core Team 2015) using the lpSolveAPI package (Konis 2013), which provides an interface to lp_solve (Berkelaar et al. 2004), an efficient linear programming solver based on the revised simplex method. Compositional control was tested for each of the nine multispecies groundfish by calculating ϕ using daily landings observations from all vessels occurring in the same month. This required K x M solutions to (4) and (5) (67 158 total linear programming problems). One-sided sign tests contained in the R package BSDA (Arnholt 2012) were used to test if monthly median values of ϕ were significantly greater than zero.

Results

When evaluating compositional control in New England groundfish daily landings data, it was generally found that landings of one species could not increase without simultaneous increases in the landings of other species. These results indicate that similarly capitalized vessels landing in the same month tended to exhibit large daily landings of one species together with large daily landings of other species (likewise, small daily landings of one species were observed together with small daily landings of other species). Across all species, vessels, and months, an average ϕ value of 1 413 kg ($SD = 1\ 910$) was found.

For all species and in all months, median ϕ values were found to be significantly greater than zero. That is, during the first five months of FY 2010, daily landings technologies for this group of vessels exhibited statistically significant evidence of imperfect selectivity and costly compositional control. The ability to selectively produce individual species was seen to vary across species and months however (Figure 3). Some species, like cod, redfish, and white hake, were found to have large median values of ϕ early in the season and smaller values later on. For these groundfish, early season landings tended to be composed of large or small amounts of the individual species together with proportionate amounts of other species. This apparent lack of compositional control could have been due to high rates of encounter, minimal incentives to target or avoid, or some combination of both factors.

Pollock, and to a lesser extent plaice, were conversely seen to have small ϕ values early in the season and larger values later on. Prior to the start of FY 2010, abundance estimates of pollock indicated that the stock was considerably depleted. On May 1st the fleet received an allocation of approximately 35% recent annual landing levels, however a subsequent assessment suggested the stock was in good health and the allocation was revised upwards six-fold on July

15th. The low initial allocation for pollock may have led to early season pollock avoidance and thus small landing amounts for pollock and plaice—a frequent joint target—during the months of May and June. Small values of ϕ for these species early in the season suggests that this behavior might have been moderately successful (i.e., a small amount of separation between free and costly output disposal frontiers indicates landings of other species could increase without requiring large corresponding increases in pollock or plaice). Median values of ϕ were still significantly greater than zero during this time however (702 kg and 261 kg for pollock and plaice during May, respectively), and imperfect compositional control, paired with a constraining single-species allocation, could have led to lost revenues and profits derived from other species.

Measures of ϕ were found to be highly variable ($c_v(\phi) = 1.35$). Variability of ϕ across observations could be the result of differences in species availability, driven by differences in environmental or ecological conditions across space and time, as well as by differences in the use of inputs, targeting ability and selective fishing incentives across individual vessels. Values of ϕ were found to be ~20% more variable across different vessels landing in the same month than for the same vessel landing in different months. While possibly resulting due to the limited scope of inputs considered, this finding suggests that individual factors (including choices of gear and variable inputs) may affect multispecies landings compositions to a greater extent than spatiotemporal variables.

Discussion

Fisheries managers have historically relied on command-and-control measures in regulating multispecies fisheries (e.g., limited entry, time/area closures, and gear restrictions). This style of management can promote perverse behaviors by fishermen and produce costly and inefficient

outcomes (Wilén 2006). Additionally, input controls generally provide fishermen few incentives to avoid overfished species, which may thwart stock rebuilding efforts (Hilborn et al. 2005, Grafton et al. 2006). Output controls, on the other hand, enable the direct management of fishing mortality and have been found to reduce variability in key ecological and fishery indicators (Essington 2010) while also limiting over-exploitation (Melnichuk et al. 2012). In multispecies fisheries, managing outputs can present several difficulties however.

The successful application of output controls in multispecies fisheries depends both on institutional design (Hilborn et al. 2005, Grafton et al. 2006) and flexibility in the production of managed species (Copes 1986, Squires et al. 1998). Balancing catch with quotas can be facilitated through management provisions intended to reconcile the frequent mismatch between harvest technology and species availability (Sanchirico et al. 2006), as well as by prudent intra- and inter-trip decision making (Branch and Hilborn 2008). However, absent catch-quota balancing opportunities and mechanisms, or if in cases of extremely divergent allocations across stocks, the inability to shift output from low to high allocation species may constrain contemporaneous harvests, revenues, and profits.

In this paper we developed and applied an empirical tool to investigate multi-output production of New England groundfish. We found that the underlying production technology characterizing daily landings may allow for only limited compositional control. Our measure was seen to be variable through time and across vessels, and possibly in response to a mid-season shift in allocation. However, increases or decreases in landings of individual species were generally found to require corresponding increases or decreases in landings of other, jointly produced species. Imperfectly selective multispecies production technologies may make output

management of New England groundfish challenging, especially when allocations represent a mix of healthy and overfished species.

The group allocation system implemented for New England groundfish allows for intra-sector quota management, inter-sector quota trade, as well as the ability to carry forward up to 10% of unfished allocation for most stocks. Despite these measures, matching catches with quota has been problematic and allocations for several species are often underutilized. It is possible that the issue may only be temporary—a short-run tradeoff necessary to rebuild depleted stocks. As stocks rebound the need for selectivity may decline, and as fishers learn to adapt their fishing behavior, the ability to selectively target should increase. Still, when rebuilding depleted multispecies stocks in New England and elsewhere, there may exist a tradeoff between current harvests of healthy stocks and those in the future for rebuilt species. Whether or not these short-term costs are outweighed by long-term benefits will depend on rebuilding time horizons, rates of discount, and the relative profitability of healthy and overfished stocks. In order to better evaluate such tradeoffs, future modeling efforts should seek to link multispecies biological models with economic models of joint production which allow for imperfectly selective harvest technologies.

While we think our measure of compositional control will prove useful in evaluating management tradeoffs in multispecies fisheries, there are several limitations and weaknesses which must be addressed. First, satisfying all constraints in linear programming routines (4) and (5) can become challenging as the number of outputs and inputs increases or the dimension of the directional vector expands. In fisheries which harvest diverse multispecies assemblages, some level of output aggregation may be necessary. Second, solving large, complex, multi-constraint linear programming problems can be computationally burdensome. Our analysis,

which required solving over 60 thousand linear programming problems, took a multi-core processor running in parallel over 24 hours to complete. Evaluating compositional control with respect to only key species, or for specific areas and times, would significantly reduce computing time. Finally, the quality and usefulness of empirical measures of ϕ is conditional on the data supplied to the model; if critical inputs or outputs are missing, these measures may be biased or uninformative. Having data on only fixed factor inputs, our measures of ϕ were thought to be conservative since production technologies, though capacity-bound by fixed factors, did not account for the differential effects on composition of specific gears or effort levels. If different gear types lead to harvest and landings of certain species more often than others, comparing production technologies across all vessels when calculating ϕ would not capture this gear-specific inflexibility. In such cases, stratification by gear would allow for computation of more accurate ϕ values. Additional stratification of inputs, time, or space might also be necessary. Spatial and temporal restrictions were used here to control for unobserved factors affecting production which vary over space and time, however our model can also accommodate more sophisticated methods (see e.g. the multi-stage approach used by Kjærsgaard et al. 2009).

Empirical measures of compositional control should be of value to fisheries scientists, managers, and policy analysts working in multispecies fisheries. Constructed as the difference between free and costly output disposal efficient frontiers, our measure compares actual multispecies production technologies against a hypothetical of perfect compositional control. By differencing efficient production frontiers we control for the myriad of processes thought to generate technical inefficiencies in fishing fleets (Kompas et al. 2004, Tingley et al. 2005), isolating the production tradeoffs characterizing an underlying technology. This measure may be useful in ex-ante identification of “choke stocks”, where a certain quota combination is found to

be technological infeasible, as well as in evaluating economic and biological tradeoffs in multispecies fisheries over the short- and long-run.

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Table 1 Mean landing amounts (kg), percentage of observations with non-zero landings, and total sector FY 2010 allocations (mt). Standard deviations for means are shown in parentheses.

Species	Landing Amount	% Non-zero	FY 2010 Allocation*
Cod (<i>Gadus morhua</i>)	422 (582)	96	7 954
Haddock (<i>Melanogrammus aeglefinus</i>)	553 (2339)	50	52 898
Plaice (<i>Hippoglossoides platessoides</i>)	201 (639)	48	2 748
Pollock (<i>Pollachius virens</i>)	500 (1557)	66	16 178
Redfish (<i>Sebastes fasciatus</i>)	759 (3574)	27	6 756
White Hake (<i>Urophycis tenuis</i>)	188 (524)	57	2 505
Winter Flounder (<i>Pseudopleuronectes americanus</i>)	18 (131)	35	1 956
Witch Flounder (<i>Glyptocephalus cynoglossus</i>)	80 (183)	48	827
Yellowtail Flounder (<i>Limanda ferruginea</i>)	41 (87)	33	1 767

* Allocations reflect sector sub-ACLs (annual catch limits) following the July 15th pollock allocation revision. Allocations for cod, haddock, winter flounder, and yellowtail flounder combine ACLs for multiple stocks.

Table 2 Descriptive statistics for production inputs. Standard deviations for mean values are shown in parentheses.

Input	Mean	Min	Max
Length (m)	14 (3)	9	30
Gross Tons	31 (31)	4	198
Horsepower	335 (118)	150	940

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Figure captions

Figure 1. Two product output frontiers exhibiting free (a) and costly (b) disposability. All boundary and interior points are producible given a fixed input level.

Figure 2. Multispecies output frontiers with an inefficient interior production observation y shown. Arrows depict distances to the efficient frontiers from the observed output bundle y in the species 2 direction. Free and costly output disposal frontiers and distances are shown in (a) and (b), respectively. In panel (c), efficient production points A, B, C, and D are shown. A dashed line represents the free output disposal efficient frontier over the range of production space where free and costly output disposal frontiers differ. Output distances to free (right arrow) and costly (left arrow) output disposal efficient frontiers are also shown in (c).

Figure 3. Median ϕ values by month and species (kg of individual vessel daily landings). ϕ values correspond to the difference between free and costly output disposal efficient frontiers in the listed species direction, and indicate additional landings which could have been efficiently produced under perfect compositional control.

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Appendix

A multispecies production technology may be defined as:

$$(A1) \quad T = \{(x, y) : x \text{ can produce } y\},$$

Where $x = (x_1, \dots, x_N) \in \mathbb{R}_+^N$ is a vector of N fishing inputs, $y = (y_1, \dots, y_M) \in \mathbb{R}_+^M$ is a vector of M multispecies outputs, and T is the set of all feasible input-output combinations.

In both free and costly output disposal technologies, inputs are assumed to be freely disposable. That is, additional inputs should never decrease output. A free output disposal technology (T_F) must satisfy:

$$(A1.a) \quad (x, y) \in T_F, \ x' \geq x, \ y' \leq y \text{ imply } (x', y') \in T_F.$$

If (x, y) is within the producible set T_F , any input-output combination using more inputs or producing fewer outputs is also feasible and within the producible set. Under free output disposal, compositional control is not costly: output of any species in the vector of multispecies outputs y can be reduced without additional inputs or reductions in output of other species.

Costly output disposal technologies (T_C) must satisfy:

$$(A1.b) \quad (x, y) \in T_C, \ x' \geq x, \ 0 \leq \theta \leq 1 \text{ imply } (x', \theta y) \in T_C.$$

Condition (A1.b) is stricter than (A1.a), allowing only for proportionate contractions in the multispecies output vector y . For a costly output disposal technology, output reductions in one

species require proportionate output reductions in all species. In a departure from specifications of environmental technologies (see Färe et al. 1994, 2007), null-jointness is not assumed as it is possible to produce one species without corresponding production of other species.

If we consider k observations of fishing inputs and outputs, two output oriented reference technologies corresponding to free (P_F) and costly (P_C) output disposal may be defined:

$$(A2) \quad \begin{aligned} P_F(x) = \{y : & \sum_{k=1}^K \lambda_k x_{n,k} \leq x_n, \quad n = 1, \dots, N \\ & \sum_{k=1}^K \lambda_k y_{m,k} \geq y_m, \quad m = 1, \dots, M \\ & \sum_{k=1}^K \lambda_k = 1 \\ & \lambda_k \geq 0, \quad k = 1, \dots, K \}; \end{aligned}$$

$$(A3) \quad \begin{aligned} P_C(x) = \{y : & \sum_{k=1}^K \lambda_k x_{n,k} \leq x_n, \quad n = 1, \dots, N \\ & \theta \sum_{k=1}^K \lambda_k y_{m,k} = y_m, \quad m = 1, \dots, M \\ & \sum_{k=1}^K \lambda_k = 1 \\ & 0 \leq \theta \leq 1, \lambda_k \geq 0, \quad k = 1, \dots, K \}. \end{aligned}$$

In (A2) and (A3), convex combinations of observed inputs and outputs form feasible technology polytopes which adhere to the conditions of free (A1.a) and costly (A1.b) output disposal, respectively. The $k \lambda$'s are intensity variables, giving positive weight to those observations which define the technological frontier. Variable returns to scale, which allows the technology to exhibit constant, increasing, or decreasing returns at different production points, is imposed by requiring the summation of intensity variables equal one (Banker et al. 1984). The scalar factor θ in (A3) allows for simultaneous contraction of outputs and is necessary when constructing a weakly disposable, variable returns to scale technology (Färe and Grosskopf 2003, 2009, Zhou et

al. 2008). Note additionally that (A2) and (A3) are compact and allow for inactivity—common restrictions placed on output sets (Shephard 1970, Färe et al. 1994).

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