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Seasonal Harvest Patterns in Multispecies Fisheries

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Abstract: Fishers face multidimensional decisions: when to fish, what species to target, and how much gear to deploy. Most bioeconomic models assume single-species fisheries with perfectly elastic demand and focus on inter-seasonal dynamics. In real-world fisheries, vessels hold quotas for multiple species with heterogeneous biological and/or market conditions that vary intraseasonally. We analyze within-season behavior in multispecies fisheries with individual fishing quotas, accounting for stock aggregations, capacity constraints, and downward-sloping demand. Numerical results demonstrate variation in harvest patterns. We specifically find: 1) harvests for species with downward-sloping demand tend to spread out; 2) spreading harvest of a high-value species can cause lower-value species to be harvested earlier in the season; and 3) harvest can be unresponsive or even respond negatively to biological aggregation when fishers balance incentives in multispecies settings. We test these using panel data from the Norwegian multispecies groundfish fishery and find evidence for all three. We extend the numerical model to account for transitions to management with individual fishing quotas in multispecies fisheries. We show that, under some circumstances, fishing seasons could contract or spread out.

Keywords: multispecies fishery, multi-fishery, sequential fishery, fishing behavior, seasonal harvest, catch shares, seafood demand

JEL: Q22

1. Introduction

Fishers face a multidimensional decision problem that requires choosing where to fish, when to fish, what to target, and how much gear to deploy. Predictive analysis of the fishery generally aims to understand how fishing behavior responds to incentives across these multiple margins (Smith, 2012) for the purpose of evaluating policy options or anticipating outcomes from changing conditions. Despite sharp theoretical predictions for open access (Smith, 1969) and regulated open access (Homans and Wilen, 1997) as well as a growing body of empirical work, our understanding of fishing behavior in realistic settings is largely incomplete. Most studies analyze single-species fisheries, open access, or long-term (inter-seasonal) dynamics. Yet, most real-world fisheries are multispecies, have some form of restricted access, and have interesting short-term (intra-seasonal) dynamics. In this paper, we address this gap in the literature by developing a numerical model to predict qualitative patterns of within-season harvest timing in multispecies fisheries managed with individual fishing quotas (IFQs). We empirically test these predictions using the Norwegian cod, haddock, and saithe trawl fishery.

Timing of catch within the fishing year can have important implications for revenues generated by the fishery, product forms, and response of the fishery to policy changes (Grafton, Squires, and Fox 2000; Homans and Wilen 2005; Smith, Zhang, and Coleman 2008; Huang and Smith 2014). Some theoretical and empirical bioeconomic models have demonstrated the importance of within-season incentives—including biological conditions, stock effects, discounting, seafood markets, and congestion externalities—in determining these catch patterns (Clark, 1980; Boyce, 1992; Fell, 2009; Valcu and Weninger, 2013). Empirical bioeconomic studies have further shown that timing within-season harvest to account for these phenomena could generate substantial rent gains (Larkin and Sylvia, 1999; Huang and Smith, 2014). However, little is known about the generality of these results in multispecies settings. Our numerical model reveals that tradeoffs across cost and revenue margins can generate complex and non-intuitive behavioral patterns in multispecies settings.

Empirical production models and discrete choice models of fishing behavior provide relevant insights, but neither literature traces out a complete positive theory for intra-seasonal behavior in multispecies fisheries.[1] Production models treat multispecies outcomes as manifestations of multi-output production technology (Asche, Gordon, and Jensen, 2007; Weninger and Walters, 2003; Squires and Kirkley, 1991; Squires, 1987). However, they abstract away from the temporal distribution of fish within the season and do not address the sequential

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[1] The multispecies context refers to a set of participants who target multiple fish species within a year, either sequentially or simultaneously, and typically under the same management plan and using the same gear. For example, cod, haddock, and saithe are often caught together in similar ocean environments and, in the Norwegian context, they are jointly managed under the same license defined by vessel- and gear-type even though the quotas are set on an individual species basis.

nature of targeting decisions with associated forward-looking dynamic incentives.[2] Discrete choice models typically use data on finer time scales such as daily or weekly to analyze incentives driving participation, gear, and location choices (Abbott and Wilen, 2011; Eggert and Tveteras, 2004; Holland and Sutinen, 2000; Smith and Wilen, 2005). Yet, with few exceptions, these models focus on single-species fisheries and abstract away from forward-looking dynamics. That is, fishers are assumed to make a sequence of myopic decisions about targeting just one species.[3] Hence, models that explicitly account for forward-looking dynamics do not consider multispecies targeting (Hicks and Schnier, 2008; Huang and Smith, 2014), whereas models of species targeting still invoke sequentially myopic decision-making (Stafford, 2018; Zhang and Smith, 2011).[4]

Recent empirical work on the effects of rights-based fisheries management further highlights these shortcomings and reinforces the need for a richer understanding than currently exists. Using a matched control fishery for each U.S. fishery treated with IFQs (or "catch shares"), Birkenbach, Kaczan, and Smith (2017) show that on average seasons lengthen for treated fisheries. This finding is broadly consistent with the hypothesis that rights-based management creates incentives to exploit revenue margins (higher prices from spreading catch over the season and avoiding market gluts) in addition to the cost savings expected under these

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[2] Although harvest can be fairly selective in multispecies fisheries—e.g., pelagics in the northeast Atlantic (Asche, Gordon, and Jensen, 2007)—duality models are largely unable to distinguish between a fleet that targets a sequence of species in completely selective fisheries and a fleet in a non-selective fishery in which the share of each species is relatively constant within the year.

[3] Smith, Zhang, and Coleman (2008) find evidence of effort substitution in response to spawning aggregations of gag (a species of grouper), but forward-looking behavior is not modeled explicitly.

[4] In a model of species choice (Zhang and Smith, 2011), the structure of the decision assumes one of three possible targets is chosen in each period and thus rules out the possibility of multispecies targeting. This feature largely reflects the general approach of discrete choice modeling. Some of the fine-scale empirical literature analyzes behavioral responses to changing stock abundance (Smith, Zhang, and Coleman, 2008; Zhang, 2011; Huang and Smith, 2014).

policies (Homans and Wilen, 2005). However, individual fisheries within multispecies complexes provide a number of counter-examples in which seasons contract, indicating that behavior is more complicated than existing single-species theory suggests (Birkenbach, Kaczan, and Smith, 2017). Distilling how fishers respond to complex economic, biological, and regulatory considerations is crucial for explaining results such as these and improving managers' ability to predict behavior under changing policy conditions.

Our central claim is that timing the harvest of fish can involve tradeoffs between cost- and revenue-side considerations, and these tradeoffs can generate non-intuitive patterns of behavior in multispecies settings. Costs may be minimized by concentrating harvest to follow seasonal biological aggregations (e.g., the Lofoten cod fishery (Hannesson, Salvanes and Squires, 2010; Kvamsdal, 2016)) or at the beginning of the season due to stock effects. Revenues, by contrast, may be increased by spreading harvest throughout the season to take advantage of a downward-sloping demand schedule. Discounting creates incentives to generate revenues earlier in the season, counteracting the spreading effect. However, timing decisions are even further complicated by the possibility of participating in other fisheries; a vessel can be in only one place at any point in time. Fishers must therefore consider cost- and revenue-side tradeoffs not only within but also across species.

We develop a numerical bioeconomic model based on the Norwegian cod, haddock, and saithe trawl fisheries to investigate the time-profile of vessel landings throughout the year in a multispecies context. We model fisheries with annual IFQs such that fishers can choose when to harvest during the season but without the threat of a season closure typically associated with industry-wide quotas under regulated open access. We use peer-reviewed and gray literature on the relevant fisheries to parameterize the model.[5] Through numerical simulations, we generate three testable predictions about intra-seasonal patterns of behavior, and we test these predictions using fishing micro-data on Norwegian trawlers targeting cod, haddock, and saithe. Finally, we extend the numerical model to explore the transition to IFQs and offer an explanation to Birkenbach, Kaczan, and Smith (2017) for their mixed findings on season length for lower-value species. Our results highlight the importance of understanding the market context in bioeconomic models, the biological context in studies of seafood markets and fishing behavior, and the complex interplay among species targets and fisheries regulations.

2. Numerical Model

We model an owner of IFQs for multiple target species where the regulator sets the total allowable catch (TAC) in each year for each species. Implicitly, we assume that other IFQ holders face the same harvest-sequencing optimization problem and choose the same behavior.

The mechanisms in our model are consistent with our qualitative understanding of the Norwegian trawl fishery, however, a number of fisheries around the world are conducted similarly, with different species being targeted by the same fleet over the course of a single fishing year. Because there is a global market for whitefish (Gordon and Hannesson, 1996; Asche, Gordon, and Hannesson, 2002), demand is effectively flat for haddock and saithe. However, cod is sufficiently segmented from the general whitefish market such that Norwegian trawlers face a downward-sloping demand schedule (Asche et al., 2002; Arnason et al., 2004). In our model, we account for harvest smoothing, harvest spikes, within-season harvest trends,

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[5] Cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), and saithe (*Pollachius virens)* are also important species in the New England groundfish complex (saithe is commonly referred to as pollock but is a different species from the Alaskan walleye pollock, *Gadus chalcogrammus*).

concentration on a single-species, and mixed-species harvesting by introducing market conditions, biological aggregations, stock effects, and capacity constraints. Using parameter estimates derived from real Norwegian trawl data, we consider a range of scenarios and the different harvest patterns they generate.[6]

In a given year, a representative IFQ owner seeks to maximize total profits across species (*i*) and time periods (*t*). The objective function can therefore be written as:

$$NPV\pi^{Total} = \sum_i \sum_t \rho^t \pi_{it} \tag{1}$$

We can think of *t* as indexing months within the year such that ρ^t is a monthly discount factor. Discounting changes results in predictable ways that are not qualitatively important for our analysis, but we include it in the analysis for completeness. The IFQ owner chooses species-specific effort (*E*) to harvest (*H*) each species *i* in each period *t* based on price (*P*), cost (*c*), and harvest technology. Fishing effort is thus the control variable in the model. The instantaneous profits can be written as:

$$\pi_{it} = P_{it}H_{it} - cE_{it} \tag{2}$$

We allow for the possibility of a downward-sloping demand curve for each species with choke price (a_i) and slope (b_i):

$$P_{it} = a_i - b_i n H_{it} \tag{3}$$

where *n* is the total number of vessels in the fleet that are assumed to behave symmetrically and effectively scales individual harvest to the market level.[7] By setting b_i=0, we nest the case of the

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[6] We note three issues that our model does not address and that suggest future research directions: 1) strategic interactions and coordination failures among multiple IFQ holders; 2) within-season leasing and trading of IFQs; and 3) the complexities of an IFQ management regime co-existing with open access and regulated open access regimes that apply to other target fisheries.

[7] The model described here produces the same results as a symmetric Nash equilibrium with Cournot competition as long as the aggregate industry-wide quota is set at a level that eliminates incentives of the fleet to withhold production from the market. This situation is highly relevant for our case study (Norwegian cod, haddock, and saithe), in which industry-wide quotas bind. Arguably, this situation also

perfectly elastic demand that may plausibly describe some seafood products for which there is a global market with ample substitutes. Different levels of a_i can distinguish premium products within the same market. Cod and haddock, for instance, typically fetch higher prices than saithe, though all are competing in the whitefish market.[8]

We model species- and time-specific harvests using Cobb-Douglas technology with two inputs, effort (*E*) and stock (*X*):

$$H_{it} = q_{it} {E_{it}}^{\alpha_i} {X_{it}}^{\beta_i} \tag{4}$$

We allow for the possibility of a catchability parameter (q) that is time- and species-dependent, which means we can capture changes in catchability due to biological aggregations for spawning or other seasonal changes in fish distributions. We assume that the effort and stock elasticities (α_i and β_i, respectively) are species-specific but independent of time. For the main results, we assume perfect selectivity. When we generalize the model to allow for non-selective harvest, the results are qualitatively similar. When $\alpha_i = \beta_i = 1$ and $q_{it} = q_i$, the production technology for species *i* reduces to the familiar Schaefer production model in fisheries. When $\beta_i = 0$, production is independent of the stock (no stock effects). As a consequence, per-unit harvest costs are independent of the stock level. When $\alpha_i < 1$ or $\beta_i < 1$, there are diminishing returns to the inputs.[9]

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describes most fisheries; other explanations such as ecological co-occurrence and bycatch are typically offered when non-binding quotas occur at the industry level.

[8] Equation (3) could be written as a more general demand model to allow market interactions between species, but we assume that species are neither substitutes nor complements. Since the species we model empirically are considered substitutes, incentives to concentrate harvest of one species with a relatively elastic demand would be moderated by positive cross-price elasticities with species having relatively less elastic demand.

[9] The number of vessels, n, is fixed in the short term as we only analyze intra-seasonal behavior. Within the time period considered—a single fishing year—the fleet size is not expected to change. For the long-run consideration, profitability can motivate new participation, for example, when $\alpha_i < 1$, if this is

IFQ owners can at most take their share of the TAC for each species so that harvest summed across *t* does not exceed the quota share for that species:

$$\sum_{t=1}^{12} H_{it} \leq H_i^{quota} \tag{5}$$

Because we are focused on within-season behavior, we do not model stock recruitment, growth, or natural mortality. These features are more important for the cross-season performance of the fishery (with the exception of annual fisheries, like shrimp). Implicitly, our model is equivalent to assuming that all growth, mortality, and recruitment occur between fishing seasons as in Reed (1979). Thus, the stock (state variable) at *t* is initial stock less cumulative harvest:

$$X_{it} = X_{i0} - n \sum_{s=1}^{t} H_{is} \tag{6}$$

We add non-negativity constraints on effort:

$$E_{it} \geq 0 \tag{7}$$

We assume that the regulator never sets the TAC above X_{i0}, so we do not need non-negativity constraints on the stocks. We assume that harvests are also greater than or equal to zero, which closes the model.

In some simulations, we explore effort capacity constraints. In each period, effort summed across species targets is restricted:

$$\sum_i E_{it} \leq E^{max} \tag{8}$$

This capacity constraint could imply a time constraint, maximum hull capacity, amount of fishing gear on a vessel, or some combination of these. It is a reflection of a fixed, allocatable

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possible. However, in most managed fisheries, entry is limited, and this is the case for the Norwegian fleet.

input from the individual vessel's perspective in a similar fashion as agricultural land (Shumway, Pope, and Nash, 1984).[10]

With non-selective harvesting, the Schaefer harvest functions are modified as follows:

$$H_{1t} = q_1 E_{1t} X_{1t} + \tilde{q}_1 E_{2t} X_{1t} \tag{9}$$

and

$$H_{2t} = q_2 E_{2t} X_{2t} + \tilde{q}_2 E_{1t} X_{2t} \tag{10}$$

where $\tilde{q}_1$ and $\tilde{q}_2$ signify the catchability of species 1 as bycatch when fishing for species 2 and the catchability of species 2 as bycatch when fishing for species 1, respectively (Skonhoft, Vestergaard, and Quaas, 2012). Thus, the total harvest of a given species equals the amount of that species caught through deliberate targeting, as in the original harvest function, plus the amount of that species caught as bycatch when targeting another species. These bycatch volumes are the product of the bycatch catchability coefficients, the effort expended (on catching the non-bycatch species), and the stock level of the bycatch species. In our simulations with non-selectivity (Appendix C), we consider cases in which 80 percent of the total catch is the target species (and the remaining 20 percent is bycatch) (80-20) and 60 percent of the catch is the target species (60-40).

We implement the model using Matlab's nonlinear solver (FMINCON). Base parameter values are presented in Table 1.

3. Model Results

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[10] This implicitly assumes that there is not a liquid rental market for fishing capacity, which is reasonable in most real-world settings. Such a market does not exist at all in many fisheries, and, as vessels need a license, it is a complicated and time-consuming process to be allowed to use a new vessel. Another setting where such a constraint has an impact is for "high-grading," which refers to throwing lower-value fish overboard because the hold capacity on each trip is limited (Vestergaard, 1996).

The numerical model developed in Section 2 is used to explain temporal harvest patterns visible in the Norwegian trawl fishery data (Section 4). Our main conceptual results are as follows. First, downward-sloping demand creates incentives to spread out harvest that can counteract incentives to concentrate harvest early in the season due to discounting and stock effects. Second, in a multispecies setting, extending the season for a high-value species can shorten the season for a low-value species when per-period effort is constrained. As a consequence, it is possible that low-value species are caught earlier in the fishing season than the high-value species. Third, although biological aggregation increases incentives to concentrate harvest (by lowering costs), in a multispecies setting harvest levels for some species may see little change or even decrease during the period of aggregation. For a high-value species, the revenue-side gains of spreading harvest can dominate cost-side savings from aggregation, whereas the concentration of a low-value species harvest might induce less harvest of another species in that period due to a constraint on available capacity. Our results are robust to including non-selective harvesting as well as heterogeneity in catching power across vessels.

To provide intuition for our main results, we first present scenarios that vary one assumption at a time using a single species. These results establish a baseline understanding for building more complex modeling assumptions. We then analyze optimal behavior when there are two target species while varying multiple assumptions, defined as combinations of parameter values. Outcomes with three target species and varying multiple assumptions are qualitatively similar to the two-species case and are presented in Appendix B.

3.1 Results with a Single-Species (Figure 1)

We optimize the single-species model for four different scenarios: Scenario 1 - stock effects and endogenous price (inelastic demand, $b_i > 0$); Scenario 2 - stock effects and exogenous price (perfectly elastic demand, $b_i = 0$); Scenario 3 - biological aggregation and endogenous price; and Scenario 4 - biological aggregation and exogenous price. Without loss of generality, we assume aggregation occurs in month 7. In Scenario 1, the optimal strategy is to smooth harvest over the entire year to maintain higher prices. The smoothed harvest path trends downward to reflect discounting and the stock effect, and effort trends upward such that higher harvest costs are delayed. But the smoothing effect driven by product demand dominates the downward trends.[11] By contrast, the optimal strategy is to exhaust all of the quota in the first period when price is exogenous (Scenario 2). There are no incentives to spread out harvest, and both discounting and the stock effect push harvest into the first period.[12] This result is important in showing that IFQs alone are not sufficient for spreading out harvest; rather, IFQs must be coupled with market opportunities or production technologies that make this behavior profitable.[13]

The results in Scenarios 3 and 4 with biological aggregation parallel those of 1 and 2: endogenous price creates incentives to spread out harvest, and exogenous price concentrates harvest at the beginning of the season. Biological aggregation affects these tendencies by introducing cost savings from harvesting during certain months of the year.[14] If the cost reduction due to the biological aggregation is sufficiently strong, there is a moderate increase in

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[11] When stock effects and discounting are removed and the production technology is otherwise constant returns ($\alpha_i = 1$), the harvest and effort paths are completely flat (Supplemental Figure 1).

[12] Removing either discounting or the stock effect leads to the same result as long as the production technology is otherwise constant returns ($\alpha_i = 1$) (Supplemental Figure 2). With decreasing returns ($\alpha_i < 1$), the effort path reflects tradeoffs across concavity of the harvest function, which smooths effort, and discounting and the stock effect, which concentrate effort (Supplemental Figure 3).

[13] This result is corroborated by Wakamatsu and Anderson (2018) in a single-species experimental game setting.

[14] When stock effects and discounting are removed but the production technology is otherwise constant returns ($\alpha_i = 1$), the harvest path is perfectly flat and the effort path still has a dip during biological aggregation (Supplemental Figure 4).

the harvest during this period even with inelastic demand. This effect is also stronger if demand becomes more elastic, but otherwise the qualitative results in this model are not sensitive to parameter values. With exogenous price, effort spikes in the aggregation period (Scenario 4), and all of the quota is taken in this period.[15] Overall, the results in Figure 1 are not surprising, but they provide the intuitive foundation for explaining the more complex multispecies environment below.

3.2 Results with Two Species (Figures 2 and 3)

For all the multispecies fisheries scenarios, we assume that per-period capacity is constrained in the short run (within-season) due to composition of vessels in the existing fleet. As such, it is the capacity constraint (vessels as fixed inputs) that introduces a tradeoff with respect to how to allocate effort. For two-species models, we assume that the price for species 1 is endogenous ($b_1 > 0$), whereas the price for species 2 is exogenous ($b_2 = 0$). Thus, the single-species intuition implies harvest smoothing for species 1 but not necessarily for species 2, ceteris paribus. In addition, we assume that species 2 is less valuable than species 1, and we operationalize this assumption by making $a_1 > a_2$.

We solve the model without (Figure 2) and with (Figure 3) biological aggregation, where we assume biological aggregation occurs for both species in months 6 and 7. In both cases we vary the capacity constraint from a very tight one to a very loose one.[16] We investigate four

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[15] For these parameters, this biological effect on catchability outweighs within-season discounting. Again, this is conditional on having no constraint on per-period effort capacity combined with constant returns to scale technology. Relaxing either of these assumptions induces some smoothing in catch and effort (Supplemental Figure 5).

[16] We choose values for the constraints such that the tightest is an amount of capacity that does not allow the entire quota of the higher-value species to be caught, whereas the loosest is one that allows total quotas for both species to be caught flexibly. Effort can, for example, be interpreted as the number of weeks in a month that the fleet is out fishing.

scenarios—ranging from Scenario 1 with the tightest effort constraint to Scenario 4, in which the effort constraint is loosest—as follows:

1. Tightest effort constraint ($E_{max} = 1$)
2. Moderately tight effort constraint ($E_{max} = 1.5$)
3. Moderate effort constraint ($E_{max} = 3$)
4. Loose effort constraint ($E_{max} = 4$)

When effort is tightest, it is optimal to allocate all effort to the more valuable species because the endogenously determined price of species 1 is still above the exogenous price of species 2 even when all effort is allocated to species 1. Species 1 harvest trends downward as a result of the stock effect. Effort and harvest are zero for species 2 throughout the year. The short-run effort constraint is sufficiently tight that not all of the season's quota is taken for species 1, and none of the quota is taken for species 2.

For moderately tight effort, it is optimal to allocate most effort to the higher-value species during the early periods. This plan ensures that the fishery takes all quota of species 1. Then the residual effort is allocated to species 2. Due to stock effects, discounting, and market incentives to smooth species 1 harvest, harvest trends downward slightly for species 1. Eventually, the opportunity cost of harvesting species 2 (in part due to the stock effect on species 1) grows large enough that it is optimal to stop harvesting species 2 and allocate all effort to species 1 in order to harvest all of the season's quota. As a result, some of the species 2 quota is left unharvested, and empirically we would expect to see periods with landings of both species and other periods with landings of just the high-value species.

For moderate effort, harvest for the endogenously priced species 1 again trends downward, harvest for the exogenously priced species 2 trends downward, all quota of species 1 is taken, and some of species 2 quota is left unfished. Fishing for species 2 does not stop altogether at any point but continues throughout the year. Species 1 effort actually trends upward due to the stock effect; smoothing harvest requires more effort as the season progresses.

When the effort constraint is loose**,** species 1 harvest still trends downward for the same reasons as above, and all quota is taken. Species 2 harvest similarly trends downward, all quota is taken, and fishing stops when the quota is gone. Because of discounting and the stock effect, it is more valuable to catch species 2 early in the season, and there is no countervailing market incentive to smooth harvest. The qualitative pattern is similar to that of Scenario 2 in which harvest of species 2 ceases in the middle of the year, but the reason differs. In Scenario 2, there is not enough effort to continue harvesting species 2 and still catch all of the high-value species 1 quota. Under a loose effort constraint, there is sufficient slack effort to catch all of the species 2 quota early on and still smooth species 1 harvest optimally (and catch all of the species 1 quota). Hence, the same qualitative pattern—the lower value species harvest is completed first— can emerge for two very different reasons, and distinguishing them empirically is tied to whether seasonal quotas bind for both species. The main results from Figure 2 all generalize to the case of non-selective harvesting.[17]

Simultaneous biological aggregation of two species and the same four effort scenarios introduces a new set of tradeoffs (Figure 3). These aggregations produce an incentive to concentrate effort to reduce costs just as in the single-species case, and for the inelastic-demand species there is a trade-off with the incentive to spread harvest for revenue-side benefits.

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[17] To illustrate this, we consider a moderate capacity constraint ($E_{max} = 3$) and both 80-20 gear selectivity and 60-40 gear selectivity (Supplemental Figures 8 and 9).

However, the existence of two target species in the decision forces an interaction between cost savings for the elastic-demand species and revenue creation for the inelastic-demand species.[18]

When per-period effort is tightly constrained, it is optimal to allocate all effort to the more valuable species 1 in non-aggregating periods, but during biological aggregation a small amount of effort is allocated to species 2. Species 1 harvest increases during biological aggregation despite reduced effort and the incentive to smooth harvest from endogenous prices. Even with this relatively tight capacity constraint, all quota of species 1 is taken, but only a part of the quota is taken for species 2.[19]

With moderately tight effort, it is optimal to allocate most but not all effort to the higher-value species 1 in non-aggregation periods. This allocation leads the vessel to take all of its quota for species 1. The residual effort available is allocated to species 2. Species 1 effort as well as harvest dips during the period of biological aggregation, while species 2 effort increases during biological aggregation period. This pattern reflects market conditions in which the vessel wants to dampen its increase in species 1 harvest during the aggregation period to avoid downward pressure on prices. For species 2, that frees up more effort, and there is no price response as a countervailing force to spread effort over time.

For moderate effort, results are similar as with the moderately tight capacity constraint: downward (upward) trend for species 2 (1) effort, and a spike (dip) in effort for species 2 (1). The only qualitative difference is that there is enough effort to take all quota for both species 1 and species 2. This result parallels the result from two species without biological aggregation.

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[18] The results are qualitatively similar when the two species' biological aggregations are offset; the peaks and troughs in harvest patterns follow the biological patterns predictably (Supplemental Figure 6).

[19] Note that with an even tighter effort constraint ($E_{max} = 1$), none of species 2 is taken, not all of species 1 quota is taken, and effort is allocated uniformly to species 1 (Supplemental Figure 7).

When effort is loosely constrained, results are similar to Scenario 3 for species 1: a slight downward trend in harvest except for a decrease in harvest (and dip in effort) during the aggregation period. Results are very different from previous scenarios for species 2. Very little of species 2 is taken during most of the year. Both effort and harvest spike dramatically during the aggregation periods. These spikes cause species 1 effort to dip more and harvest to increase less compared to scenarios with tighter effort constraints. In essence, there is sufficient effort to concentrate harvest of species 2 almost exclusively during the aggregation periods.

In summary, the response of harvest for the valuable species during periods when it is aggregating is non-monotonic in the tightness of the capacity constraint. It depends on how the constraint induces behaviors in other parts of the year as well. In fisheries with coastal fleets that coexist with large-scale trawlers, we might expect to see more seasonality in low-value species harvest for the coastal fleet with moderate effort constraints. Coastal vessels would concentrate effort during periods of biological aggregation but cease to fish afterward to target the more valuable species. But if capacity constraints are sufficiently slack for large-scale trawlers, we might expect more seasonality from these larger vessels.

The results provide important insights for fisheries management. With limited capacity, the less valuable species will not be targeted at all. However, with greater capacity available—whether due to overcapitalization left over from an open-access era, poor management that encourages entry/capital stuffing, or technical change that increases productivity—it is profitable to target species 2. A reduction of the quota for species 1 will produce the same result. Hence, the model reveals conditions under which less valuable species are targeted: increased fishing capacity and improved management for key species. The latter is consistent with recent empirical evidence of spillovers in regional fisheries management (Cunningham, Bennear, and Smith, 2016).[20]

4. Empirical Testing: Norwegian Multispecies Groundfish Trawlers

We analyze seasonal landings patterns in the Norwegian groundfish complex with data from the Norwegian trawl fishery. Groundfish species comprise the most valuable fisheries in Norway (Cojocaru et al., 2019). Although the fleet targeting groundfish harvests a large number of species, cod, haddock, and saithe are the most important in volume and total revenue; thus, we focus our analysis on these three species. All three are part of the global whitefish market that also includes species from other regions such as Alaskan pollock (Gordon and Hannesson, 1996; Asche, Gordon, and Hannesson, 2002). Other groundfish species are primarily demersal, but shrimp, crab, and limited quantities of pelagic species are also caught by the groundfish fleet. Although fishers can target specific species by choosing where and when to fish, catches usually include some bycatch (Asche, 2009). As argued above, the cod market supports modeling downward-sloping demand due to fresh market opportunities, whereas haddock and saithe prices are driven exogenously by the global whitefish market (Asche et al., 2002; Arnason et al., 2004).

Groundfish are managed on a species-by-species basis (Årland and Bjørndal, 2002). A total allowable catch (TAC) is set for the most important species based on advice from the International Council for the Exploration of the Sea (ICES), often in collaboration with other countries. The Norwegian share of the quota for the species with a TAC is then divided among different vessel groups and gear types using a rule known as the “trawl ladder” (Guttormsen and

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[20] The three-species case explored in Figure 4 is discussed in Appendix B. This provides an extension of the intuition for the two-species scenario.

Roll, 2011).[21] Regulations vary within the vessel groups and gear types for the regulated species, while the unregulated species remain open access.

While several vessel groups target groundfish, the cod trawler group is the largest in terms of average landings and vessel dimensions, and the most efficient (Guttormsen and Roll, 2011).[22] These factory trawlers range in length from 27 to 76 meters and receive between 25 and 30 percent of the Norwegian TAC for cod, haddock, and saithe, depending on the size of the TAC, with a smaller share in years with smaller TACs. They can operate in rough weather, have the onboard capacity to produce and freeze fillets, and typically fish approximately 300 days each year.[23] For the three main species, the IFQ system permits a limited degree of transferability (Asche, Bjørndal, and Gordon, 2009). Other species like Greenland halibut and shrimp require a species-specific license and gear, whereas most of the lower-volume species are unregulated.

Using logbook data provided by the Norwegian Directorate of Fisheries for the years 2004-2006, we characterize the harvest patterns for the trawlers by aggregating the landings into monthly data. We first aggregate across vessels, take monthly averages over these three years, and compute the coefficient of variation (CV) over the resulting 12 monthly data points.[24] By quantity, saithe was the most important species, with over 41.5 percent of the landings, followed by cod, which accounts for 29 percent. However, because of substantially higher prices, cod is always the most valuable species. Average prices are 13.68 NOK/kg for cod, 9.21 NOK/kg for

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[21] The "trawl ladder" is a quota allocation instrument used in Norwegian fisheries that is based on historical rights. In an effort to keep the coastal fleet's yearly catches stable, they are granted a larger part of the fishing quota in years with relatively moderate biomass. By comparison, the larger vessels such as trawlers have more fluctuating quota quantities.

[22] Norwegian groundfish are targeted by a heterogeneous fleet broadly divided into coastal vessels, longliners, and trawlers.

[23] Larsen and Dreyer (2012) indicate that under 20 percent of the total cod catch from trawlers is landed fresh. Almost all Norwegian-caught cod, regardless of product form, is exported.

[24] The aggregate landings for the trawler fleet and the computed within-season variation are presented in Supplemental Table 1.

haddock, and 5.62 NOK/kg for saithe, so cod revenues are 67 percent higher than saithe revenues. The three IFQ species together make up 83 percent of the harvest landed by this fleet. Shrimp is the fourth most important species with an 8 percent share, and redfish makes up almost 5 percent of the landings. The remaining species contribute modest quantities and are mostly bycatch. The CVs for cod and haddock suggest that the fleet overall spreads out landings of cod and haddock quite evenly. By contrast, the saithe CV is much higher, suggesting landings that are highly concentrated in time.[25] Overall, for cod—the high-value IFQ species with potential for market segmentation—harvest follows a relatively uniform pattern across the season, though not perfectly. Haddock—the intermediate-valued IFQ species—follows a harvest pattern similar to cod but peaking at different times and slightly less uniform overall. Saithe—the low-value IFQ species with little potential for market segmentation—follows a strong seasonal harvest pattern.

We now exploit the panel structure of our data to test our theoretical predictions formally. Although our conceptual model generates many hypotheses about within-season behavior, we focus on three that are essential features of multispecies fisheries and that can be tested in our empirical setting.

Proposition 1: Landings of the highest-value species will be the most evenly spread out over the season. This proposition follows directly from the numerical results in Figures 1 and 2. The rationale for spreading harvest is that the cod market is segmented and price will respond to landing volumes (Asche et al., 2002; Arnason et al., 2004), whereas this segmentation does not appear to exist for haddock and saithe.[26]

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[25] Supplemental Figure 13 shows average landings per month for the three sample years, focusing on the three IFQ species and normalizing each year to the average monthly landings in the year.

[26] Although there is not a comparable analysis for Norway, Lee (2014) demonstrates that U.S. cod prices are responsive to quantity landed at a daily time step, and Gordon and Hannesson (1996) establish links between the U.S. and European cod markets. As such, it is reasonable to assume that the Norwegian cod prices are responsive to quantity landed at the monthly scale.

We follow Birkenbach, Kaczan, and Smith (2017) and model the concentration of the landings with a Gini coefficient. Indexing species by s, vessel by i, year by t, and denoting the Gini coefficient as G, the empirical specification is:

$$G_{s,i,t} = \delta_{i,t} + \beta_0 + \beta_1 HADDOCK + \beta_2 SAITHE \qquad (11)$$

where the δs are vessel-year fixed effects and the constant, β_0, is the excluded category, cod. If the landings of cod are spread out relative to haddock (and/or saithe), then $\beta_1 > 0$ (and/or $\beta_2 > 0$).

Across specifications using different sets of fixed effects, we find strong evidence in support of this proposition (Table 2). Because cod is the base category, the positive and significant coefficients on haddock and saithe in all three models indicate that these seasons are less spread out. The results are most precisely estimated in the most general model (Model 3) that includes vessel and year interactions, i.e., separate vessel fixed effects for each year. Also, haddock and saithe are not statistically different from each other in any of the models, suggesting that the spreading out effect is specific to cod.

Proposition 2: In a multispecies IFQ fishery, species can be landed in reverse order of value. Basic dynamic intuition implies that with fixed prices (and no mediating effects of aggregation), any positive discount rate would lead to sequencing harvests in order of value: fishers would take the high-value species first, followed by the medium-value, and then the low-value. However, when the market creates incentives to spread the catch of the high-value (endogenously-determined price) species, it is possible that the order would reverse. This proposition follows directly from the numerical results in Figures 1 and 2.

We examine this proposition using two metrics: months to reach 80 percent of the vessel's annual landings for the species (M^{80}) and months to reach 90 percent of the vessel's annual landings for the species (M^{90}). We use the same empirical model with both metrics:

$$M_{s,i,t}^{80} = \delta_{i,t} + \beta_0 + \beta_1 HADDOCK + \beta_2 SAITHE \quad (12)$$

If haddock (and/or saithe) is landed faster than cod, then $\beta_1 < 0$ (and/or $\beta_2 < 0$). We run these models both in linear form and using a proportional Cox duration model. The results strongly support the hypothesis: saithe is landed first, followed by haddock, and then cod (Table 3). Although the model is similar to the Gini model above testing for spread of the catch, the results are different in that there is a statistically significant difference between saithe and haddock.[27] Specifically, the negative and significant coefficients for saithe and haddock in the OLS models indicate that 80 percent and 90 percent of annual total landings for these species occur before the 80 percent and 90 percent thresholds of cod landings are reached. This means that the lower-value species are landed before the higher-valued species. Moreover, the larger-magnitude coefficients on saithe are statistically different from those on haddock, implying that saithe is landed before haddock. Taken together, these results imply that the species are landed in reverse order of value. The Proportional Cox models reach the same conclusions. Because Cox models are hazard models, the coefficient interpretations are relative to one such that coefficients greater than one imply landing the species earlier in the season.

Proposition 3: Biological aggregation increases landings for the low-value species, has little effect on high-value species landings, and decreases landings of the intermediate-value species. This proposition follows directly from numerical results in Figure 3. Biological cycles such as spawning can trigger stock aggregation, as in the Lofoten cod fishery (Hannesson, Salvanes, and Squires, 2010; Kvamsdal, 2016). In the single-species setting, aggregation reduces costs and increases incentives to concentrate landings in this period. However, with multiple species aggregating at the same time—as is the case with cod, haddock, and saithe (Bergstad,

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[27] To illustrate the differences across species, we also plot the hazard rates (Supplemental Figure 14).

Jørgensen, and Dragesund, 1987)—concentrating more effort on one species during aggregation means concentrating less effort on others (Figures 3 and 4). Because there is a strong incentive to spread out cod harvest, cod harvest will be relatively unaffected; however, increasing saithe harvest during the aggregation period will translate into a reduction in haddock harvest, especially if haddock has more price responsiveness than saithe. Denoting landings as Y and indexing month as m, our empirical Ordinary Least Squares (OLS) regression specification is:

$$Y_{s,i,m,t} = \delta_{i,t} + \gamma_{s,t} + \beta_0 + \beta_1 SPAWN + \beta_2 HADDOCK * SPAWN + \beta_3 SAITHE * SPAWN \quad (13)$$

where $\gamma_{s,t}$ captures species-year fixed effects and *SPAWN* is an indicator set to one for each month of the spawning season (February through April for all species). If $\beta_2 > 0$, then landings of haddock increase in response to the spawning season, and similarly for β_3 and saithe. The results (Table 4) strongly support Proposition 3: landings of saithe (low-value species) increase significantly in the spawning period ($\beta_3 =$ 65,246.28), whereas landings of haddock (medium-value species) decrease significantly ($\beta_2 =$ -35,974.13). When we run the model on the three species individually with vessel-year fixed effects, we see a non-significant coefficient on *SPAWN* for cod, a negative and significant coefficient for haddock, and a strongly positive coefficient for saithe (Table 4).

Overall, our empirical results directly support the key findings of our numerical model. Moreover, these results would be difficult (or impossible) to explain using a single-species dynamic bioeconomic model, market analysis, or production economics alone. Only by modeling multispecies production tradeoffs in a dynamic setting that accounts for market responsiveness do we intuitively account for patterns that would otherwise be surprising.

5. Extending the Multispecies Theory: Transitions to Individual Fishing Quotas

Our model and empirical work suggest possible explanations for a puzzle that emerged in Birkenbach, Kaczan, and Smith (2017), namely that the season does not expand for all species after implementing rights-based management. The seasons for some species actually contract significantly following the introduction of IFQs; for example, after IFQs took effect, the season for the New England cod fishery extended, but the corresponding season for New England haddock contracted (Birkenbach, Kaczan, and Smith, 2017). Single-species theory of IFQs and associated market incentives predicts the average effect but cannot account for these mixed results (Homans and Wilen, 2005). By modeling the period prior to allocating IFQs as one in which harvesters make sequentially myopic decisions, the mechanisms in the same model developed above can account for the possibility that some fisheries experience season compression while others experience decompression. Under sequentially myopic behavior, harvesters allocate effort to the highest-value species. This can involve allocating effort to multiple species based on the concavity of the production function and market incentives, but by construction agents are not forward-looking. Once the industry-wide quota for a species is exhausted, that species drops out of the choice set.

We consider a two-species fishery that transitions to IFQs from regulated restricted access (RRA).[28] In Figure 5, species 1 is a fishery facing downward-sloping demand and whose price in a given time period is therefore endogenous to the quantity harvested in that period, whereas species 2 is modeled as a fishery facing perfectly elastic demand. Under RRA, participants optimize period by period—mimicking racing incentives or the threat of season closures when an industry-wide cap is reached—leading them to concentrate more fishing

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[28] The topic of how incentives to target and associated behaviors change under institutional change in fisheries is of growing interest and has many complications (Abbott, Haynie, and Reimer, 2015; Reimer, Abbott, and Haynie, 2017). Our intention here is to illustrate how simple mechanisms in our model offer some possibilities for what to expect in multispecies fisheries.

activity in the early part of the season because of discounting and stock effects (top panel). Harvesters first focus on the higher-value species 1, balancing the racing incentives with the higher price achieved by spreading the season. Slack effort is filled in with harvest of species 2 until month 10, when the TAC of species 1 is exhausted and vessels switch to intensively harvesting species 2. Both species' TACs are reached by month 11, and the seasons end prematurely (the classic "race to fish" result). Under IFQs, by contrast, the quota may be fished at any point throughout the season without risk of closures. As expected when optimizing over all periods at once, vessels maximize profits by spreading out catch of species 1, leading to lower quantities on the market in each period and therefore higher prices due to the downward-sloping demand schedule. Species 2, on the other hand, fetches the same price regardless of quantity, so fishers have no incentive to spread out catch and exhaust the entire quota for species 2 early in the season (a reflection of discounting). Following the transition to IFQs, the Gini coefficient for species 1 falls (indicating a more spread-out season), while the Gini coefficient for species 2 actually increases. This occurs because, as the season for species 1 becomes less rushed, fishing capacity is freed up early in the season such that more effort can be devoted to fishing more intensively for species 2. This result is consistent with the findings in Birkenbach, Kaczan, and Smith (2017)—that that higher-value species with viable fresh markets achieve increases in season length post-catch shares—and also helps to account for the puzzling counterexamples in which seasons for lower-value species in multispecies contexts significantly contracted.

6. Discussion

The single-species results from our model are simple and intuitive. Discounting and stock effects create incentives to harvest more of the TAC early in the season; endogenous price encourages spreading the harvest more uniformly over the season; biological aggregations create incentives to concentrate harvest due to lower harvest cost; and effort constraints generally spread out the harvest. These results are consistent with existing literature on within-season harvest in catch share fisheries (Boyce, 1992; Valcu and Weninger, 2013). Still, it is worthwhile to emphasize how much harvest patterns can vary depending on market conditions, stock characteristics, and harvesting capacity even in this simple setting.

The basic intuition about fishing behavior rooted in single-species bioeconomic models breaks down when there are multiple target species. In essence, shadow values on fishing constraints in the single-species case can be viewed as representing a partial equilibrium, but the true shadow values are revealed in the general equilibrium that considers all of the feedbacks across species. Effort devoted to one species changes the opportunity cost of effort devoted to another, and these relationships are fully dynamic and bioeconomic. Moreover, feedbacks exist even in the absence of ecological interdependence, a feature that would add further complications to the modeling. Our detailed predictions from multispecies models are reconcilable with economic intuition based on the single-species case, but predicted multispecies harvest and effort patterns within the season are not immediately intuitive without the supporting bioeconomic model. For example, it is not obvious why a fleet would take all of the quota for a low-value species before landing all of the quota for a high-value species. The model shows that this can occur due to market conditions, biological aggregations, and capacity constraints, and we find empirical support in the Norwegian groundfish data for the first two causes, with potential implications for the third.

The Norwegian groundfish IFQ fisheries provide evidence for our main conceptual findings. Harvests of the high-value IFQ species (cod) with fresh markets and corresponding inelastic demand are more spread out than the lower-value saithe and haddock. This finding is consistent with leveraging market timing to avoid gluts. We also find evidence that the species are landed in reverse order of value as our numerical model predicts. The specific conditions for this to occur that are necessary in the two-species model are enough effort to harvest all quota of both species, exogenous price for the low-value species and endogenous price for the high-value species. Cod and saithe fit this explanation well. Our empirical results show that haddock (the intermediate-value species) is landed second in the order of three. We also find in our numerical model that biological aggregation provides complicated incentives in multispecies fisheries when one species faces downward-sloping demand and the other does not. The cost-saving incentive to aggregate is unmediated by revenue-side considerations for the low-value species with perfectly elastic demand. But adapting behavior to this incentive can reduce effort devoted to the high-value species during the same period. We find this effect empirically. Relative to cod, more fishing takes place for saithe during aggregation, but this ultimately affects haddock, and haddock harvest actually decreases during aggregation. In essence, the fleet had to reduce harvest of something to focus on saithe during aggregation, and it was most profitable to maintain cod harvest and reduce haddock. The possibility of a high-value cod roe market during spawning, which we do not model, could also contribute to this result.

An important policy implication of our findings is that management of one species can affect the harvest patterns of other target species. If there is slack effort overall, the ability to time the harvest to the market or biological conditions may increase exploitation for other targets (e.g., taking all of the quota rather than just some of it). This result is consistent with findings of spillovers from tightly regulated species to unregulated or less tightly regulated species (Asche, Gordon, and Jensen, 2007; Hutsniczak, 2014; Cunningham, Bennear, and Smith, 2016), although our model shows this can happen even when all species have IFQs.

The combination of constrained harvest capacity, species targeting, and effort timing raises interesting management questions. Low-valued species are generally harvested only when available effort is sufficiently high, although stock aggregations can reduce harvest costs and make low-value fish attractive to target such that they are taken before high-value fish. We know that poor management policies can contribute to overcapacity in fisheries despite successful biological control with TACs (Homans and Wilen, 1997). Our results suggest that even when vessel quotas are introduced into such a system, as long as excess capacity is not immediately removed, the fleet may continue to target species that may not otherwise have been optimal to exploit. Fixed costs of entry incurred under an open access regime become sunk costs, yet available evidence indicates that capacity reduction after individual vessel quotas are introduced takes time (Grafton, Squires, and Fox, 2000; Asche, Bjørndal, and Bjørndal, 2014). Moreover, Kroetz, Sanchirico, and Lew (2015) show that restrictions on individual quota trading lead to a fleet composition that squanders some rents. Our results suggest that, depending on cost structure, a key attribute of fleet composition, namely aggregate capacity, can influence how many species are targeted and how much fish ultimately is caught. This implication raises questions of whether legacies of previous management systems cause multispecies fisheries to harvest more species than is optimal and the extent to which particular mixes of fisheries and levels of specialization are artifacts of this history.

The non-intuitive patterns that our model and empirical results reveal are also consistent with sequencing resource stocks in non-renewable resource economics. The conventional wisdom is that, given multiple deposits of the same resource, those with the lowest extraction costs will be depleted first (Herfindahl, 1967; Solow and Wan, 1976; Lewis, 1982). This intuition dates back to Ricardo's theory of the mine. However, in a two-resource, two-demand case comparable to a multispecies fishery, simultaneous extraction can be optimal over some interval of time (Chakravorty and Krulce, 1994). For instance, although oil and coal both generate electricity, oil is more readily used to power vehicles and thus faces additional demand from the transportation sector. Hence, the optimal sequencing of exploitation across these two assets is driven by revenue- as well as cost-side differences between them. The order of extraction of multiple resource deposits may even be reversed from the intuitive Ricardian pattern such that lower-value resources are used first (Amigues et al., 1998).

We close with some suggestions for future research. Our conceptual analysis presumes that the species relevant to the decision problem are all managed with IFQs that are non-tradable within the season.[29] While this setup describes the Norwegian system accurately, extending the model to allow for trading and vessel heterogeneity could generate more insights. Moreover, when some fisheries are regulated without IFQs, commons issues can further complicate the fisher's decision environment. The IFQ program in Norway captures much of the groundfish complex but not all of it. Some species are regulated with industry-wide quotas such that they are regulated open access. Others have no restrictions at all and are effectively pure open access. Thus, the general equilibrium for shadow values of effort also includes species not managed with IFQs, and harvest patterns for IFQ species could be influenced by incentives for species outside of the management regime. Further extending our model to allow for IFQ fisheries that

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[29] Alternatively, one can think of this conceptual model as one in which quota is tradable but already efficiently allocated—that is, one in which a market equilibrium has been achieved following a period of trading.

contemporaneously exist with fisheries that have racing incentives is an important topic for future research.

References

Abbott, J.K., A.C. Haynie, and M.N. Reimer. 2015. Hidden flexibility: institutions, incentives, and the margins of selectivity in fishing. *Land Economics,* 91(1):169-195.

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

Amigues, J.P., Favard, P., Gaudet, G. and Moreaux, M. 1998. On the optimal order of natural resource use when the capacity of the inexhaustible substitute is limited. *Journal of Economic Theory*, *80*(1), pp.153-170.

Årland, K. and T. Bjørndal (2002). Fisheries Management in Norway. *Marine Policy* 26:307-313.

Arnason, R., L.K. Sandal, S.I. Steinshamn, and N. Vestergaard. 2004. Optimal Feedback Controls: Comparative Evaluation of the Cod Fisheries in Denmark, Iceland, and Norway. *American Journal of Agricultural Economics* 86(2):531-542.

Asche, F., O. Flaaten, J.R. Isaksen, J. R., and T. Vassdal. 2002. Derived Demand and Relationships between Prices at Different Levels in the Value Chain: A Note. *Journal of Agricultural Economics* 53(1):101-107.

Asche, F. 2009. Adjustment Cost and Supply Response: A Dynamic Revenue Function. *Land Economics* 85(1):201-215.

Asche, F., M. T. Bjøndal and T. Bjørndal. 2014. Development in Fleet Fishing Capacity in Rights Based Fisheries. *Marine Policy*. 44:166-171.

Asche F., T. Bjørndal and D.V. Gordon. 2009. Resource Rent in Individual Quota Fisheries. *Land Economics* 85(2):279-91.

Asche F., D.V. Gordon, and R. Hannesson. 2002. Searching for Price Parity in the European Whitefish Market. *Applied Economics* 34(8):1017-1024.

Asche F., D.V. Gordon, and C.L. Jensen. 2007. Individual vessel quotas and increased fishing pressure on unregulated species. *Land Economics* 83:41-49.

Asche, F., and D. Zhang. 2013. Testing Structural Changes in the U.S. Whitefish Import Market: An Inverse Demand System Approach. *Agricultural and Resource Economics Review* 42(3):453-470

Bergstad O.A., T. Jørgensen, and O. Drangesund. 1987. Life history and ecology of the gadoid resources of the Barents Sea. *Fisheries Research* 5:119-161.

Birkenbach, A.M., D. Kaczan, and M.D. Smith. 2017. Catch Shares Slow the Race to Fish. *Nature* 544(7649):223-226.

Boyce, J.R. 1992. Individual Transferable Quotas and Production Externalities in a Fishery. *Natural Resource Modeling* 6(4):385-408.

Chakravorty, U. and Krulce, D.L. 1994. Heterogeneous Demand and Order of Resource Extraction. *Econometrica*, 62(6):1445-1452.

Clark, C. W. 1980. Towards a predictive model for the economic regulation of commercial fisheries. *Canadian Journal of Fisheries and Aquatic Sciences*, *37*(7):1111-1129.

Cojocaru, A., F. Asche, R.B. Pincinato, and H-M. Straume. 2019. Where Are the Fish Landed? An Analysis of Landing Plants in Norway. *Land Economics*. 95(2), 246-257.

Cunningham, S., L.S. Bennear, and M.D. Smith. 2016. Spillovers in regional fisheries management: do catch shares cause leakage? *Land Economics* 92(2):344-262.

Das, C. 2013. Northeast Trip Cost Data – Overview, Estimation, and Predictions. NOAA Technical Memorandum NMFS-NE-227. Accessed on 08.15.2019 at https://www.nefsc.noaa.gov/publications/tm/tm227/tm227.pdf

Eggert H and R. Tveteras. 2004. Stochastic production and heterogeneous risk preferences: Commercial fishers' gear choices. *American Journal of Agricultural Economics* 86:199-212.

Fell, H. 2009. Ex-vessel pricing and IFQs: a strategic approach. *Marine Resource Economics* 24(4):311-328.

Gordon, D.V. and R. Hannesson. 1996. On Prices of Fresh and Frozen Cod. *Marine Resource Economics* 11:223-238.

Grafton, R. Q., Squires, D., and K.J. Fox. 2000. Private Property and Economic Efficiency: A Study of a Common-Pool Resource. *The Journal of Law and Economics 43*(2):679-714.

Guttormsen, A.G. and K.H. Roll. 2011. Technical Efficiency in a Heterogeneous Fishery. *Marine Resource Economics* 26(4):293-308.

Hammarlund, C. 2015. The Big, the Bad, and the Average: Hedonic Prices and Inverse Demand for Baltic Cod. *Marine Resource Economics* 30(2):157-177

Hannesson, R., K.G. Salvanes, and D. Squires. 2010. Technological change and the Tragedy of the Commons: The Lofoten fishery over 130 years. *Land Economics* 86(4):746-765.

Haynie, A.C. and D.F. Layton. 2010. An expected profit model for monetizing fishing location choices. *Journal of Environmental Economics and Management* 59:165-176.

Herfindahl, O. C. 1967. Depletion and economic theory. *Extractive resources and taxation* 63-90.

Hicks, R.L. and K.E. Schnier. 2008. Eco-labeling and dolphin avoidance: A dynamic model of tuna fishing in the Eastern Tropical Pacific. *Journal of Environmental Economics and Management* 56:103-116.

Holland, D. and J.G. Sutinen. 2000. Location Choice in the New England trawl fisheries: old habits die hard. *Land Economics* 76:133-149.

Homans, F.R. and J.E. Wilen. 1997. A Model of Regulated Open Access Resource Use. *Journal of Environmental Economics and Management* 32:1-21.

Homans, F.R. and J.E. Wilen. 2005. Markets and Rent Dissipation in Regulated Open Access Fisheries. *Journal of Environmental Economics and Management* 49:381-404.

Huang, L. and M.D. Smith. 2014. The Dynamic Efficiency Costs of Common-pool Resource Exploitation. *The American Economic Review* 104(12):4071-4103.

Hutniczak, B. 2014. Increasing pressure on unregulated species due to changes in Individual Vessel Quotas: an empirical application to trawler fishing in the Baltic Sea. *Marine Resource Economics* 29(3):201-217.

Kroetz, K., J.N. Sanchirico, and D.K. Lew. 2015. Efficiency costs of social objectives in tradable permit programs. *Journal of the Association of Environmental and Resource Economists* 2(3):339-366.

Kvamsdal, S.F. 2016. Technical Change as a Stochastic Trend in a Fisheries Model. *Marine Resource Economics* 31(4):403-419.

Larkin, S.L. and G. Sylvia. 1999. Intrinsic Fish Characteristics and Intraseason Production Efficiency: A Management-Level Bioeconomic Analysis of a Commercial Fishery. *American Journal of Agricultural Economics* 81:29-43.

Larsen, T. A., and Dreyer, B. 2012. Norske torsketrålere - Struktur og lønnsomhet (from Norwegian: Norwegian cod trawlers – fleet structure and profitability). *Nofima Report*. Retrieved from http://www.nofima.no/filearchive/Rapport 12-2012.pdf

Lee, Min-Yang. 2014. "Hedonic pricing of Atlantic cod: Effects of size, freshness, and gear." *Marine Resource Economics* 29(3): 259-277.

Lee, M.-Y., and E.M. Thunberg. 2013. “An Inverse Demand System for New England Groundfish: Welfare Analysis of the Transition to Catch Share Management.” *American Journal of Agricultural Economics* 95(5):1178-1195.

Lewis, T.R. 1982. Sufficient Conditions for Extracting Least Cost Resource First. *Econometrica* 50:1081-1083.

NOU 2016: 26. 2016. Et Fremtidsrettet Kvotesystem (from Norwegian: A quota system for the future). *Ministry of Trade, Industry and Fisheries.*

NSC. 2018. How Effectively Does the Norwegian Seafood Council Promote Norwegian Whitefish Exports. *Research Report to the Norwegian Seafood Council*, June 2018, Tromsø, Norway.

Reed, W.J. 1979. Optimal escapement levels in stochastic and deterministic harvesting models. *Journal of Environmental Economics and Management* 6(4):50-363.

Reimer, M.N., J.K. Abbott, and A.C. Haynie. 2017. Empirical Models of Fisheries Production: Conflating Technology with Incentives? *Marine Resource Economics* 32(2):169-190.

Scheld, A. M. and C.M. Anderson. 2014. Market effects of catch share management: the case of New England multispecies groundfish. *ICES Journal of Marine Science* 71(7):1835-1845.

Shumway, C.R., R.D. Pope, and E.K. Nash. 1984. Allocatable Fixed Inputs and Jointness in Agricultural Production: Implications for Economic Modeling. *American Journal of Agricultural Economics* 66(February):72-78

Singh, K., M.M. Dey, and P. Surathkal. 2012. Analysis of a Demand System for Unbreaded Frozen Seafood in the United States Using Store-Level Scanner Data. *Marine Resource Economics* 27(4):371-387.

Skonhoft, A., N. Vestergaard, and M. Quaas. 2012. Optimal Harvest in an Age Structured Model with Different Fishing Selectivity. *Environmental and Resource Economics* 51:525-544.

Smith, M.D. 2005. State Dependence and Heterogeneity in Fishing Location Choice. *Journal of Environmental Economics and Management* 50:319-340.

Smith, M.D. 2012. The New Fisheries Economics: Incentives Across Many Margins. *Annual Review of Resource Economics* 4:379-402.

Smith, M.D. and J.E. Wilen. 2005. Heterogeneous and correlated risk preferences in commercial fishermen: The perfect storm dilemma. *Journal of Risk and Uncertainty* 31:53-71.

Smith, M.D., J. Zhang, and F.C. Coleman. 2008. Econometric modeling of fisheries with complex life histories: Avoiding biological management failures. *Journal of Environmental Economics and Management* 55:265-280.

Smith, V.L. 1969. On Models of Commercial Fishing. *Journal of Political Economy* 77:181-198.

Solow, R.M. and Wan, F.Y., 1976. Extraction costs in the theory of exhaustible resources. *The Bell Journal of Economics*, pp.359-370.

Squires, D. 1987. Long-Run Profit Functions for Multiproduct Firms. *American Journal of Agricultural Economics* 69:558-569.

Squires, D. and J.E. Kirkley. 1991. Production Quota in Multiproduct Pacific Fisheries. *Journal of Environmental Economics and Management* 21:109-126.

SSB. Statistics Norway. https://www.ssb.no/en/fiskeri. Accessed 07.18.2019

Stafford, T. 2018. Accounting for Outside Options in Discrete Choice Models: An Application to Commercial Fishing Effort. *Journal of Environmental Economics and Management* 88:159-179.

Valcu, A. and Q. Weninger. 2013. Markov-Perfect rent dissipation in rights-based fisheries. *Marine Resource Economics* 28(2):111-131.

Vestergaard, N. 1996. Discard behavior, highgrading and regulation: the case of the Greenland shrimp fishery. *Marine Resource Economics* 11(4):247-266.

Wakamatsu, M., and Anderson C. M. 2018. "The Endogenous Evolution of Common Property Management Systems." *Ecological Economics* 154:211-217.

Weninger, Q. and J.R. Waters. 2003. Economic Benefits of Management Reform in the Northern Gulf of Mexico Reef Fish Fishery. *Journal of Environmental Economics and Management* 46:207-230.

Zhang, J. 2011. Behavioral response to stock abundance in exploiting common-pool resources. *The BE Journal of Economic Analysis & Policy* 11(1).

Zhang J. and M.D. Smith. 2011. Heterogeneous Response to Marine Reserve Formation: A Sorting Model approach. *Environmental & Resource Economics* 49:311-325.

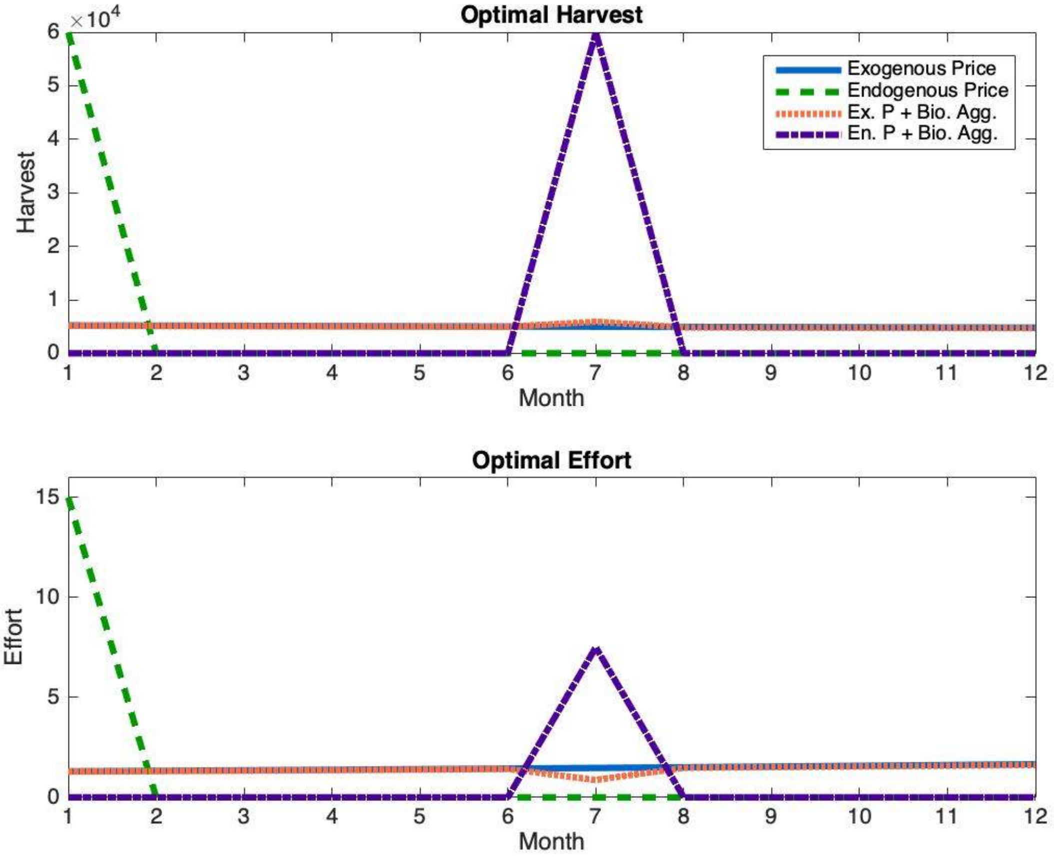

Figure 1. Seasonal Harvest (Top) and Effort (Bottom) Pattern in a Single-Species Fishery.

Scenarios include stock effects and endogenous price (1), stock effects and exogenous price (2), biological aggregation and endogenous price (3), and biological aggregation (month 7) and exogenous price (4).

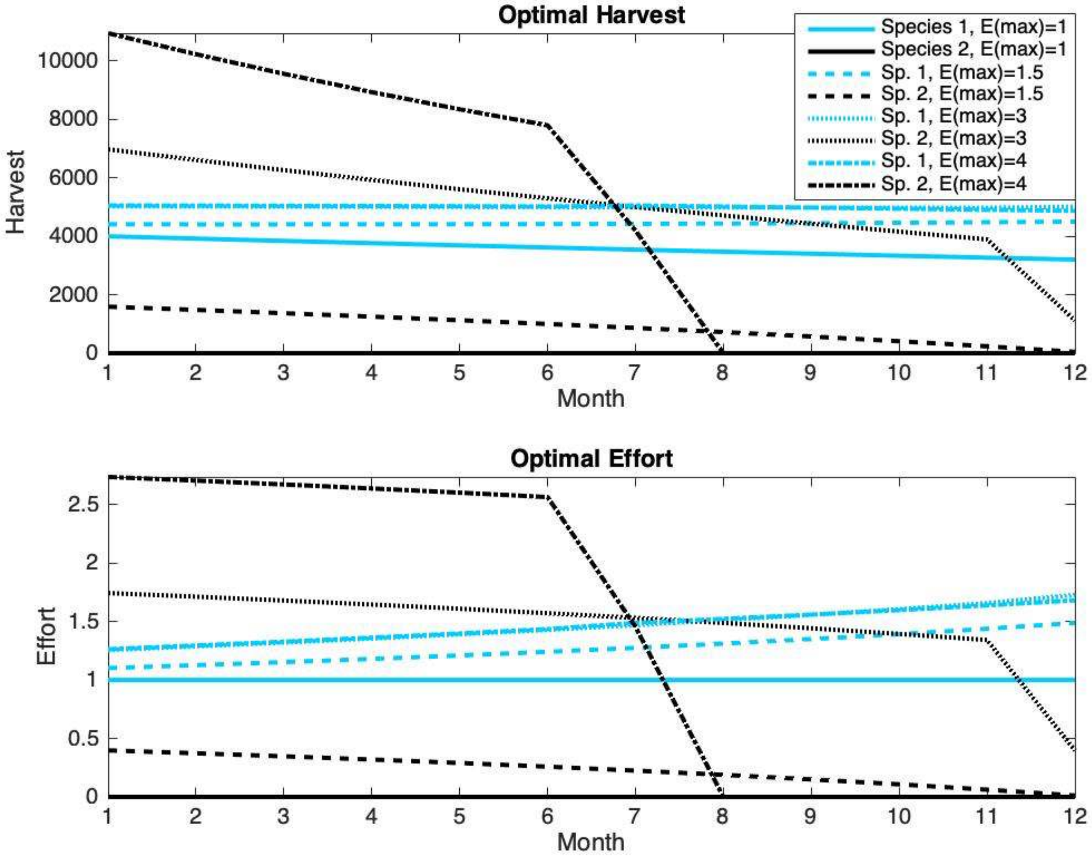

Figure 2. Two-Species Harvest (top) and Effort (Bottom) Paths without Biological Aggregation. Scenarios 1 through 4 reflect the tightest through loosest per-period effort/capacity constraints. Species 1 faces downward-sloping demand, whereas species 2 has perfectly elastic demand. The scenarios for both sets of results include capacity constraints: 1) Tightest (E_{max} = 1); 2) Moderately tight (E_{max} = 1.5); 3) Moderate (E_{max} = 3); and 4) Loose (E_{max} = 4).

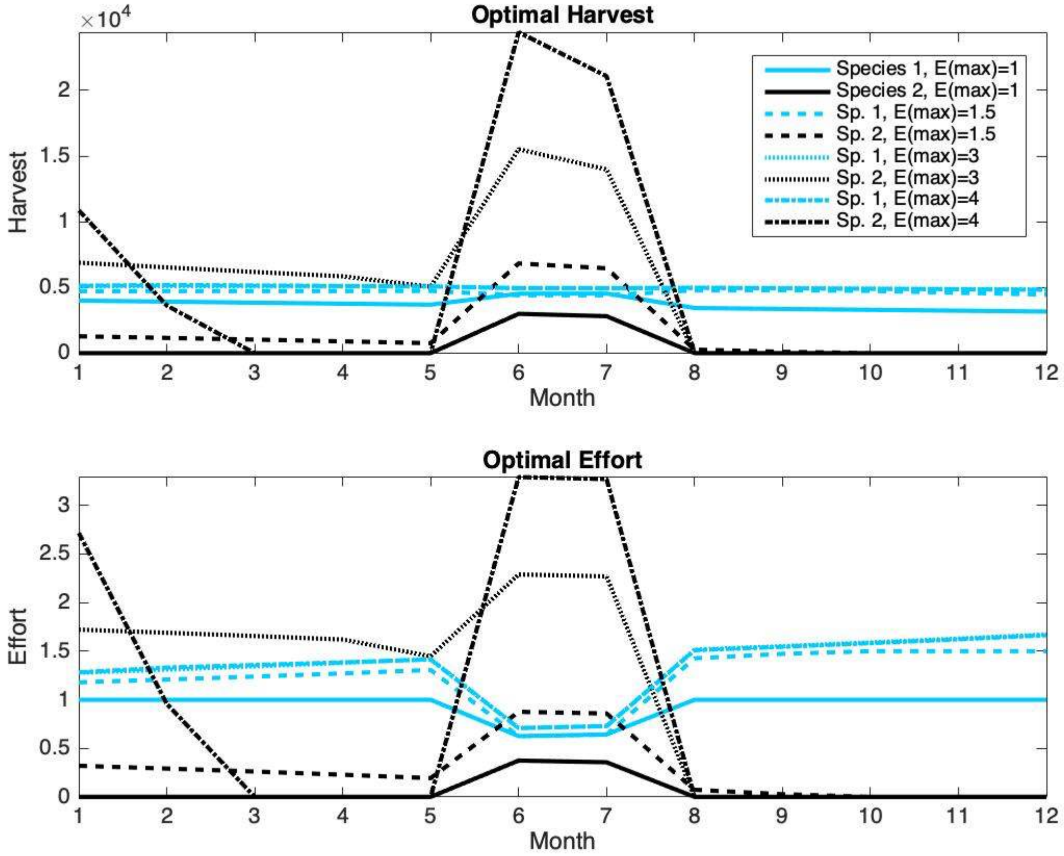

Figure 3. Two-Species Harvest (top) and Effort (Bottom) Paths with Biological Aggregation in Months 6 and 7 for Both Species. The scenarios include capacity constraints: 1) Tightest effort constraint ($E_{max} = 1$); 2) Moderately tight effort constraint ($E_{max} = 1.5$); 3) Moderate effort constraint ($E_{max} = 3$); and 4) Loose effort constraint ($E_{max} = 4$).

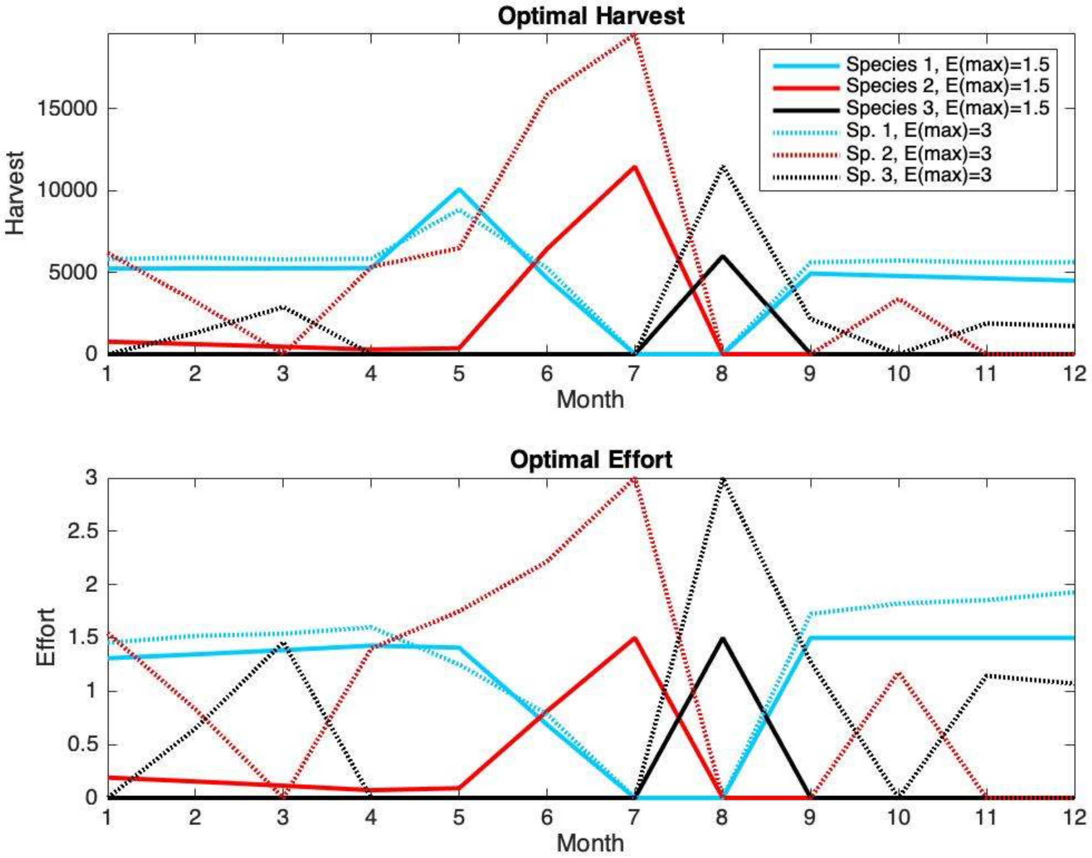

Figure 4. Three-Species Harvest (Top) and Effort (Bottom) Paths with Biological Aggregation for Species 1 (Months 5 and 6), Species 2 (Months 6 and 7), and Species 3 (Months 7 and 8). The capacity constraint scenarios are: 1) Tightest ($E_{max} = 1$); 2) Moderately tight ($E_{max} = 1.5$); 3) Moderate ($E_{max} = 3$); 4) Somewhat loose ($E_{max} = 3.5$); and 5) Loosest – no effort constraint. The figure depicts just Scenarios 2 and 3.

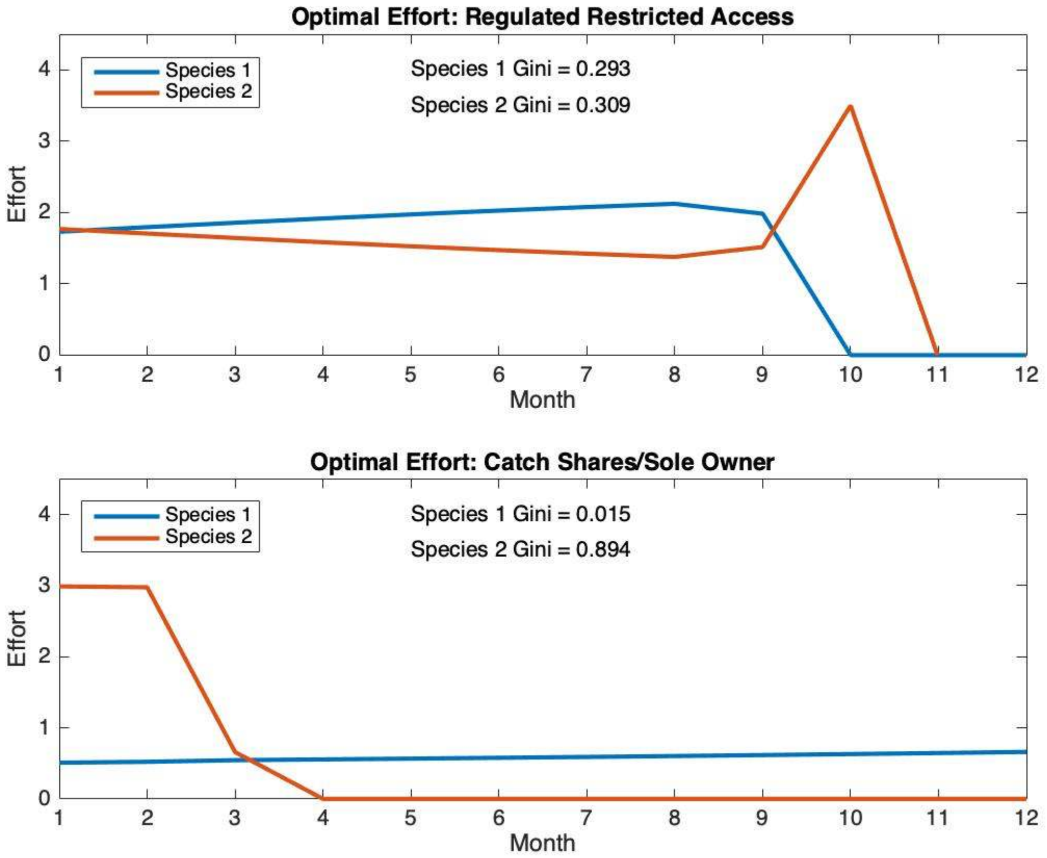

Figure 5. Two-Species Effort Paths Before (Top) and After (Bottom) IFQs. Species 1 faces downward-sloping demand, and species 2 faces perfectly elastic demand (constant price).

Table 1. Base Parameter Values Used in Numerical Simulations.

Parameter values were chosen based on the Norwegian trawl fishery to illustrate tradeoffs across revenue and cost dimensions in multispecies IFQ fisheries.

Parameter	Value	Description	Motivation	Reference
a_1	21,500	Choke price species 1	Maximum price (NOK) for a tonne of cod – based on Norwegian trawl fishery data	NSC (2018)
b	0.65	Slope of the demand curve species 1*	Demand slopes for similar whitefish species are reported in the range of 0.4 to 0.7. Note that reported price elasticities for cod of various origins range from 0.21 to 1.17.	Lee & Thunberg (2013); Hammarlund (2015) Asche et al. (2002); Singh et al. (2012); Asche & Zhang (2013)
a_2	12,500	Choke price species 2	Max price (NOK) per tonne of saithe – based on Norwegian trawl fishery data	
a_3	17,500	Choke price species 3	Max price (NOK) per tonne of haddock – based on Norwegian trawl fishery data	
c	9,000,000	Cost of effort**	Minimal weekly cost of operating the Norwegian cod trawling fleet – given 45 vessels in the fleet and an average crew size of 17 (similar to Norwegian data), provided an average Norwegian salary	SSB
δ	0.05	Annual discount rate		
H_{max}	60,000	Total allowable catch+	Estimate of assigned quota (tonnes) for Northeast Arctic Cod based on Norwegian	SSB; NOU 2016: 26 (2016)

			data and documentation for cod trawlers	
X_0	200,000	Initial stock level[+]	Estimate of stock biomass (tonnes) for Northeast Arctic Cod for period 2004-2006, in non-coastal region	SSB; NOU 2016: 26 (2016)
α	1	Effort elasticity	Schaefer model	
β	1	Stock elasticity	Schaefer model	
q	0.02	Catchability coefficient (non-aggregating)	Slack parameter	N/A
q_a	0.04	Catchability coefficient (during aggregation)	Slack parameter	N/A

[*] We tested an array of demand slopes, in the range of 0.4 to 0.9, without a significant effect on presented results and intuition.

[**] This is minimal cost, given that fuel expenses have been found to account for almost 80 percent of trip costs in New England cod fisheries (Das, 2013 – Table 7). Even with a doubling of cost of effort, the results hold. Moreover, the vessels fishing for cod, haddock, and saithe are the same, so the cost of effort is also assumed to be the same for all three species.

[+] These have been kept the same for the two-species case, where saithe is considered the additional species. Cod and saithe share biological traits and their ICES and SSB estimates are similar in terms of biomass and catch from 2004 to 2006. Haddock, on the other hand, has a smaller assessed stock, as well as smaller catch, and that is taken into account for the three-species case presented in Appendix B.

Table 2. Spread of Landings for Each Species at the Vessel Level. The dependent variable is the Gini coefficient for the vessel-year-species combination, and cod is the base category. Saithe and haddock landings are statistically less spread out than cod but comparable to each other.

	Model 1	**Model 2**	**Model 3**
	b/se	b/se	b/se
Saithe	0.03*	0.03+	0.03*
	(0.02)	(0.02)	(0.02)
Haddock	0.04*	0.04**	0.04***
	(0.02)	(0.01)	(0.01)
Vessel FEs	No	Yes	No
Vessel*Year FEs	No	No	Yes
N	405	405	405

+ $p<0.10$, * $p<0.05$, ** $p<0.01$, *** $p<0.001$

Table 3. Time for Each Vessel to Reach X Percent of the Landings of a Species in Each Year. The dependent variable is decimal months to reach 80 or 90 percent of landings for the species. The base species is cod. Both models indicate that species are landed in reverse order of value (saithe, haddock, and cod).

	OLS	**OLS**	**Proportional Cox**	**Proportional Cox**
	Months-to-80%	**Months-to-90%**	**Months-to-80% Duration**	**Months-to-90% Duration**
	b/se	b/se	hazard ratio/se	hazard ratio/se
Saithe	-2.28***	-1.55***	2.96***	2.65***
	(0.28)	(0.24)	(0.37)	(0.34)
Haddock	-0.83***	-0.79***	1.60***	2.00***
	(0.24)	(0.20)	(0.18)	(0.23)
Constant	10.28***	10.82***		
	(0.18)	(0.17)		
Vessel FEs	Yes	Yes	Yes	Yes
N	405	405	405	405

*** p<0.001

Table 4. Landings Response to Biological Aggregation. The dependent variable is vessel-level landings of each species at the monthly time step.

	All Species	**All Species**	**Cod Only**	**Haddock Only**	**Saithe Only**
	b/se	b/se	b/se	b/se	b/se
Spawn	77632.91***		7217.6	-7232.48*	308478.20***
	(7307.73)		(7018.41)	(3427.10)	(21336.13)
Haddock*Spawn		-35974.13***			
		(6593.23)			
Saithe*Spawn		65246.28***			
		(12533.73)			
Constant	67626.13***	87034.35***	87833.41***	46484.93***	12001.48
	(5859.59)	(5469.87)	(16825.50)	(10907.22)	(37857.56)
Vessel*Year FEs	No	No	Yes	Yes	Yes
Species*Year FEs	Yes	Yes	No	No	No
N	4860	4860	1620	1620	1620

* p<0.05, ** p<0.01, *** p<0.001

Online-Only Appendix A – Supplemental Tables

Supplemental Table 1. Aggregate Landings for the Trawler Fleet and Within-Season Variation. We use logbook data provided by the Norwegian Directorate of Fisheries for the years 2004-2006 and characterize the harvest patterns for the trawlers by aggregating the landings into monthly data. To compute the coefficient of variation, we first aggregate across vessels, take monthly averages over these three years, and compute the CV over the resulting twelve monthly data points.

Species	Average annual landings (metric tons)	Share of landings	Coefficient of variation	Average annual Gini coefficient
Cod	59,697	0.290	0.33	0.223
Haddock	25,547	0.124	0.39	0.307
Saithe	85,281	0.415	0.86	0.408
Redfish	10,459	0.051	1.36	0.582
Shrimp	15,421	0.075	0.87	0.561
Wolffish	505	0.002	0.86	0.477
Ling	344	0.002	0.77	0.407
Total	205,602		0.34	0.176

Online-Only Appendix B – Results with Three Species (Figure 4)

With three species, as in the two-species fishery, we assume that species 1 has an endogenous price. Species 2 and 3 both have exogenously determined prices, but species 3 is higher value than species 2. This is meant to reflect the Norwegian cod, haddock, and saithe joint-management context. Cod and saithe are more similar in catch and stock biomass, while haddock, which is somewhat more valuable than saithe, has a much lower assessed stock and is thus more difficult to catch. We allow for biological aggregation in two periods for each species, but these periods do not perfectly coincide. Species 1 is assumed to aggregate in months 5 and 6, species 2 in months 6 and 7, and species 3 in months 7 and 8. This is not reflective of the real biology for the species, but it is meant to serve illustrative purposes. We explore five levels of capacity constraint tightness, use the same parameters as in the two-species model, and depict just two of the scenarios in Figure 4.[30]

Under a moderately tight effort constraint (Figure 4), most effort is directed to species 1 in non-aggregating periods but in a way that smooths harvest to account for endogenously determined prices. Species 1 quota binds. Residual effort is allocated to species 2 in non-aggregating periods. During aggregation, all effort goes to species 1 for month 5 despite downward-sloping demand, but more of species 2 is harvested in month 6 while both are

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[30] Under the tightest effort constraint (Supplemental Figure 10), effort is so tightly constrained that all effort in every period is allocated to species 1, except in months 7 and 8, the second month of species 2's biological aggregation, and the second month of species 3's biological aggregation. Effort intuitively flows to the higher-value species 1, but in month 7, the stock effect on species 1 is sufficiently large (by then the stock has been fished down some) that it is worth switching harvest to species 2 for just one period to capitalize on the species 2 aggregation. Once species 2's stock is somewhat reduced and aggregation ends, it is never worth harvesting it again. Note that species 2 is not harvested in its first period of aggregation because species 1 is still aggregating, and foregoing species 1 harvest during aggregation is too costly when effort is so constrained. Species 3 is only somewhat fished during aggregation, but unlike species 2, not all effort is allocated to it. No species exhausts its quota. Overall, this scenario shows that even when capacity is highly constrained, low-value species will still be exploited some if biological aggregation is sufficiently pronounced.

aggregating. There is a dip in species 1 harvest in month 6 relative to its non-aggregating months. Species 3 receives no effort except in month 8, when it is the only aggregating species, while the harvests for species 1 and 2 are almost zero. Quotas for species 2 and 3 do not bind.

The economic intuition for this scenario is as follows. In month 5, species 1 is the only species aggregating, so the sole owner finds it worthwhile to depress prices and allocate all of what is a highly constrained amount of total effort to species 1 due to the cost reduction (for the monopolist, marginal cost is lower in this period, so equilibrium marginal revenue will also be lower). This allocation allows for the catch of all quota for species 1 over the course of the season while still allocating some effort to other species, especially when the marginal product of effort for other species is high during aggregation months. In month 6, both species 1 and 2 are aggregating, so effort is split between them. The marginal value of harvesting species 2 is sufficiently high during aggregation to compensate for the higher price of species 1, which still reflects some movement down the species 1 demand curve. The capacity constraint ultimately drives the total shutdown of species 1 harvest in month 7, when all effort is allocated to the aggregating species 2 (and species 1 is no longer aggregating). It is only worth harvesting species 3 (the lowest value species) when species 3 is the only species aggregating (month 8), and given its higher price relative to species 2, it remains the only species caught in this period.

Under a moderate effort constraint (Figure 4), there is enough total effort in the system to exhaust quota for all three species. Species 2 has a mostly declining but positive harvest pattern before its aggregation. Then species 2 harvest spikes during aggregation, and finally another declining pattern starts when residual effort becomes available. By contrast, species 3 harvest ramps up and spikes during aggregation periods and for those times when species 2 is not harvested. Species 1 harvest exhibits its usual smooth harvest pattern during non-aggregating periods, increases during its aggregation periods slightly, then dips dramatically while the other species biologically aggregate. In essence, when species aggregate and have exogenously determined prices, the effect on the production function is isomorphic to a price increase; low-value species are associated with higher profits when they aggregate due to lower harvesting cost. When demand is not perfectly elastic, however, this effect is partially offset by dampened prices.

Despite the many moving parts in the optimization, the guiding principle of marginal value of effort can explain most of what we see. Starting with species 3, the marginal value of effort is low in all periods except during aggregation. As such, nearly all of the species 3 quota is taken during aggregation (periods 7 and 8). For species 2, harvest is high in period 6 because the marginal value of effort is highest when both species 1 and 2 are aggregating: species 3 marginal value of effort is low in this period (not aggregating), and species 1 marginal value of effort is dampened by the price response. When only species 1 is aggregating, it is worth increasing species 1 harvest despite the price response because the opportunity cost of effort is generally low (i.e., there is less benefit to allocating effort to other species that are not aggregating). With stock effects, the marginal value of effort for species 2 declines as the quota is taken. Why does species 3 effort increase during this period? These increases coincide with achieving equi-marginality from stock effects across species 2 and 3. When species 2 is heavily exploited during aggregation, the stock is reduced to the point where, after aggregation, effort is more valuable in each of the other fisheries. Interestingly, the season quota binds for the lowest-value species first (species 2). This creates a second pattern of declining species 3 harvest after the aggregation period. Intuitively, the marginal value of effort for species 2 is too low after aggregation due to stock effects, whereas the marginal value of species 3 effort is sufficiently high after aggregation because the price is strictly higher. The harvest and effort patterns of species 3, with local peaks in March and October, are also interesting because there is no way to explain these outcomes from biological or market conditions for only this species. It is the multispecies setting, when the marginal value of effort applied to other species is accounted for, that creates this type of pattern.[31]

Online-Only Appendix C – Supplemental Figures

Supplemental Figure 1. Optimal Harvest and Effort in a Single-Species Setting with Endogenous Price and Without Stock Effects or Discounting. When stock effects and

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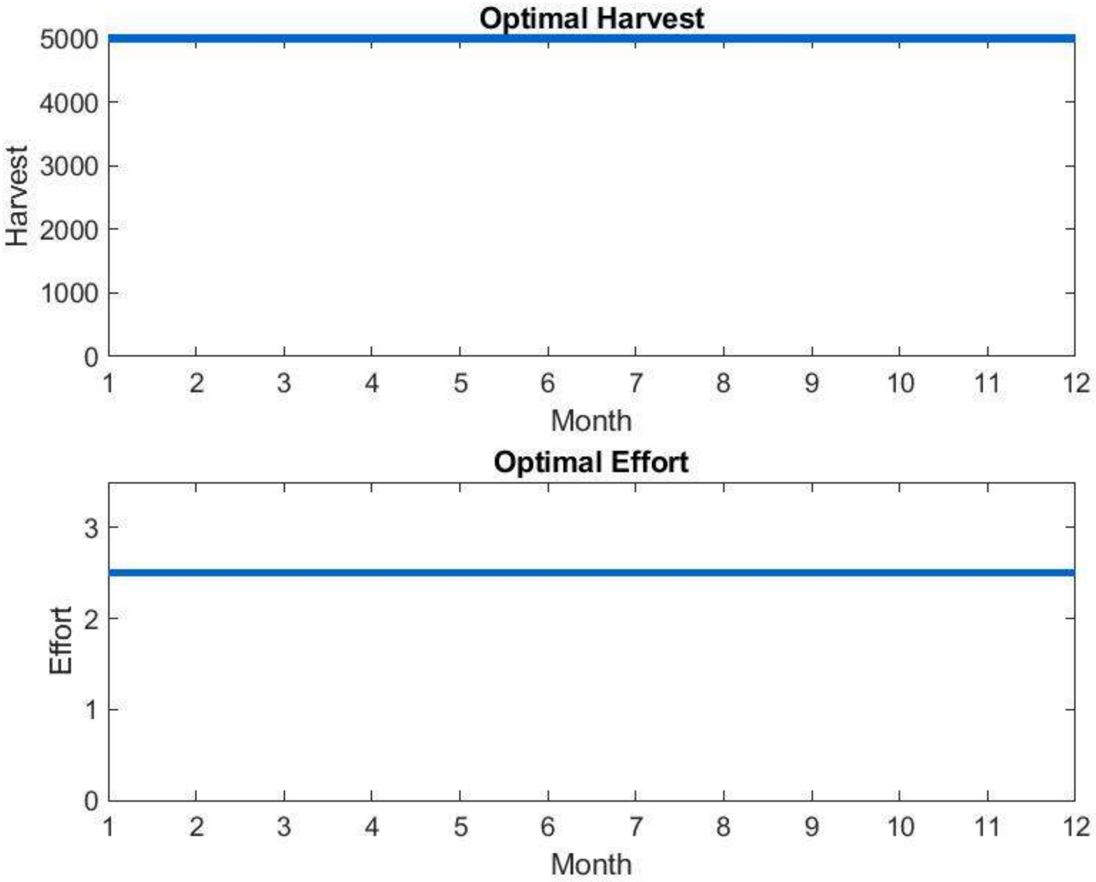
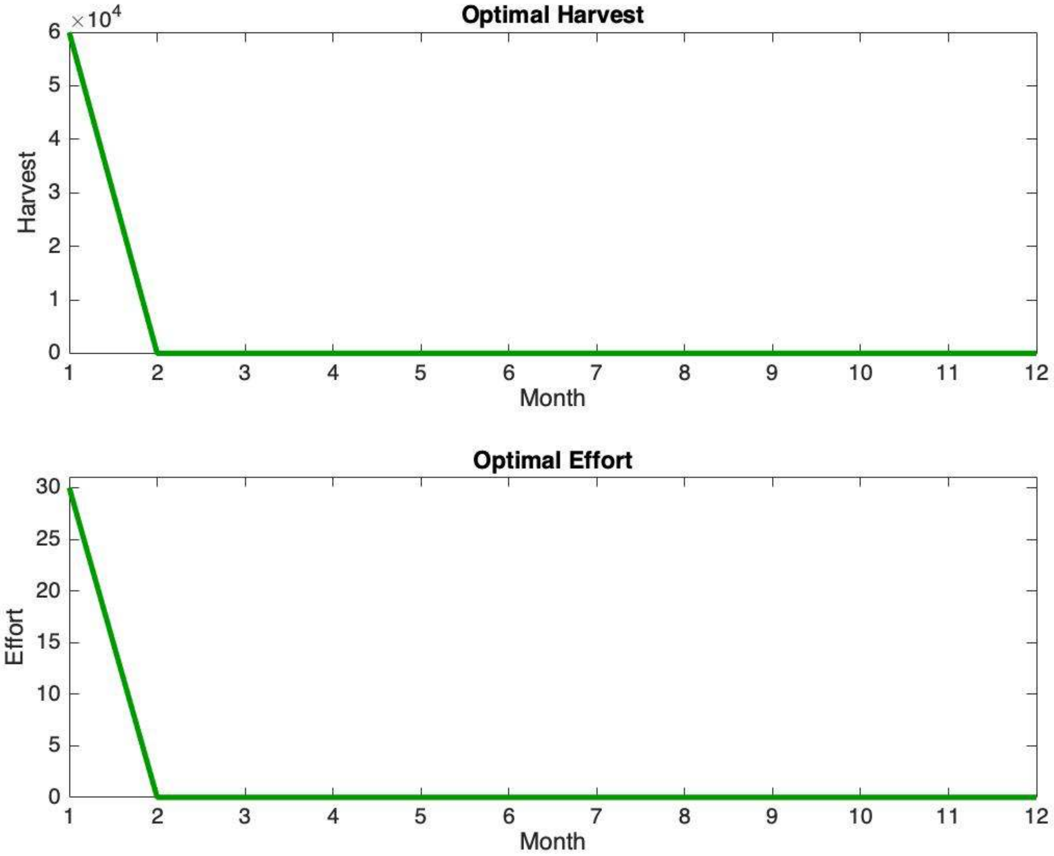
[31] With a loose effort constraint (Supplemental Figure 11), results are similar to those under the moderate effort constraint but with more pronounced spikes. All quotas bind. Species 1 appears most similar but still has a zero harvest in month 8 (so does species 2). Spikes for species 2 and 3 are more pronounced, but there are artifacts of the same pattern we see in Scenario 3. When effort is effectively unconstrained (Supplemental Figure 12), all aggregate quotas bind. Species 1 harvest is smoothed during non-aggregating periods, with increases during the aggregating periods and corresponding dips in effort. As in the two-species case, species 1 harvest slightly trends downward reflecting the effects of discounting and stock effects. All catch of species 2 is taken in month 6, and all catch of species 3 is taken in month 7. These are each species' first month of aggregation, reflecting the availability of sufficient effort combined with discounting and stock effects.

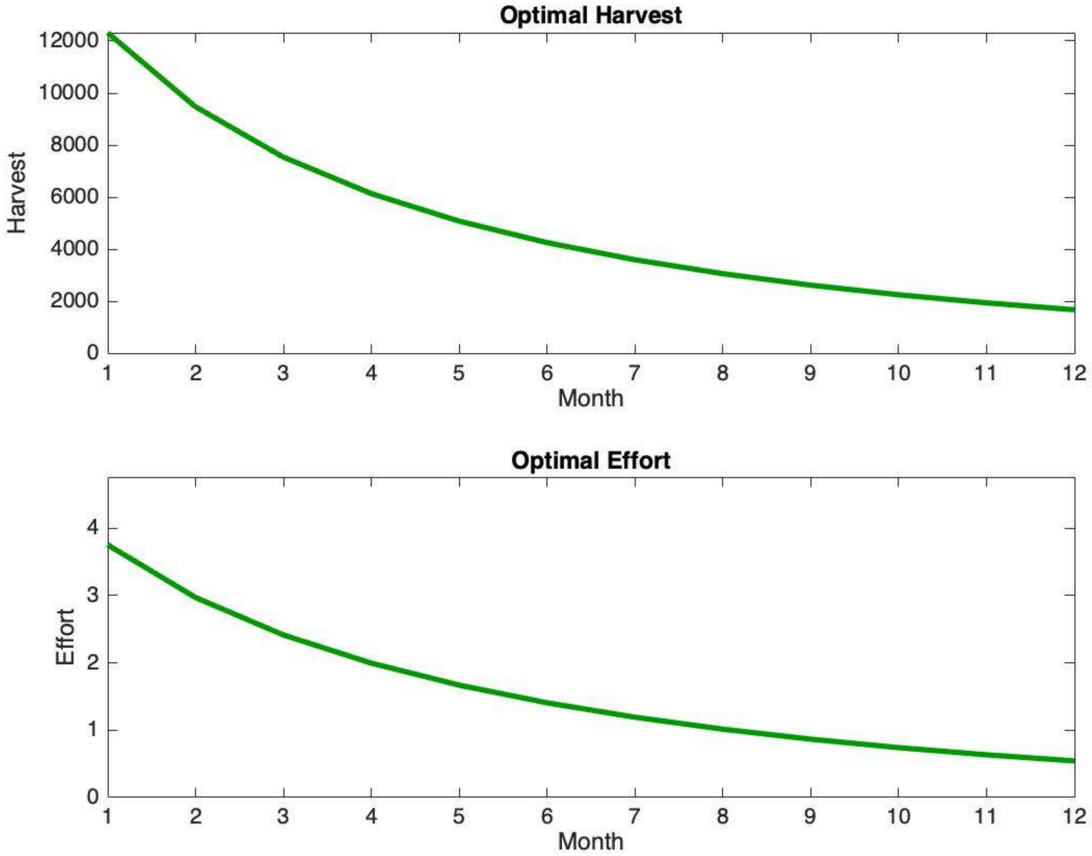
discounting are removed and the production technology is otherwise constant returns (α_i=1), the harvest and effort paths are completely flat.



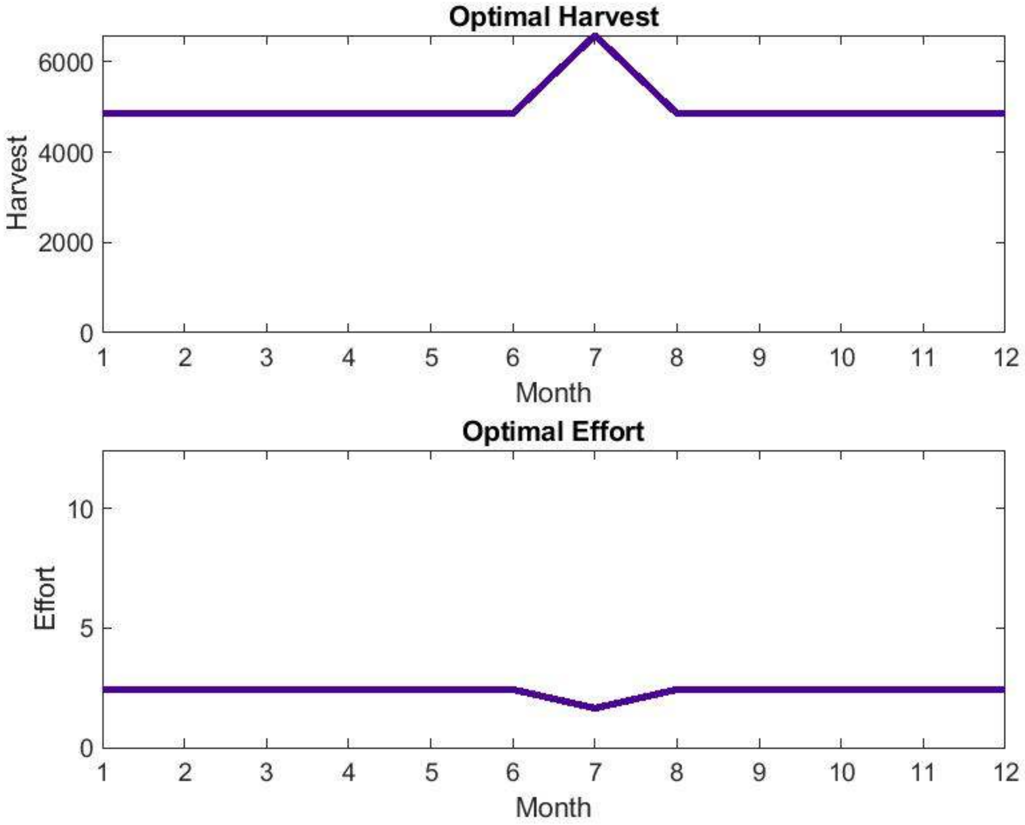
Supplemental Figure 2. Optimal Harvest and Effort in a Single-Species Setting with Exogenous Price and Stock Effects or Discounting Removed. Removing either discounting or the stock effect leads to the same result as in Figure 1, Scenario 2 as long as the production technology is otherwise constant returns (α_i=1).



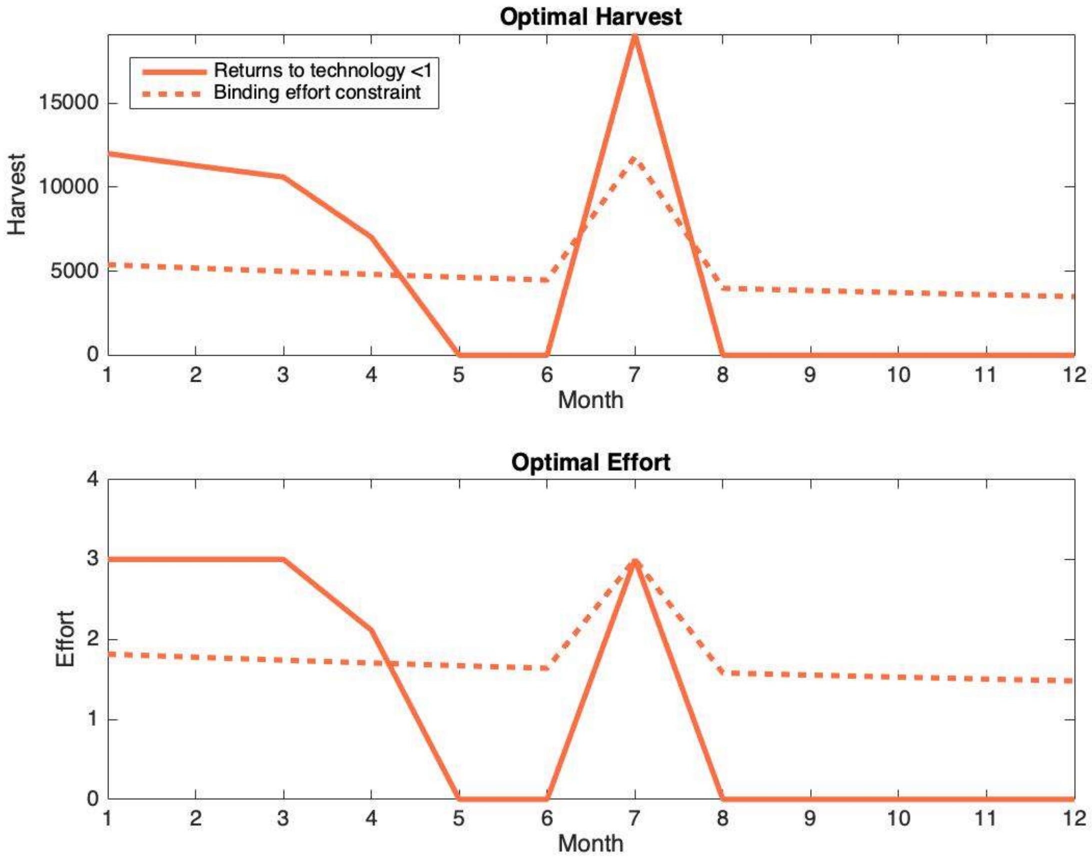
Supplemental Figure 3. Optimal Harvest and Effort in a Single-Species Setting with Exogenous Price and Decreasing Returns ($\alpha_i < 1$). The effort path reflects tradeoffs across concavity of the harvest function, which smooths effort, and discounting and the stock effect, which concentrate effort.



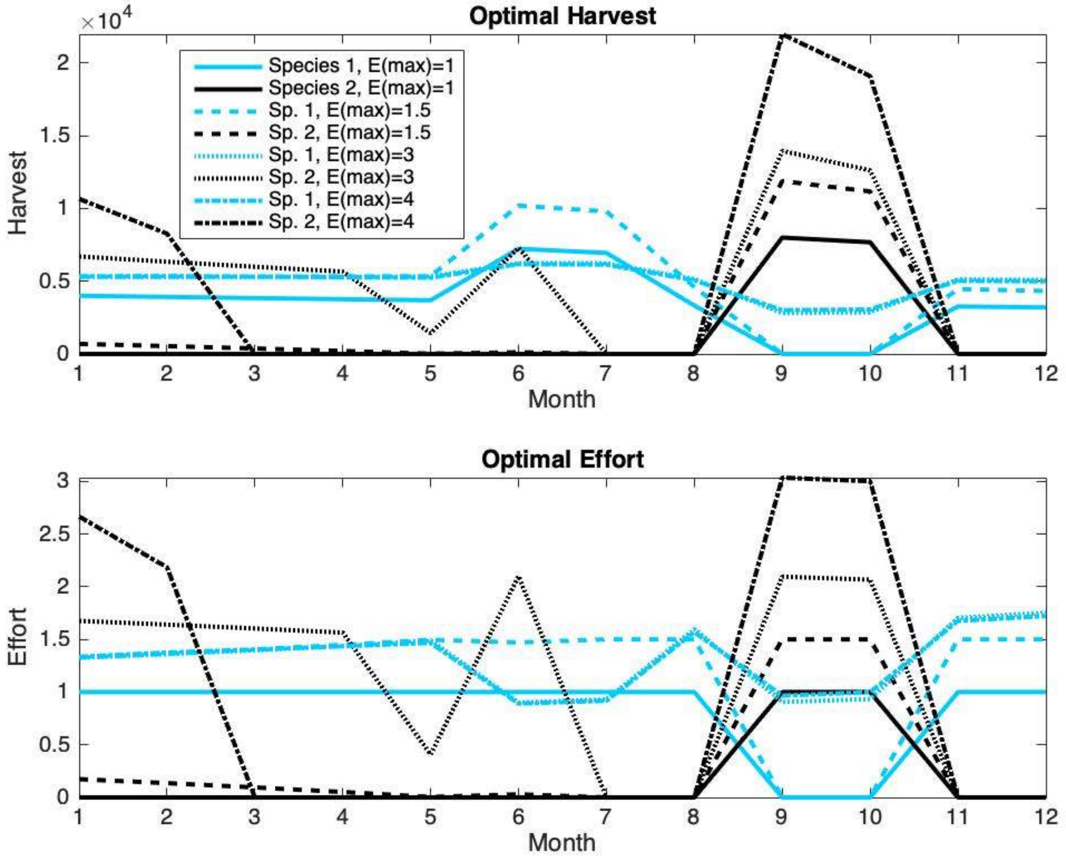
Supplemental Figure 4. Optimal Harvest and Effort in a Single-Species Setting with Biological Aggregation in month 7 and Endogenous Price and Without Stock Effects or Discounting. When stock effects and discounting are removed but the production technology is otherwise constant returns (α_i=1), the harvest path is flat and the effort path still has a dip during biological aggregation. If the cost reduction due to the biological aggregation is sufficiently strong, there is a moderate increase in the harvest during this period, even with inelastic demand.



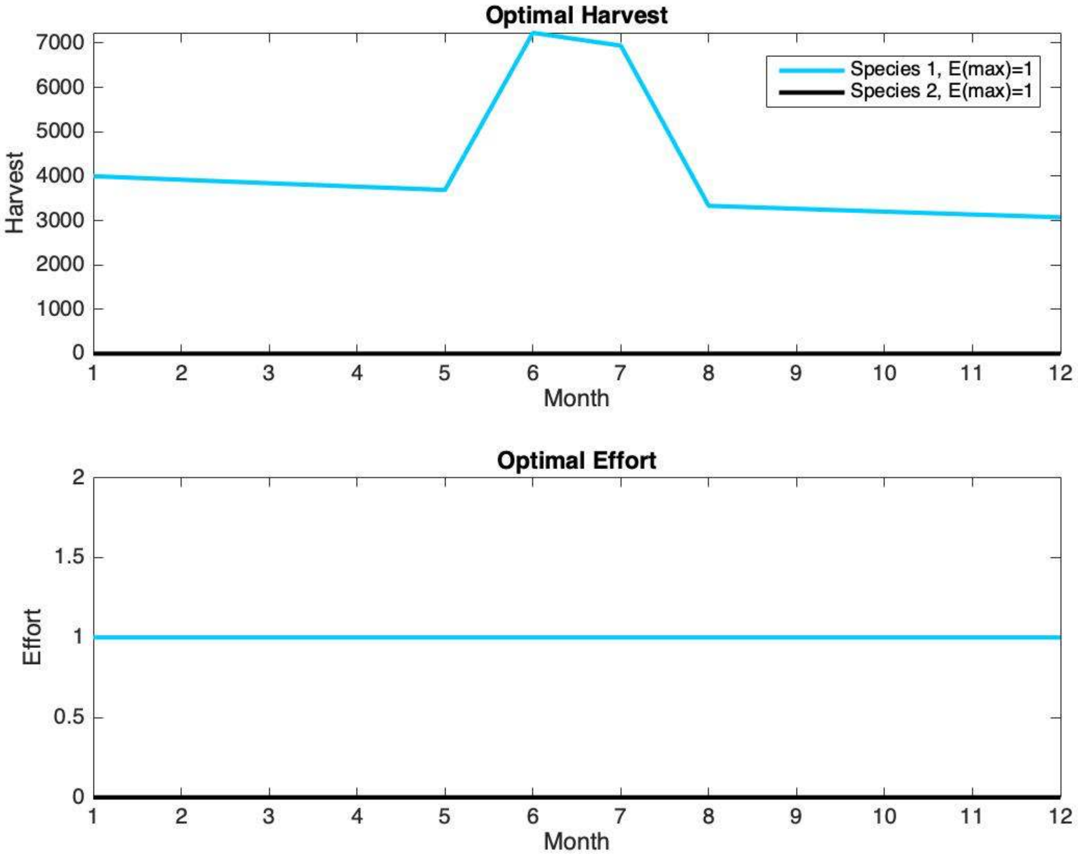
Supplemental Figure 5. Optimal Harvest and Effort in a Single-Species Setting with Biological Aggregation in month 7 and Exogenous Price and Decreasing Returns to Technology or Binding Effort Constraint. Relaxing the effort constraint in Figure 1—namely the assumptions of unconstrained per-period effort and constant returns to technology—induces some smoothing of catch and effort.



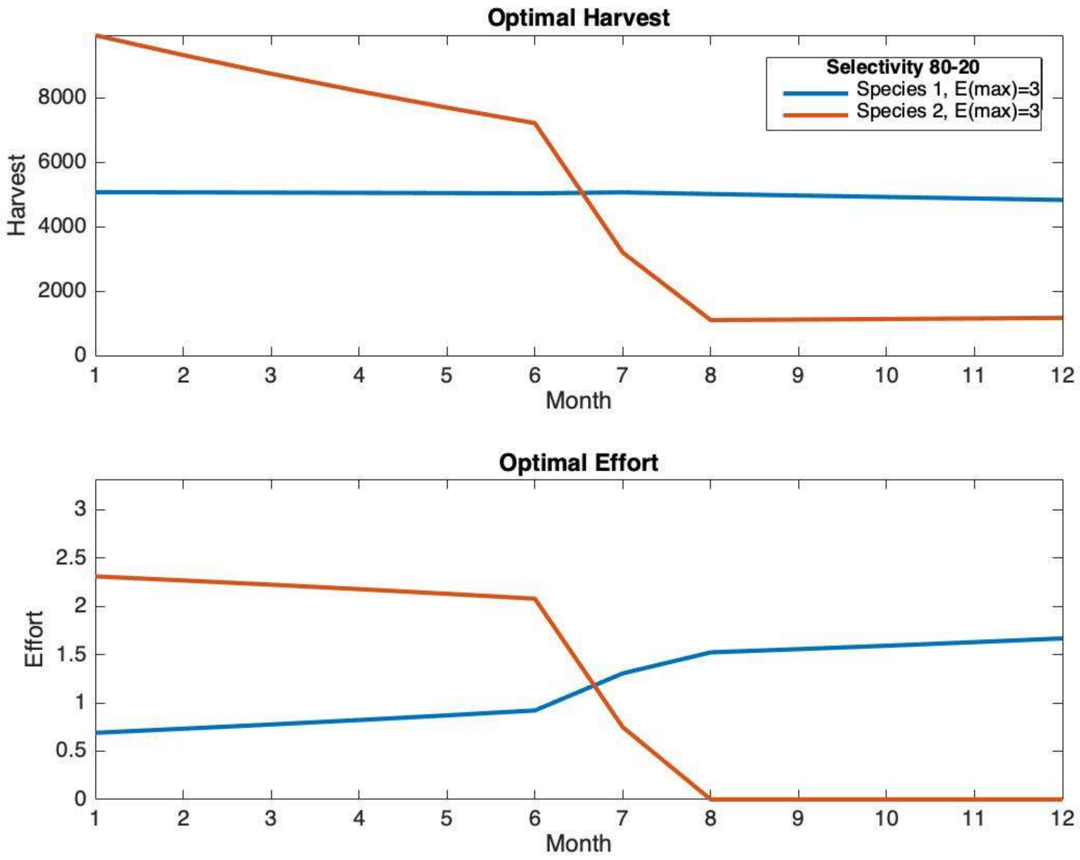
Supplemental Figure 6. Optimal Harvest and Effort in a Two-Species Setting with Offset Biological Aggregation Periods and Varying Effort (Capacity) Constraints. The scenarios include: 1) Tightest effort constraint (E_{max} = 1); 2) Moderately tight effort constraint (E_{max} = 1.5); 3) Moderate effort constraint (E_{max} = 3); and 4) Loose effort constraint (E_{max} = 4). Species 1 has biological aggregation in months 6 and 7, and species 2 has biological aggregation in months 9 and 10. Thus the results are qualitatively similar to those in Figure 3 when the biological aggregation periods align; the peaks and troughs follow the biological patterns predictably in either case.



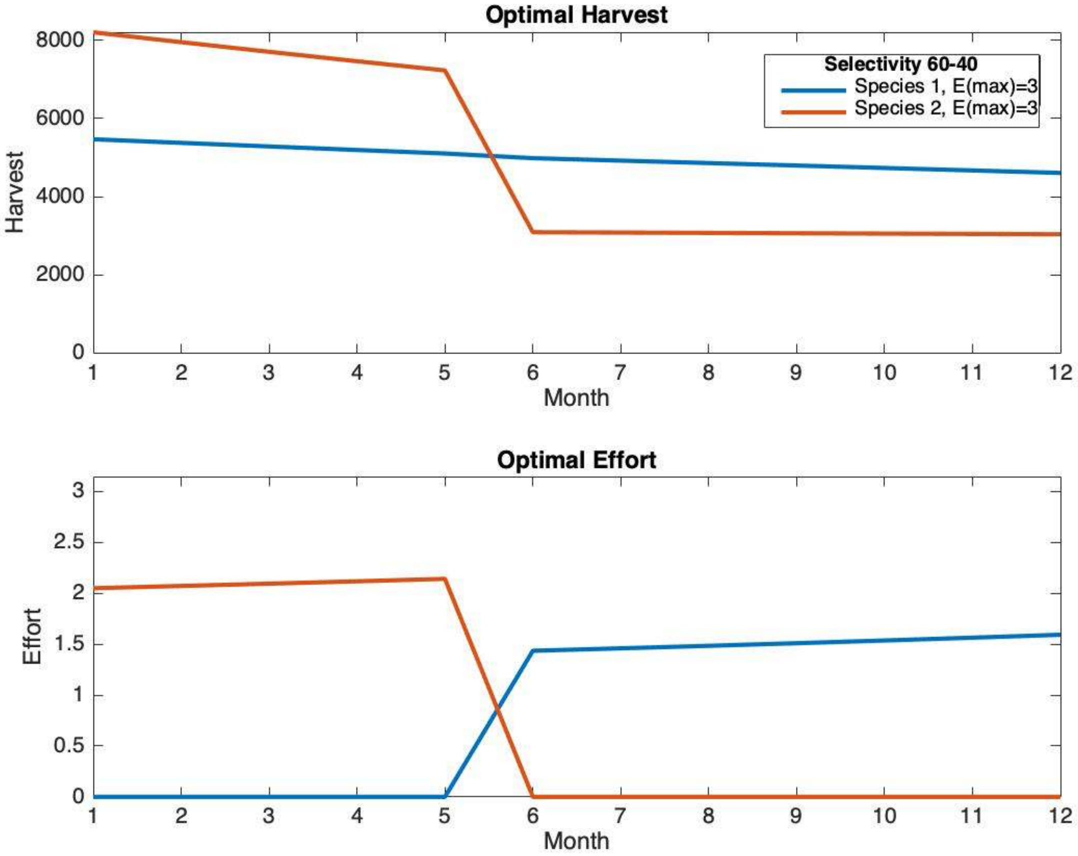
Supplemental Figure 7. Optimal Harvest and Effort in a Two-Species Setting with Biological Aggregation in Months 6 and 7 for Both Species, and Tight Effort Constraint. With an even tighter effort constraint ($E_{max} = 1$) than that in Figure 3, none of species 2 is taken, not all of species 1 quota is taken, and effort is allocated uniformly to species 1.



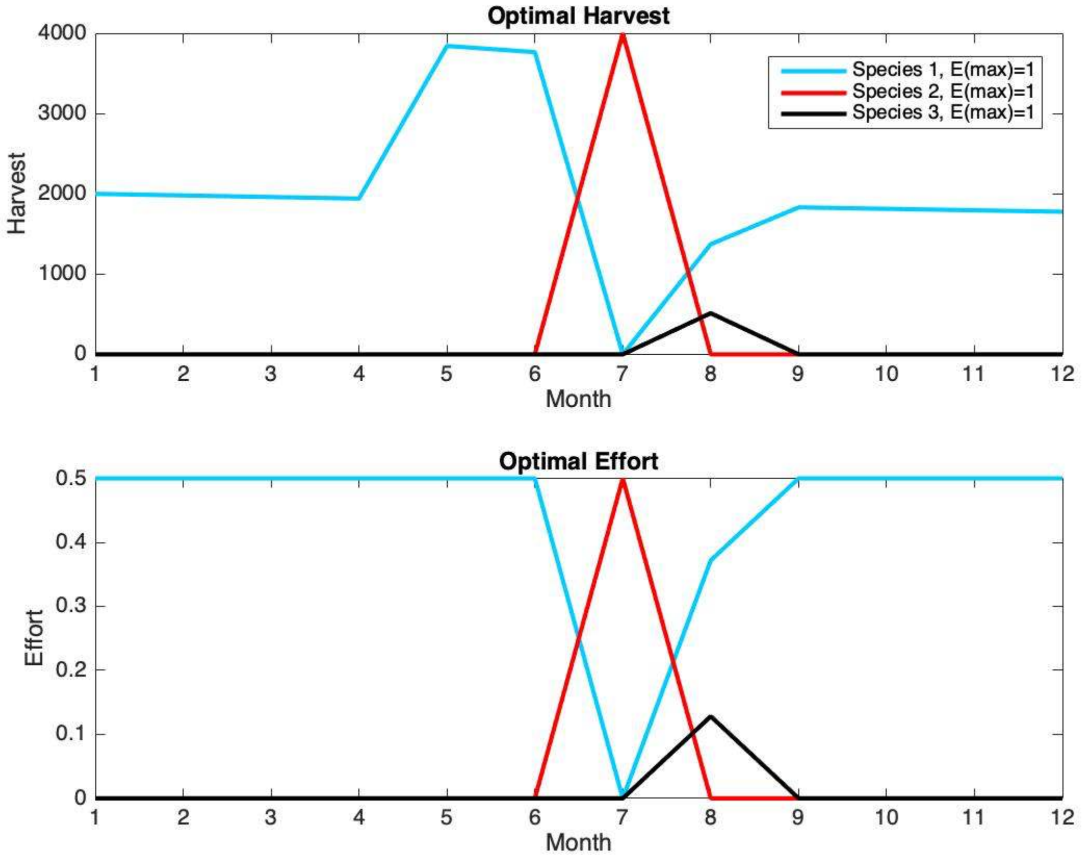
Supplemental Figure 8. Optimal Harvest and Effort in a Two-Species Setting with Moderate Effort Constraint (E_{max} = 3) and 80-20 Gear Selectivity. This means that, in targeting one species, 80 percent of what the fisher catches is that target species and 20 percent is unintended catch of the other species. Harvests for both endogenously priced species 1 and the exogenously priced species 2 continue to trend downward, but the species 1 harvest path is flatter due to price responsiveness. Both quotas are taken in full. This is not surprising, as the effort expended to catch the higher-valued species 1 leads to some species 2 being taken as bycatch. Also, the low-value species 2 is harvested earlier in the season as in the case of perfectly selective harvest. Lastly, harvest for both species continues throughout the year as a consequence of non-selectivity; effort to spread out harvest of species 1 leads to sustained catches of species 2 even after target effort for species 2 stops.



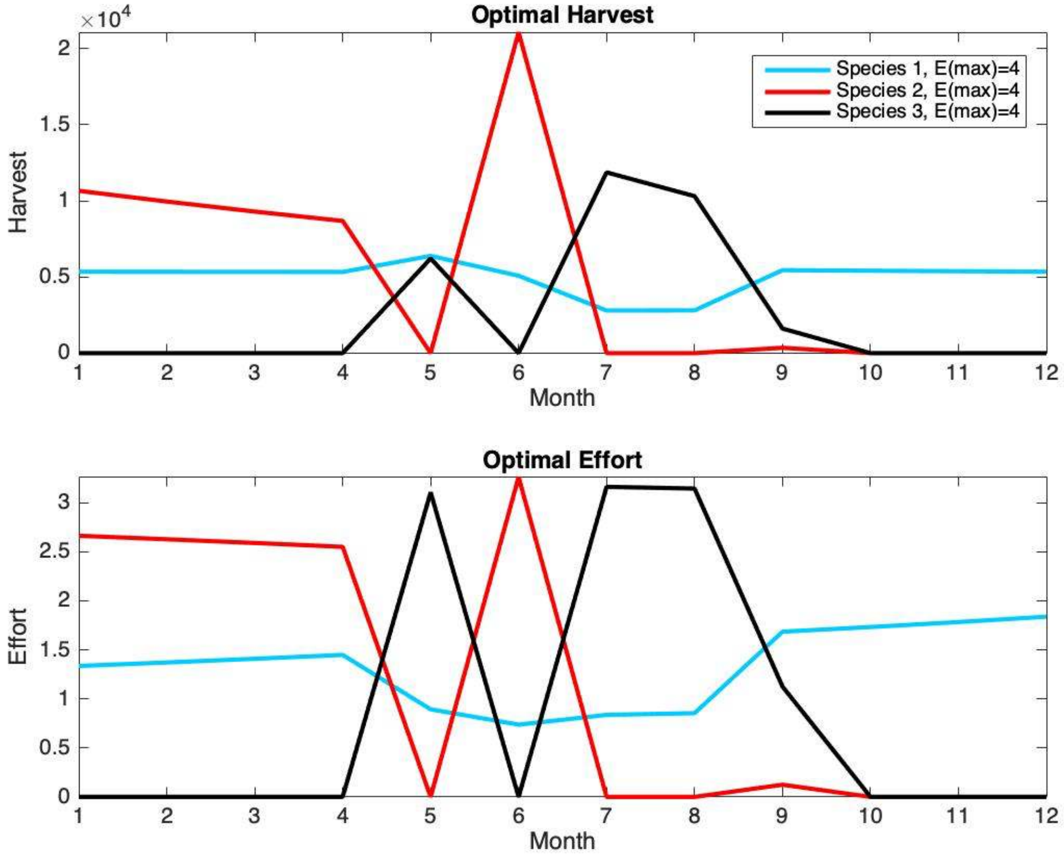
Supplemental Figure 9. Optimal Harvest and Effort in a Two-Species Setting with Moderate Effort Constraint (E_{max} = 3) and 60-40 Gear Selectivity. This means that, in targeting one species, 60 percent of what the fisher catches is that target species, and 40 percent is unintended catch of the other species. Harvests for both endogenously priced species 1 and the exogenously priced species 2 continue to trend downward, but the species 1 harvest path is flatter due to price responsiveness. Both quotas are taken in full. This is not surprising, as the effort allocated to catching the higher-valued species 1 generates species 2 bycatch. Also, the low-value species 2 is harvested earlier in the season, as in the case of perfectly selective harvest. Lastly, harvest for both species continues throughout the year as a consequence of non-selectivity; effort to spread out harvest of species 1 leads to sustained catches of species 2 even after effort expenditure for species 2 stops.



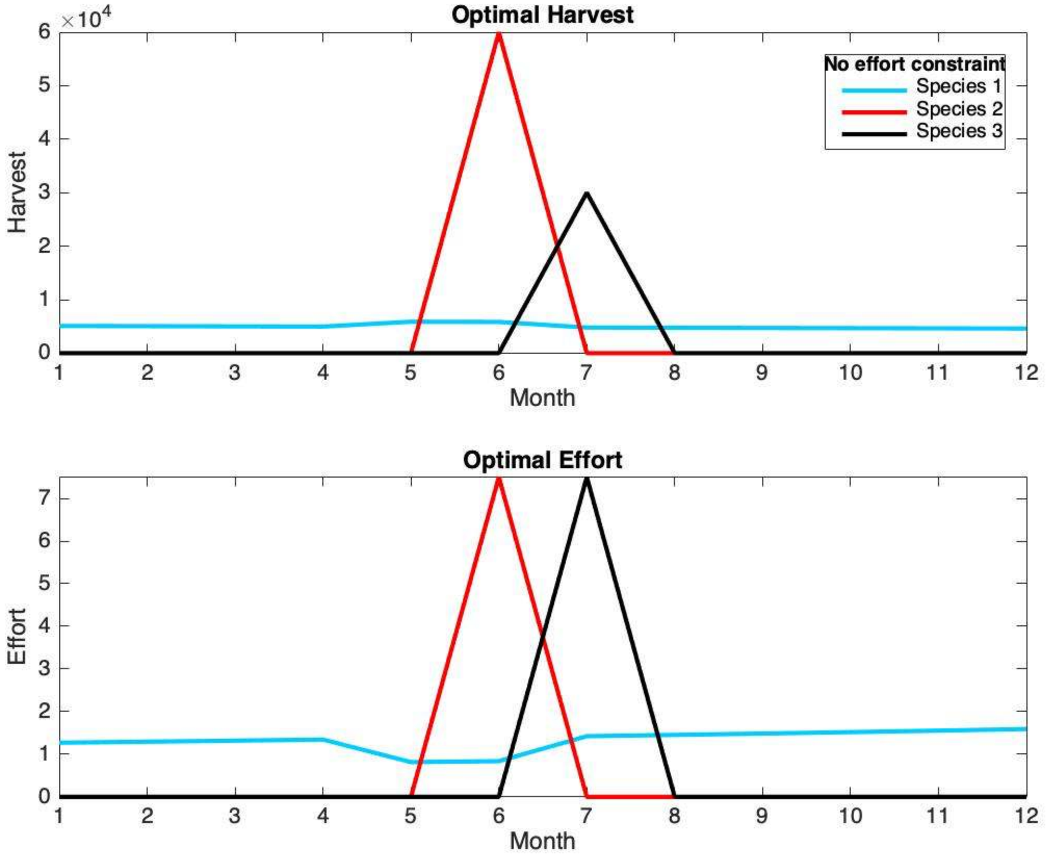
Supplemental Figure 10. Optimal Harvest and Effort in a Three-Species Setting with Tight Effort Constraint and Biological Aggregation for Species 1 (Months 5 and 6), Species 2 (Months 6 and 7), and Species 3 (Months 7 and 8). In Scenario 1 effort is so tightly constrained (E_{max} = 1) that all effort in every period is allocated to species 1 except in month 7, the second month of species 2's biological aggregation. Effort intuitively flows to the higher value species 1, but in month 7, the stock effect on species 1 is sufficiently large (by then the stock has been fished down some) that it is worth switching harvest to species 2 for just one period to capitalize on the species 2 aggregation. Once species 2's stock is somewhat reduced and aggregation ends, it is never worth harvesting it again. Note that species 2 is not harvested in its first period of aggregation because species 1 is still aggregating, and foregoing species 1 harvest during aggregation is too costly when effort is so constrained. Species 3 is only fished during its last aggregation month. No species exhausts its quota. Overall, this scenario shows that, even when capacity is highly constrained, low-value species will still be exploited some if biological aggregation is sufficiently pronounced.



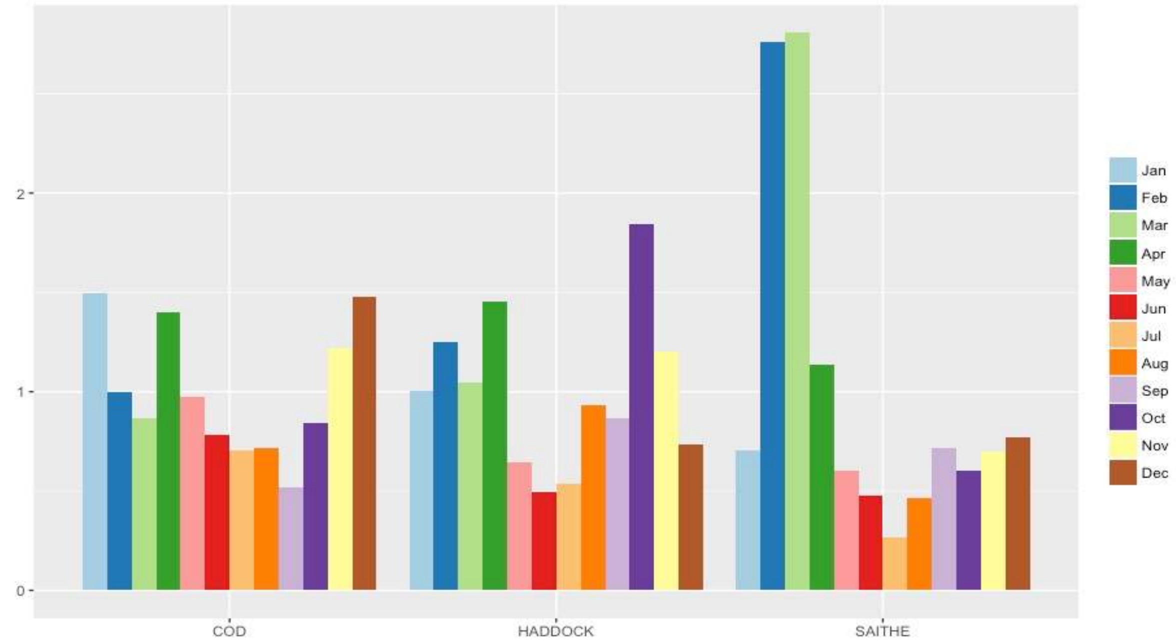
Supplemental Figure 11. Optimal Harvest and Effort in a Three-Species Setting with Somewhat Loose Effort Constraint and Biological Aggregation for Species 1 (Months 5 and 6), Species 2 (Months 6 and 7), and Species 3 (Months 7 and 8). In Scenario 4, with loose effort constraint (*E_{max}* = 4), results have some similarities to the moderate effort constraints imposed in Figure 4. All quotas bind. Species 2 appears most similar but still has no harvest in month 8, while species 1 begins to smooth also during the period of aggregation. Spikes for species 2 and 3 are more pronounced, but there are artifacts of the same pattern we see when effort is more constrained (E_{max}=3).



Supplemental Figure 12. Optimal Harvest and Effort in a Three-Species Setting with Effectively Unconstrained Effort and Biological Aggregation for Species 1 (Months 5 and 6), Species 2 (Months 6 and 7), and Species 3 (Months 7 and 8). In the last scenario, effort does not bind in any period, and all aggregate quotas bind. Species 1 harvest is smoothed during non-aggregating periods with increases during the aggregating periods and corresponding dips in effort. As in the two-species case, species 1 harvest slightly trends downward, reflecting the effects of discounting and stock effects. All catch of species 2 is taken in month 6, and all catch of species 3 is taken in month 7. These are each species' first month of aggregation, reflecting the availability of sufficient effort combined with discounting and stock effects.



Supplemental Figure 13. Seasonal landings pattern for cod, haddock, and saithe. For each species, landings are normalized to average monthly landings across the three years.



Supplemental Figure 14. Hazard functions from Proportional Cox Model estimates. The hazard rate for individual vessels to reach 80 percent (top) and 90 percent (bottom) of their annual landings for each species.