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Intra-seasonal Behavior in Multispecies Catch Share Fisheries

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Abstract: Fishermen face multidimensional decisions: when to fish, what 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 or market conditions that vary intra-seasonally. We generate predictions about within-season behavior in multispecies catch share fisheries, accounting for stock aggregations, effort constraints, and downward-sloping demand. Results show variation in harvest patterns, including season length, acceleration or delay of harvests, and sequencing individual species harvests. Harvest patterns are consistent with those observed in Norwegian multispecies groundfish fisheries.

Keywords: multispecies fisheries, fishing behavior, intra-seasonal harvest, catch shares, bioeconomic modeling, seafood demand

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1. Introduction

Fishermen face a multidimensional decision problem that involves choices about where to fish, when to fish, what to target, and which gear to deploy. Although the structure of the decision problem varies across fisheries and regulatory systems, positive (i.e. predictive) analysis of the fishery generally aims to understand how fishing behavior responds to incentives across these multiple margins (Smith, 2012). Under open access, fishing behavior drives rent dissipation and biological overexploitation through excess entry (Smith 1969; Wilen 1976; Bjørndal and Conrad 1987). Fishing behavior can exacerbate excess capital accumulation under regulated open access despite controlling biological overfishing (Homans and Wilen 1997). With individual transferable quotas, fishing behavior theoretically is the mechanism by which the constructed market generates rents (Arnason 1990). Despite some sharp theoretical predictions and a growing body of empirical work, our positive understanding of fishing behavior is largely incomplete. Most of the positive literature reflects single species fisheries, open access, or long

(inter-seasonal) dynamics. In this paper, we fill some of this gap with qualitative predictions about within-season fishing behavior in multispecies catch share fisheries.

A complete positive model of the fishery requires reconciling multiple time scales; fishing decisions about participation, fishing grounds, and species targets unfold over time scales of days-to-months, whereas fisheries management institutions typically regulate with industry-wide quotas or individual fishing quotas (IFQs) on annual time scales. The theory of fishing behavior under IFQs begins to address multiple time scales by analyzing within-season behavior for vessels that have annual quotas. Clark (1980) shows that annual vessel quotas are suboptimal when fish stocks vary seasonally, but this externality can be solved by matching the time scale of the quota allocation to the seasonal pattern. Boyce (1992) demonstrates that tradable IFQs, while addressing the commons problem broadly, do not solve short time-scale externalities such as congestion and within-season stock effects. Costello and Deacon (2007) argue that rents can be dissipated in the spatial dimension in IFQ fisheries. Fell (2009), using an open-loop differential game, shows that strategic interactions of harvesters under IFQs can prevent rent transfers from the processing sector to the harvest sector. Valcu and Wenginger (2013), employing a closed-loop dynamic game, find that within-season externalities can persist with annually allocated IFQs, but the conditions under which these problems dissipate rents are quite specialized. Results in Fell (2009) and Valcu and Wenginger (2013) illustrate within-season harvest patterns for a single-species fishery with various biological and market characteristics. In many real-world fisheries, however, vessels hold quotas for multiple species with heterogeneous biological or market conditions. What seasonal harvesting patterns might we expect to see in these settings?

Empirical studies offer insights on multispecies and seasonal harvest patterns but do not paint a complete picture. To investigate multi-output behavior in fisheries, studies typically use

annual data to model revenue functions (Squires and Kirkley, 1991), profit functions (Squires, 1987), profit functions with restricted outputs (Asche, Gordon and Jensen, 2007), or distance functions (Weninger and Walters, 2003). By construction, these approaches abstract away from the spatial or temporal distribution of the fish within the season, and with the exception of price signals, pay little attention to the fact that quality can vary during the season (Larkin and Sylvia, 1999). Although harvest can be relatively selective in some multispecies fisheries—e.g. pelagic fisheries 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 clean fisheries and a fleet in a dirty fishery in which the share of each species is relatively constant within the year.ⁱ These studies similarly ignore dynamic effects of forward-looking behavior on harvest timing and the output mix.

Empirical studies of finer scales use trip data to analyze multiple margins of fishing behavior but ignore the multi-output dimension of fisheries. Like the long time-scale literature, studies with fine-scale data abstract away from the dynamics of forward-looking behavior. Trip data are used to analyze fishing participation (Smith and Wilen 2005; Huang et al. 2012), location choice (Eales and Wilen 1986; Holland and Sutinen 2000; Smith 2005; Haynie and Layton 2010; Abbott and Wilen 2011), gear choice (Eggert and Tveteras 2004), and species target (Zhang and Smith 2011). Results show that fishermen are responsive across a range of behavioral margins, but the potential revenue for each alternative is treated as exogenous in the models, and fishermen are assumed to make a sequence of myopic decisions.ⁱⁱ Two empirical studies allow for forward-looking fishing behavior in modeling fine-scale decisions (Hicks and Schnier 2008; Huang and Smith 2014), but neither accounts for multispecies behavior, and only Huang and Smith (2014) models endogenously determined revenue.ⁱⁱⁱ

Many fisheries reflect a sequence of decisions in which a vessel targets different species at different times; some trips involve multi-output production, others are intended to be clean single-species catches, and the sequencing involves a forward-looking reconciliation of short time-scale decisions with annual quotas. Regulatory design may drive harvest timing—e.g. the very short seasons in the regulated open access Pacific halibut fishery (Homan and Wilen, 1997)— or biological stock characteristics such as spawning can influence timing—e.g. the Lofoten cod fishery (Hannesson, Salvanes and Squires, 2010). Quotas that restrict harvest for some species can also incentivize targeting of unregulated species (Asche, Gordon and Jensen, 2007; Hutniczak 2014). We might expect this insight to translate more broadly to collections of similarly regulated species. In relatively clean fisheries, *ceteris paribus*, highly priced species will be more attractive initially if there is a within-season stock effect. But for some species, high-valued market segments, downward sloping demand, and perishability stimulate long harvest seasons (Homans and Wilen, 2005).

Under IFQs, fishermen can orient the time profile of their landings to economic conditions for quota species. Timing the harvest can create a trade-off between costs and revenues. Costs may be lowest by concentrating harvest to follow seasonal biological aggregations or at the beginning of the season due to stock effects. Revenues, in contrast, may be highest by spreading harvest throughout the season to take advantage of a downward sloping demand schedule. However, timing decisions are complicated by the possibility of participating in other fisheries; a vessel can be in only one place at any point in time.

Here we illustrate seasonal patterns of landings in the Norwegian groundfish complex. Motivated by these empirical patterns, we then develop a numerical bioeconomic model to investigate the time-profile of vessel landings throughout the year in a multispecies context. We

model fisheries with annual IFQs such that fishermen 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. The model parsimoniously explains dramatic differences in harvest patterns across the stocks that can be attributed to market conditions and biological factors. In numerical results, we find harvest patterns that are broadly consistent with patterns in data on Norwegian trawlers targeting cod, haddock, saithe, and other groundfish species. Because there is a global market for whitefish (Gordon and Hannesson, 1996; Asche, Gordon and Hannesson, 2002), demand is effectively flat for most species in the analysis. 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). 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 amongst species targets and fisheries regulations.

2. Background: Norwegian Multispecies Whitefish Trawlers

Whitefish species make up the most valuable fisheries in Norway. The fleet targeting whitefish harvests a large number of species, with cod, haddock and saithe as the most important. Other species are primarily demersal, but shrimp, crab, and limited quantities of pelagics are also caught by the whitefish fleet. Fishermen can target specific species by choosing where and when to fish, but catches usually include some bycatch (Asche, 2009).

Management is 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 ICES, often in collaboration with other countries. The Norwegian (share of the) quota is then divided between

different vessel groups and gear types using a rule known as the trawl ladder for the species with a TAC (Guttormsen and Roll, 2011). Regulations vary within the vessel groups and gear types for the regulated species, while it is open access for the unregulated species.

While several vessel groups target whitefish, the cod trawlers group is the largest. These vessels receive between 25% and 30% of the Norwegian TAC for cod, haddock and saithe, depending on the size of the TAC, with a smaller share in years with a small TAC. The trawlers are relatively large vessels with lengths ranging from 20 to 76 meters. They can operate in rough weather, and they typically operate around 300 days each year. 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, while 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 summarize the landing patterns as monthly averages over these three years to reduce year-specific noise. In Table 1, the average annual catch is shown together with the coefficient of variation calculated across months in the year (CV). On average, the trawlers in our sample landed 230 thousand metric tons. Measured by quantity, saithe was the most important species making up over 40% of the landings, followed by cod with 29.4%. However, because of substantially higher prices, cod is always the most valuable species.^{iv} The three IFQ species together make up 83% of the quantity landed by this fleet. Shrimp is the fourth most important species with an 8% share, and redfish makes up almost 5% of the landings. The remaining species contribute modest quantities and are mostly bycatch. The CV is lowest for the total landings, indicating that by targeting different species throughout the year, the fleet

achieves a more even landing pattern in aggregate. However, the CV is not much higher for cod and haddock. Thus, the fleet spreads out landings of cod and haddock quite evenly. In contrast, CVs are much higher but at similar levels for saithe, shrimp, wolffish, and ling, and even higher for redfish. That is, landings for these species are highly concentrated in time. In the modeling below, we explore features of the multispecies fishery that result in some highly concentrated harvests and other highly diffuse harvests. To show the annual landing patterns, average landings per month for the three years are computed and normalized to one in the month with the lowest landings (Figure 1).^v As expected given the CVs, there is substantial variation in the landing patterns for the different species. Wolffish landings peak in October at 38 times the March landings. Redfish landings peak in June with 32 times as much as in February. Shrimp has its peak in July but also has high landings in May and June. Beyond highlighting the existence of peaks, this figure highlights the sequential nature of the fishery; not all species peak at the same time.

The three IFQ species have relatively uniform landings patterns compared to the non-IFQ species. Since the strong seasonality for the other species masks most of the seasonality for IFQ species, we show these three species separately (Figure 2). Cod peaks in January, but landings are only three times as high as the landings in September. Haddock peaks in October at four times as high as the landings in June. The saithe peak in February is almost 10 times higher than in July and follows the traditional seasonal pattern for whitefish in the north Atlantic, and ling (Figure 1), as an obvious bycatch species, follows the same pattern.

In summary, we see cod—the high-value IFQ species with potential for market segmentation—following a uniform seasonal pattern but not perfectly. Haddock—the intermediate-valued IFQ species—follows a 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 pattern.

In the next section, we develop a bioeconomic model that explains temporal harvest patterns visible in the empirical data. In particular, we account for harvest smoothing, harvest spikes, within-season harvest trends, concentration on a single species, and mixed species harvesting by introducing market conditions, biological aggregations, stock effects, and capacity constraints. We produce these harvest patterns without appeals to gear non-selectivity or multi-output production technology that incorporate economies of scope.

3. Model

Many of the fisheries described above are managed with individual fishing quotas (IFQs). 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 optimization problem and choose the same behaviors. We are primarily interested in the extent to which our framework could account for the patterns we see in the empirical data. We note three important caveats that our model does not address: 1) strategic interactions of multiple IFQ holders, 2) coordination failures amongst IFQ holders, 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. All of these caveates represent opportunities for future research.

In a given year, the IFQ owner seeks to maximize total profits across species (i) and time periods (t):

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

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) of each species i in each period t based on price (P), cost (c), and the harvest technology:

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

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

$$P_{it} = a_i - b_i n H_{it}$$

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. By setting $b=0$, we nest the case of the perfectly elastic demand that may plausibly describe some seafood products for which there is a global market with ample substitutes. Different levels of a can distinguish premium products within the same market. Cod, for instance, typically fetches a higher price than saithe, though both are similar whitefish. We model species- and time-specific harvests using Cobb-Douglas technology with two inputs, effort (E) and stock (X):

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

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. 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.

IFQ owners takes the TAC and their corresponding share of TAC for each species as given such that its harvest summed across t must not exceed the quota share:

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

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 at t is initial stock less cumulative harvest:

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

We add non-negativity constraints on effort:

$$E_{it} \geq 0.$$

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

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

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

This effort constraint could reflect a time constraint, maximum hull capacity, amount of fishing gear on a vessel, or some combination of these.

We implement the model using Matlab's nonlinear solver (FMINCON). For a single-species case, we derive three results analytically using a continuous-time optimal control model that parallels our discrete-time model above (see Appendix A). Although some of the results can be shown analytically, the most interesting results require numerical techniques. We present all results numerically in the main text for consistency. Base parameter values are in Appendix B, noting that our main interest is in qualitative results.

4. Results

We solve the model using a range of assumptions about parameters that generate different harvest patterns. We begin with simple experiments that vary one assumption at a time using a single species. These results are quite intuitive and 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. Finally, we explore outcomes varying multiple assumptions with three target species.

4.1 Results with a Single Species (Figure 3)

We optimize the single-species model for four different scenarios:

1. Stock effects and endogenous price (some demand inelasticity, $b_i > 0$)
2. Stock effects and exogenous price (perfectly elastic demand, $b_i = 0$)
3. Biological aggregation and endogenous price
4. Biological aggregation and exogenous price

In Scenario 1, the optimal strategy is to smooth harvest over the entire year to maintain higher prices. Note that harvest paths for Scenarios 1 and 3 appear the same, but differences can be seen in the effort paths. 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. When stock effects and discounting are removed and the production technology is otherwise constant returns, $\alpha_i = 1$, the harvest and effort path is completely flat (not pictured).

In Scenario 2, the optimal strategy is to take all of the quota in the first period. Because we do not impose an effort constraint and price is perfectly elastic, there are no incentives to spread out harvest. Both discounting and the stock effect push harvest into the first period. Removing either discounting or the stock effect leads to the same result as long as the production technology is otherwise constant returns, $\alpha_i = 1$ (not pictured), and with decreasing returns, $\alpha_i < 1$, the effort path reflects standard tradeoffs across concavity of the harvest function that smooth effort and discounting and the stock effect that concentrate effort (not pictured). This result is important in showing that IFQs are not sufficient for spreading out harvest. Spreading harvest only happens in conjunction with market opportunities or production technologies that make this behavior profitable, as with the inelastic supply in scenario 1.

In Scenario 3, the harvest path is smooth to maintain high prices due to downward-sloping demand. The same incentives are present as in Scenario 1, so the paths exactly coincide. The only difference is that the effort path dips during the period of biological aggregation. This dip reflects the fact that less effort is needed during this period to maintain the smooth harvest path. 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 (not pictured). 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. This effect is also stronger if demand becomes more elastic, but otherwise the qualitative results in this model are not sensitive to parameter values.

In Scenario 4, the harvest path tracks the biological aggregation. Effort spikes in the aggregation period, and all of the quota is taken in this period. For these parameters, this biological effect on catchability outweighs within-season discounting. Again, this is conditional on having no constraint on per-period effort in combination with constant returns technology. Relaxing either of these assumptions induces some smoothing in catch and effort (not pictured). Overall, none of the results in Figure 3 are surprising, but they provide the intuitive foundation for explaining the more complex multispecies environment below.

4.2 Results with Two Species (Figures 4, 5, and 6)

For all the multispecies fisheries scenarios, we assume that per-period effort is constrained. Without this assumption, the results follow from layering individual single-species cases as described in the previous section. As such, it is the effort constraint that introduces a trade-off with respect to how to allocate effort. As noted in section 3, the effort constraint could reflect a time constraint, maximum hull capacity, amount of fishing gear on a vessel, or some combination of these that limits how much effort that can be exerted in any period. For multispecies models, we also 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, *ceteris paribus*, harvest smoothing for species 1 but not necessarily for species 2. 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 with (Figure 4) and without (Figure 5) biological aggregation. For both models we vary the effort constraint from a very tight one to a very loose one. The scenarios for both sets of results include:

1. Tightest effort constraint ($E_{max} = 1.5$)
2. Moderately tight effort constraint ($E_{max} = 2$)
3. Moderate effort constraint ($E_{max} = 3$)
4. Loose effort constraint ($E_{max} = 5$)

In Scenario 1, 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 effort constraint is sufficiently tight that not all of the season's quota is taken for species 1, and none of quota is taken for species 2.

In Scenario 2, 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 effect, 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.

In Scenario 3, 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. Fishing for species 2 does not stop altogether at some point and continues throughout the year. Species 1 effort actually trends upward due to the stock effect; smoothing harvest requires more effort as the season progresses.

In Scenario 4, species 1 harvest still trends downward for the same reasons as in the previous scenarios, 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 Scenario 2 in which harvest of species 2 ceases in the middle of the year, but the reason different. In Scenario 2, there is not enough effort to continue harvesting species 2 and still catch all of the high-value species 1 quota. In Scenario 4, 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 can emerge from two very different reasons and distinguishing them empirically is tied to whether seasonal quotas bind for both species.

Figure 5 depicts the same four effort constraint scenarios with two species when both have biological aggregation in June and July. The results are qualitatively similar when the biological aggregations are offset; the peaks and troughs follow the biological patterns predictably (not pictured).

In Scenario 1 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 effort constraint, all quota of species 1 is taken, but only a part of the quota for species 2. 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 (not pictured).

In Scenario 2, 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. As in Scenario 1, species 1 effort trends upward during non-aggregation periods, and species 2 effort trends downward. Species 2 effort eventually goes to zero when it is no longer valuable enough to take species 2 due to binding effort constraint, stock effect, and value of taking all of species 1 quota.

In Scenario 3, results are similar as in the moderately tight effort: 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.

In Scenario 4, 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 of aggregation is non-monotonic in the tightness of the effort constraint. It depends on how tightness of the effort constraint induces behaviors in other parts of the year as well. And the overall responsiveness of harvest to effort constraints is greater in the lower-value fishery (compare species 2 harvests for each scenario). 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 effort constraints are sufficiently slack for large-scale trawlers, we might expect more seasonality from these larger vessels.

Because effort constraints have such a substantial impact on the qualitative results above, it is worth exploring further what the total value of loosening these constraints is. We compute present value rents from the two-species fishery without biological aggregation to shed light on this question (Figure 6). The vertical line indicates the point at which all quota for both species is taken. There are rent gains beyond this point that are attributable to within-season effort reallocation. However, these gains are modest. The more significant gains in expanding capacity are those associated with reaching a capacity level that is sufficient to catch all of the quota. Moreover, at the point where both quotas are taken, the gains from reallocation to smooth species 1 harvest and avoid downward price pressure have already been realized. Only if the two

species were closer in price but still having different market structures would we expect to see significant reallocation gains from the endogenously priced species after the quotas are exhausted. The result that there is limited rent gains when sufficient effort is available to take the whole quota conforms with the results of Valcu and Weninger (2013) in a single species setting. Although the two-species scenario varies the effort constraint and keep quotas constant, similar results can be obtained by keeping effort constant and varying the quota. Hence, it is the tightness of the quota relative to effort that matters.

The results provide important insights for fisheries management. If effort is relatively constrained, the less valuable species will not be targeted. However, with increased effort availability either due to effort attracted to fish down stocks, poor management that encourages entry, or technical change, it becomes profitable to target also 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, Benneer, and Smith 2016).

4.3 Results with Three Species (Figure 7)

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 2 is higher value than species 3. We allow for biological aggregation is two periods for each species, but these periods do not perfectly coincide. Species 1 aggregates in months 5 and 6, Species 2 in months 6 and 7, and Species 3 in months 7 and 8. We explore five levels of effort constraint tightness but otherwise use the same parameters as in the two-species model. The scenarios are:

1. Tightest effort constraint ($E_{max} = 1$)

2. Moderately tight effort constraint ($E_{max} = 2$)
3. Moderate effort constraint ($E_{max} = 4$)
4. Somewhat loose effort constraint ($E_{max} = 6$)
5. Loosest effort constraint ($E_{max} = 10$)

Below we describe all of the results but only depict harvest and effort for Scenarios 2 and 3 visually in Figure 7.

In Scenario 1 (not pictured) effort is so tightly constrained 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 reduced some 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 never fished even during aggregation. 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.

In Scenario 2 (Figure 7), 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 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, species 1 harvest is low, and species 2 harvest is zero. Quotas for species 2 and 3 do not bind.

The economic intuition for Scenario 2 is as follows. In month 5, species 1 is the only species aggregating, so the vessel 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 the vessel to catch all of its quota for species 1 over the course of the season but still allocate 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 effort constraint ultimately drives the shut down of species 1 harvest entirely in month 7, where 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), but here some effort still goes to the high-value species 1.

In Scenario 3 (Figure 7), there is enough total effort in the system to exhaust quota for all three species. Species 2 has a declining harvest pattern that goes to zero before its aggregation. Then species 2 harvest spikes during aggregation and returns to zero, and finally another declining pattern starts. Species 3, in contrast, ramps up harvest, then back down, and then spikes for both aggregation periods before returning to zero for the remainder of the time horizon. Species 1 harvest exhibits its usual smooth harvest pattern during non-aggregating periods, increases during species 1's aggregations 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 become higher value when they aggregate due to lower harvesting cost. In contrast, this tendency is partially offset by dampened prices when demand is not perfectly elastic.

Although the many moving parts in the optimization create difficulties in interpreting Scenario 3, the general guiding principal 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 highest 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. less benefit of allocating to other species that are not aggregating. This also helps to explain the declining pattern of species 2 harvest leading up to aggregation. 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? It appears that these increases coincide with achieving equi-marginality from stock effects across species 2 and 3; species 3 harvest costs increase after species 2 harvest costs increase because the lower marginal value of species 2 effort effectively frees up effort for species 3. Interestingly, the season quota binds for the lowest value species first (species 3). This creates a second pattern of declining species 2 harvest after the aggregation period. Intuitively, the marginal value of effort for species 3 is too low after aggregation due to stock effects, whereas the marginal value of species 2 effort is sufficiently high after aggregation because the

price is strictly higher. The harvest and effort patterns of species 3, with a local peak in April, are also interesting because there is no way to explain these outcomes from biological or market conditions for only this species. It is the multi-species setting, when the marginal value of effort applied to other species is accounted for, that creates this type of pattern.

In Scenario 4 (not pictured), results are similar to Scenario 3 but not exactly the same. All quotas bind. Species 1 appears most similar but still has a zero harvest in month 8 (so too 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.

In Scenario 5 (not pictured), effort is effectively unconstrained; 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.

5. Discussion

Our single-species results 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

strongly harvest patterns vary depending on market conditions, stock characteristics, and harvesting capacity even in this simple setting.

Our results demonstrate that simple intuition about fishing behavior rooted in single-species bioeconomic models breaks down when there are multiple target species. In essence, shadow values 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 immediately 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 effort constraints. However, taking the low-value TAC first does not occur in all cases and depends on the relative strength of these effects.

Our model produces patterns that generally conform to those observed in the Norwegian whitefish fisheries. High-value IFQ species (cod and haddock) with fresh markets and corresponding inelastic demand have harvests that are spread out, which is consistent with market timing to avoid gluts. In contrast, saithe harvest is more concentrated to fit its biological aggregation and to reflect the predominantly frozen market. And the saithe quota is not binding in all years. Harvest peaks for the three species are correlated with biological aggregation but not

perfectly, and peaks are sequenced in a way that is consistent with a forward-looking multispecies harvest plan accounting for the opportunity costs of using the vessel. When vessels can target, allocating effort to one species generally implies not allocating effort to the other species.^{vi}

An important policy implication from our modeling is that fishery rationalization in the form of individual quotas 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 in our model it can happen when all species have IFQs.

The combination of harvest capacity, species targeting, and effort timing raises interesting management questions. Low-valued fish is generally harvested only when available effort is sufficiently high, although stock aggregations can reduce harvest costs and make low-value fish attractive to target. 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 too many species. And the 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 leads to a sub-optimal fleet composition. 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 multi-species 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.

Our modeling presumes that the species relevant to the decision problem are all managed with IFQs. When some fisheries are regulated without individual quotas, commons issue can further complicate the fisherman'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 effectively are 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. Extending our model to allow for IFQ fisheries in conjunction with fisheries that have derby fishing incentives is an important topic for future research.

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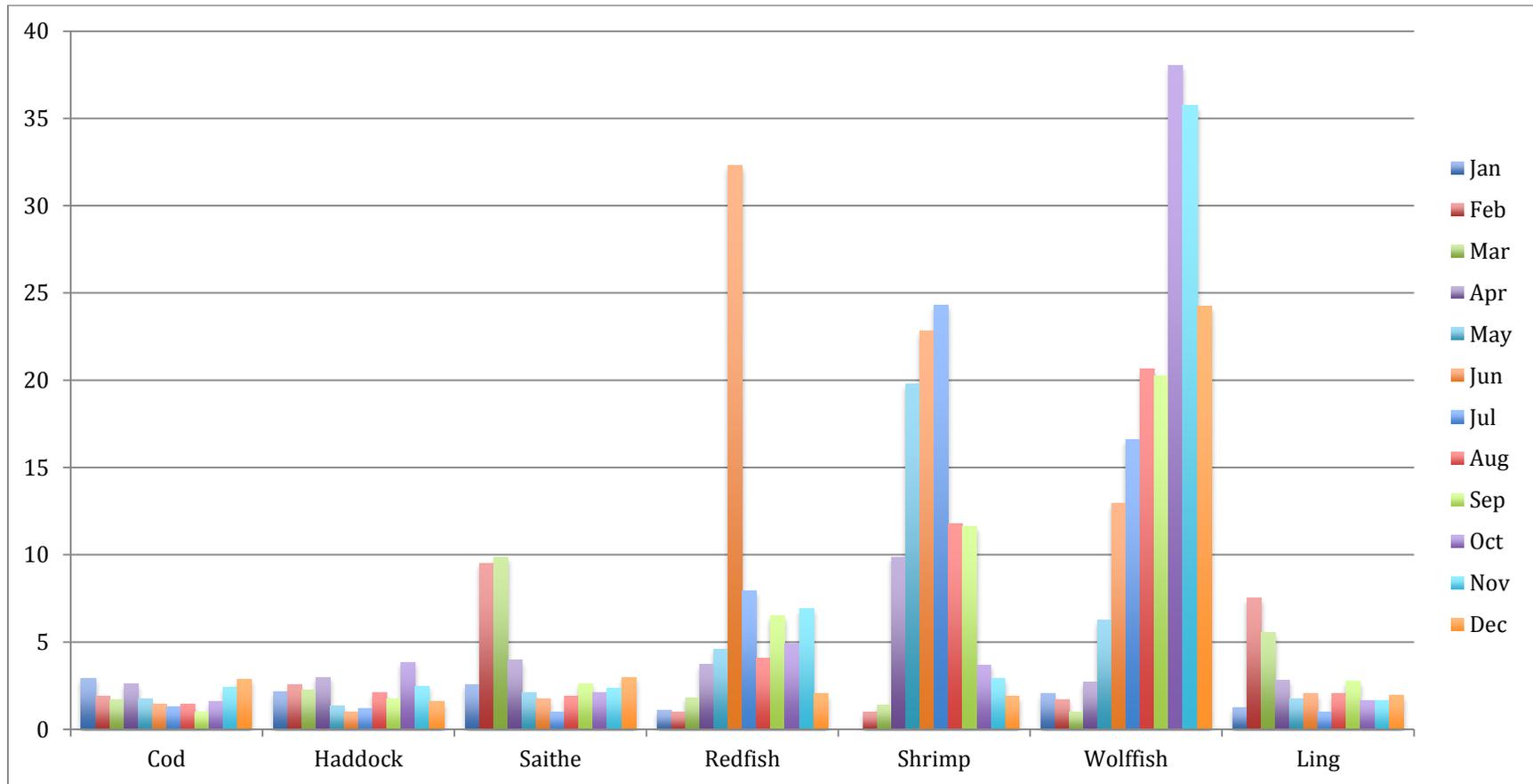


Figure 1. Seasonal landing pattern for different species. For each species, landings are normalized to one for the month with the lowest landings.

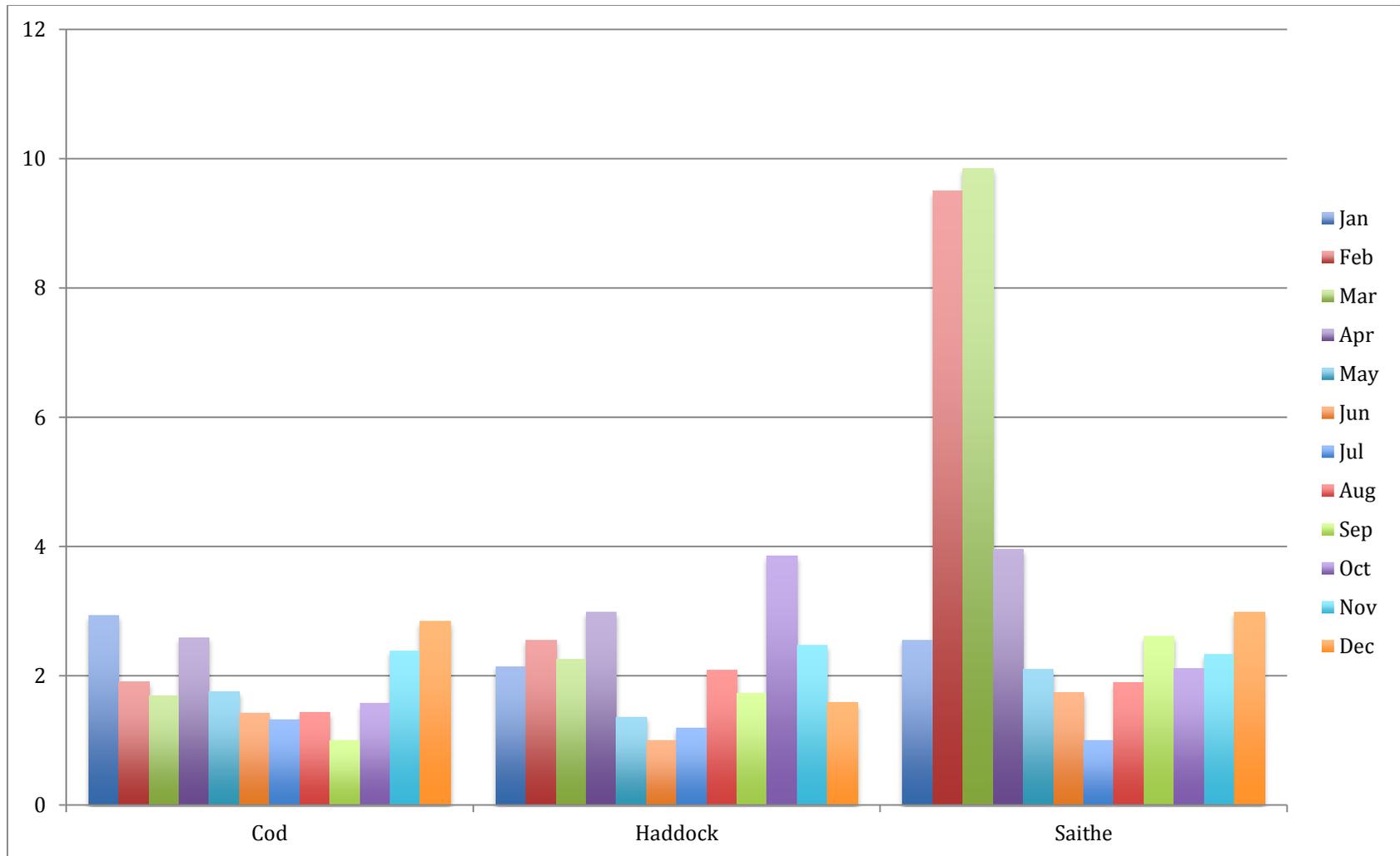


Figure 2. Seasonal landings pattern for cod, haddock and saithe. For each species, landings are normalized to one for the month with the lowest landings.

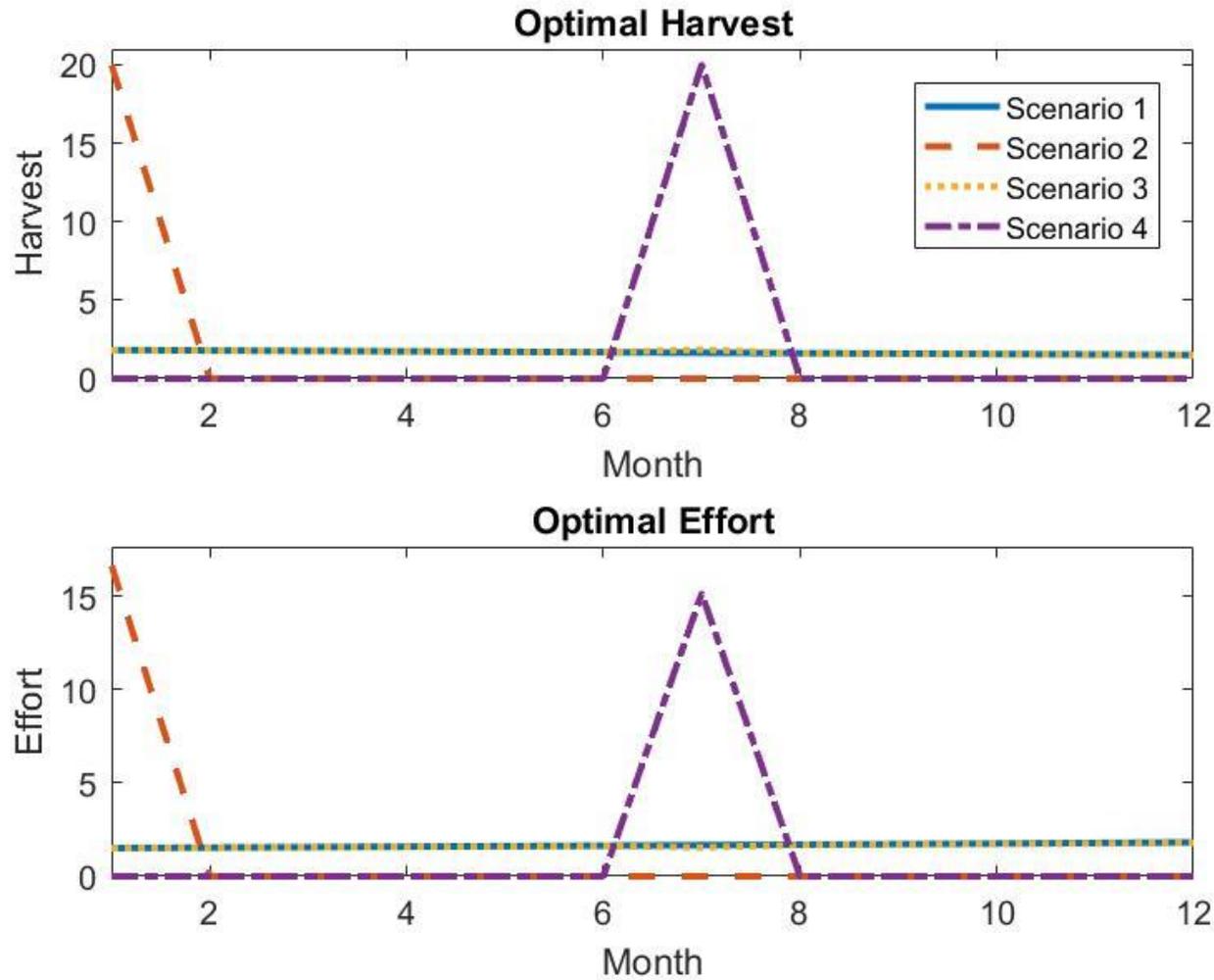


Figure 3. Seasonal harvest (top) and effort (bottom) pattern in a single species fishery. Scenarios include stock effects and endogenous price (1), stock effects and exogenous price (2), biological aggregation and endogenous price (3), and biological aggregation and exogenous price (4).

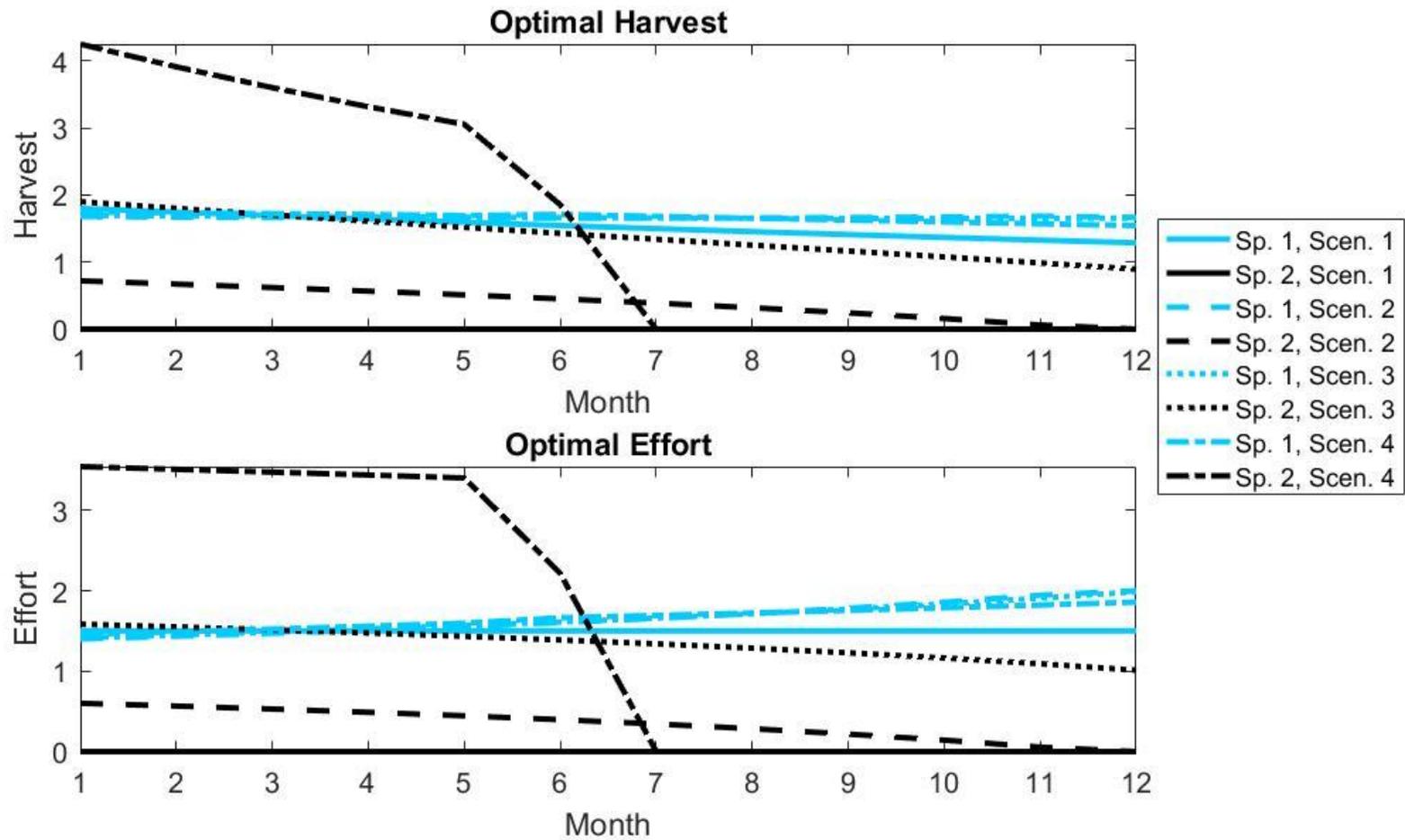


Figure 4. Two-species harvest (top) and effort (bottom) paths without biological aggregation. Scenarios 1 through 4 reflect the tightest through loosest per-period effort constraint. Species 1 faces downward-sloping demand, whereas species 2 has perfectly elastic demand.

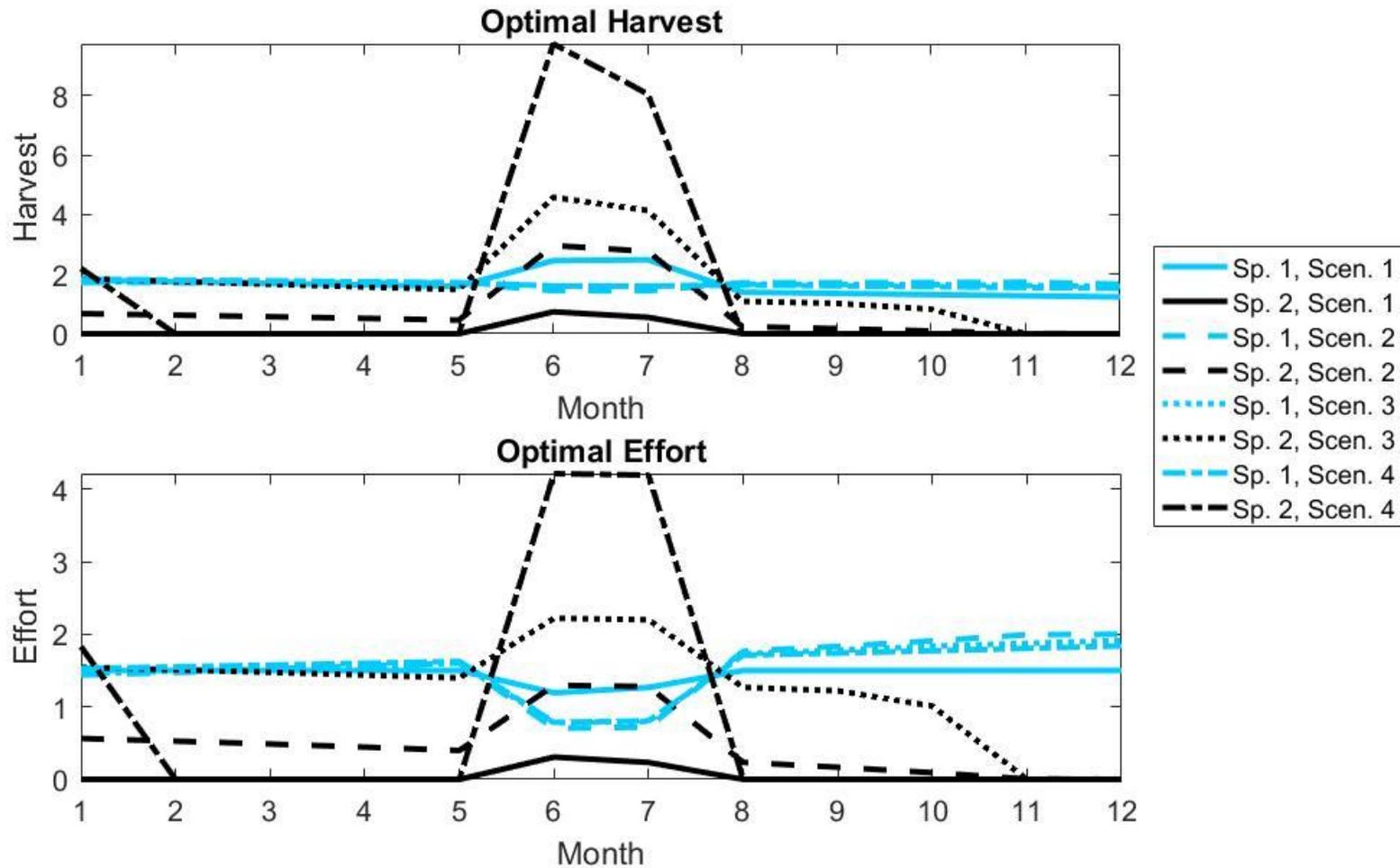


Figure 5. Two-species harvest (top) and effort (bottom) paths with biological aggregation. Scenarios 1 through 4 reflect the tightest through loosest per-period effort constraint.

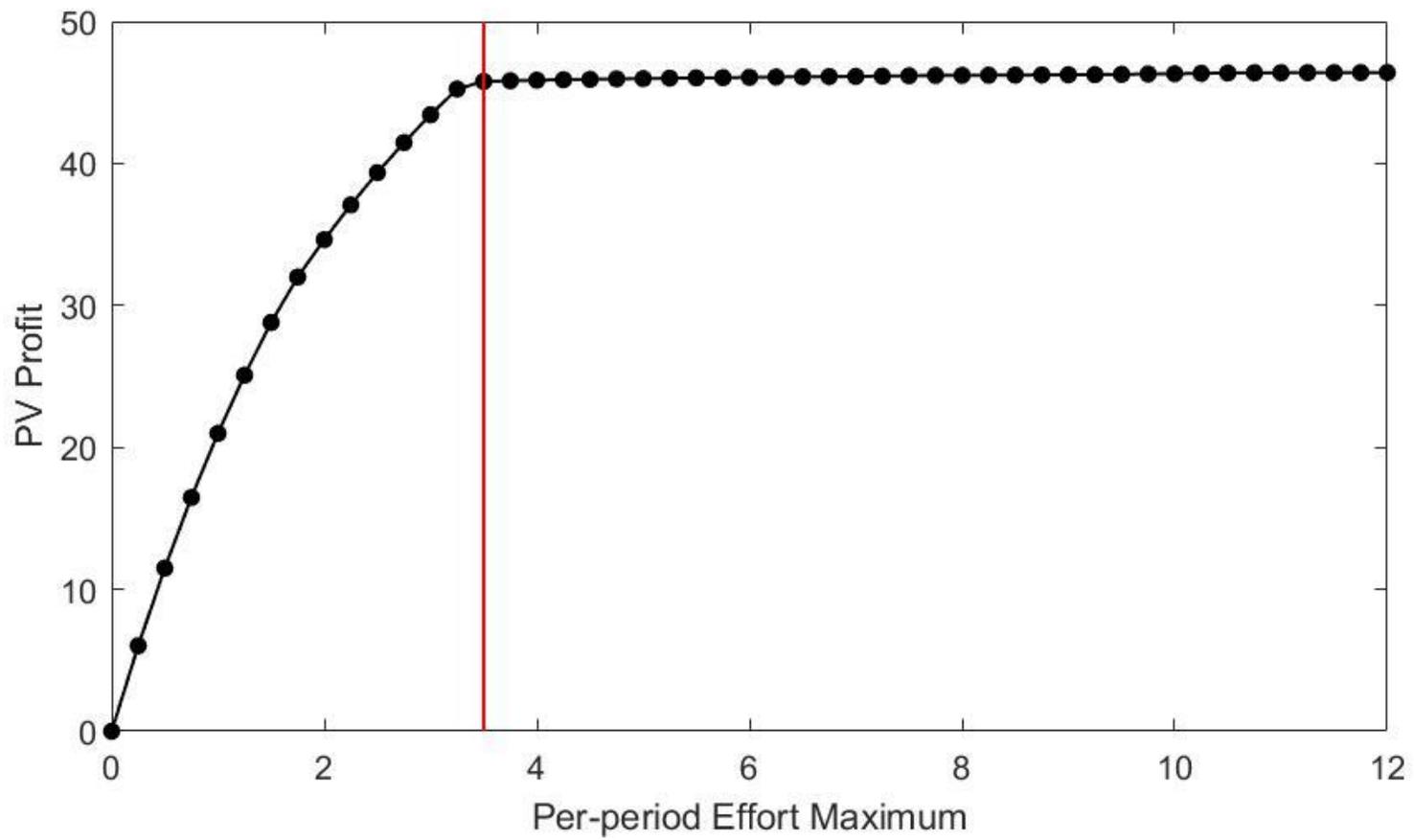


Figure 6. The value of loosening the effort constraint

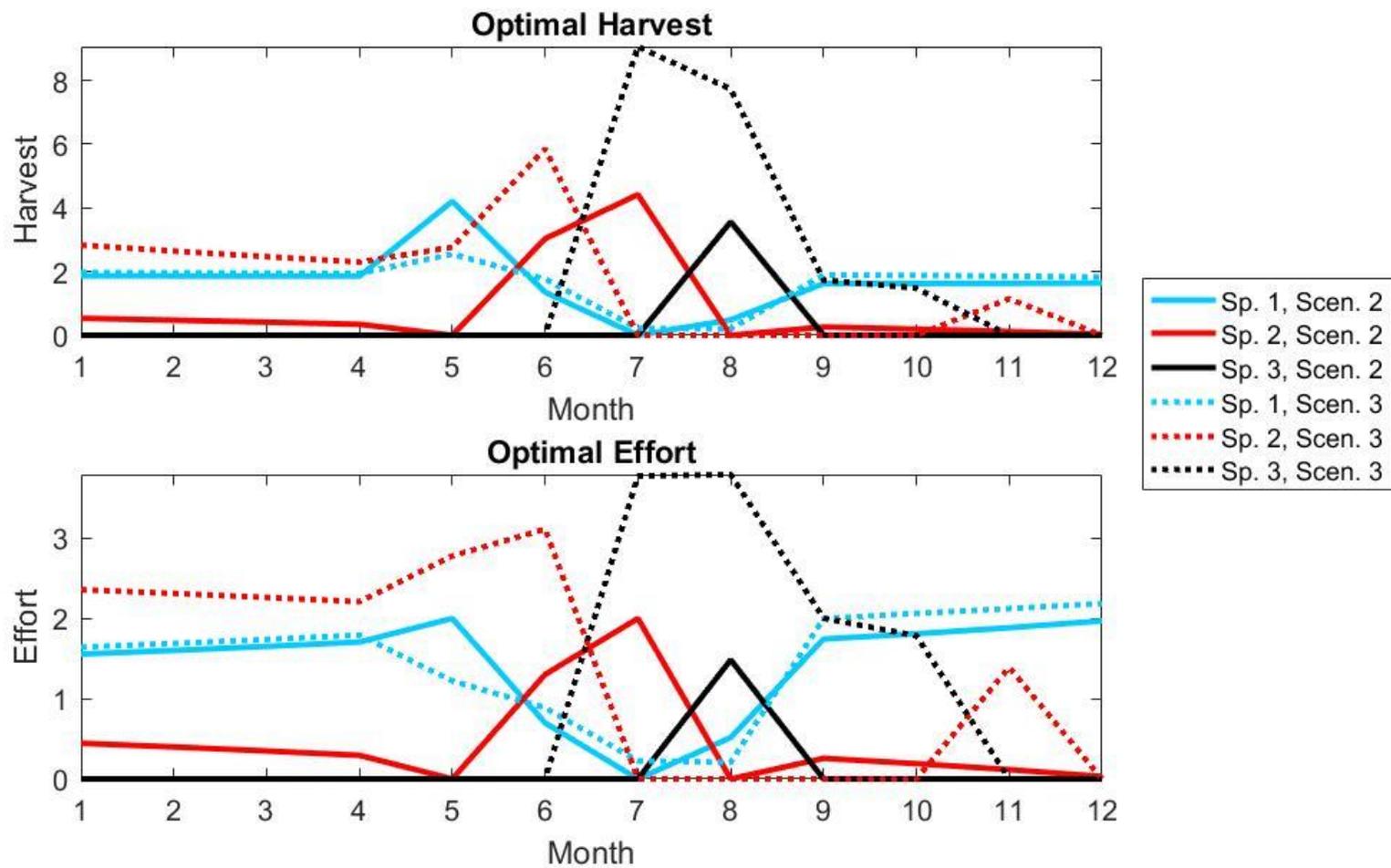


Figure 7. Three-species harvest (top) and effort (bottom) paths with biological aggregation.

Table 1. Landings and variation

Species	Average annual landings	Share of landings	Coefficient of variation
Cod	67,634	0.294	0.33
Haddock	28,218	0.123	0.39
Saithe	95,087	0.413	0.83
Redfish	10,803	0.047	1.32
Shrimp	18,360	0.080	0.88
Wolffish	566	0.002	0.86
Ling	396	0.002	0.72
Total	230,050		0.30

Appendix A –Analytical Results from a Single-Species Model

Some of the results for a single species can be derived and proved in a continuous-time optimal control framework without resorting to numerical simulations. The three propositions that we prove are the key mechanisms driving our more complex multispecies results. Here we focus on the sole owner, exclude biological aggregations (which add significant complications to the analytics), define harvest as h , define the discount rate as δ , and make two assumptions.

Assumption 1: The effort elasticity in the harvest function is one.

$$h(t) = qE(t)X(t)^\beta$$

In essence, this assumption allows us to control the stock effect simply by changing the parameter β . A higher β implies a bigger stock effect.

Assumption 2: The TAC always binds.

This assumption will allow us to analyze the effects of discounting, stock effects, and endogenous pricing by focusing on the slope of the harvest path, $\dot{h}(t)$.

Instantaneous profits are $\pi(t) = p(t)h(t) - cE(t) = [a - b[h(t)]]h(t) - cE(t)$. By rearranging the harvest equation to isolate effort, and substituting into the profit function, we can rewrite profits as $\pi(t) = [a - b[h(t)]]h(t) - \frac{ch(t)}{q(t)X(t)^\beta}$.

Because we assume no within-season biological growth, the state equation takes on a simple, Hotelling-like form:

$$A1) \quad \dot{X}(t) = -h(t).$$

As such, the sole owner solves the following problem:

$$A2) \quad \max_{h(t)} \int_0^T e^{-\delta t} \left\{ [a - b[h(t)]]h(t) - \frac{ch(t)}{q(t)X(t)^\beta} \right\} dt$$

subject to

$$A3) \quad \int_0^T h(t)dt = TAC,$$

and the state equation A1.

The current-value Hamiltonian is:

$$A4) \quad \tilde{H} = [a - b[h(t)]]h(t) - \frac{ch(t)}{q(t)X(t)^\beta} + \tilde{\lambda}(t)[-h(t)],$$

where $\tilde{\lambda}(t)$ is the current-value co-state variable. Because the Hamiltonian is strictly concave in $h(t)$, we expect an interior solution, and the corresponding first order necessary conditions are:

$$A5) \quad \frac{\partial \tilde{H}}{\partial h} = a - 2bh(t) - \frac{c}{q(t)X(t)^\beta} - \tilde{\lambda}(t) = 0$$

and

$$A6) \quad \dot{\lambda}(t) - \delta\tilde{\lambda}(t) = \frac{-\partial \tilde{H}}{\partial X} = \frac{-c\beta h(t)}{q(t)X(t)^{\beta+1}}.$$

Rearranging A5 and taking the time derivative yields:

$$A7) \quad \dot{\lambda}(t) = -2b\dot{h}(t) + \frac{c\beta\dot{X}(t)}{q(t)X(t)^{\beta+1}} = -2b\dot{h}(t) + \frac{-c\beta h(t)}{q(t)X(t)^{\beta+1}}.$$

Now using A7 and the expression for $\tilde{\lambda}(t)$ from A5 to substitute into A6, we can isolate the time derivative of the harvest path:

$$A8) \quad \dot{h}(t) = \frac{-\delta}{2b} \left[a - 2bh(t) - \frac{c}{q(t)X(t)^\beta} \right].$$

Lemma 1: The harvest path is monotonically decreasing.

Proof: The expression inside the square brackets in A8 is marginal revenue less marginal costs, i.e. the scarcity rent. Because scarcity rent is strictly positive, $\dot{h}(t) < 0, \forall t$.

Lemma 2: For any two harvest paths A and B, if $\dot{h}_A(t) > \dot{h}_B(t)$, then $h_B(0) > h_A(0)$.

Proof: Consider four cases: 1) the harvest paths never cross, 2) the harvest paths both reach zero, 3) the harvest paths cross just once, and 4) the harvest paths cross multiple

times. Cases 1 and 4 will lead to contradictions, and $h_B(0) > h_A(0)$ holds for cases 2 and 3.

Case 1: If the paths never cross then, either $\int_0^T h_A(t)dt > \int_0^T h_B(t)dt$ or

$\int_0^T h_A(t)dt < \int_0^T h_B(t)dt$. Assumption 2 states that the TAC always binds. Thus,

$\int_0^T h_A(t)dt = \int_0^T h_B(t)dt$, which contracts both possibilities. Hence, Case 1 cannot

hold.

Case 2: Because $\dot{h}_A(t) > \dot{h}_B(t)$, $\int_0^T \dot{h}_A(t)dt > \int_0^T \dot{h}_B(t)dt$. Integrating both sides yields

$h_A(T) - h_A(0) > h_B(T) - h_B(0)$. Case 2 implies $h_B(T) = h_A(T) = 0$. Thus, $h_B(0) > h_A(0)$.

Case 3: A unique crossing occurs at τ such that $h_B(\tau) = h_A(\tau)$. Because $\dot{h}_A(\tau - \Delta) >$

$\dot{h}_B(\tau - \Delta)$, $h_B(\tau - \Delta) > h_A(\tau - \Delta)$, and thus $h_B(0) > h_A(0)$.

Case 4: Suppose crossings occur at τ and $(\tau + \Delta)$ such that $h_B(\tau) = h_A(\tau)$ and

$h_B(\tau + \Delta) = h_A(\tau + \Delta)$. Because $\dot{h}_A(\tau) > \dot{h}_B(\tau)$, $h_B(\tau + \Delta) > h_A(\tau + \Delta)$, which

combined with $\dot{h}_A(\tau + \Delta) > \dot{h}_B(\tau + \Delta)$, implies that the paths will never cross again and

hence a contradiction.

The following propositions follow from comparative statics of equation A8 combined with these two lemmas and the assumption that the TAC always binds. By signing the change in $\dot{h}(t)$ with respect to each parameter, we can treat the paths with and without the change as $\dot{h}_A(t)$ and $\dot{h}_B(t)$.

Proposition 1: A higher discount rate concentrates more harvest early in the season.

Proof: $\frac{\partial h(t)}{\partial \delta} = \frac{-1}{2b} \left[a - 2bh(t) - \frac{c}{q(t)X(t)^\beta} \right]$. The expression inside the square brackets is the scarcity rent (marginal revenue less marginal cost) from A5, which is strictly positive. Thus, $\frac{\partial h(t)}{\partial \delta} < 0$. By Lemma 2, more harvest occurs early in the season.

Proposition 2: Downward-sloping fish demand spreads harvest more uniformly across the season.

Proof: $\frac{\partial h(t)}{\partial b} = \frac{1}{2b^2} \left[a - 2bh(t) - \frac{c}{q(t)X(t)^\beta} \right] - \left(\frac{-1}{2b} \right) (2h(t)) = \frac{1}{2b^2} \left[a - 2bh(t) - \frac{c}{q(t)X(t)^\beta} \right] + \frac{h(t)}{b}$. The first term is positive as in Proposition 1. Since both terms are positive, $\frac{\partial h(t)}{\partial b} > 0$.

By Lemma 2, less harvest occurs early in the season. By Assumption 2 and Lemma 1, more harvest occurs later in the season, and the harvest path is overall flatter.

Proposition 3: A larger stock effect concentrates more harvest early in the season.

Proof: $\frac{\partial h(t)}{\partial \beta} = \left(\frac{-\delta}{2b} \right) \left(\frac{-c}{q} \right) (-\beta) X(t)^{-\beta-1} = \frac{-\delta c \beta}{2bq} X(t)^{-\beta-1} < 0$. By Lemma 2, more harvest occurs early in the season.

Appendix B – Base parameter values used in numerical simulations (Figures 3-7)

Parameter	Value	Description
q	0.02	Catchability coefficient (non-aggregating)
q_a	0.04	Catchability coefficient (during aggregation)
α	1	Effort elasticity
β	1	Stock elasticity
a_1	2	Choke price species 1
b	0.1	Slope of the demand curve species 1
a_2	1	Choke price species 2
a_3	0.5	Choke price species 3
c	0.25	Cost of effort
δ	0.05	Annual discount rate
H_{max}	20	Total allowable catch
X_0	60	Initial stock level

ⁱ This is also the case for the studies using this approach with trip level data, as one do not interact seasonality with species.

ⁱⁱ 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.

ⁱⁱⁱ Some of the fine-scale empirical literature analyzes behavioral response to changing stock abundance (Smith, Zhang, and Coleman 2008; Zhang 2011; Huang and Smith 2014). These studies highlight the importance of understanding within-season behavior and the cost implications of seasonally fluctuating abundance, but they do not provide a complete understanding of multi-scale dynamics with multispecies fisheries. 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. Zhang (2011) analyzes the entire Gulf of Mexico reef fish complex and finds strong evidence of effort responsiveness to stocks, but the mix of species within the reef fish complex is taken as exogenous. Huang and Smith (2014) account for forward-looking responses to seasonally changing abundance, within-season variation in pricing, and congestion externalities, but they only model shrimp.

^{iv} The average price for cod is 13,68 NOK/kg, for haddock it is 9.21 NOK/kg and for saithe it is 5.62 NOK/kg. This makes cod revenues 67% higher than the saithe revenues.

^v There are no landings of shrimp in January.

^{vi} To what extent a species is targeted varies with biological characteristics, but also with regulatory system (Abbot, Haynie and Reimer, 2015).