Methods

We built a simulation model for three fisheries that are linked by cross-fishery participation. The fisheries are loosely based on Dungeness crab (*Metacarcinus magister*), Chinook salmon (*Oncorhynchus tshawytscha*) and groundfish (Sablefish: *Anoplopoma fimbria*)on the U.S. West Coast. Crab and salmon populations are modeled with random recruitment pulses each year and no across-year survival. This is reasonable for crab, as populations on the U.S. west coast display no stock-recruit relationship and nearly all legal-sized males are caught every year. Salmon populations are almost entirely of hatchery origin, so availability to the fishery depends mainly on hatchery production and ocean survival rates. After being available to the fishery, salmon return to their natal streams to spawn and die, so the available biomass in one year is not dynamically linked to that of the previous year. [Ole ?: are the same fish available from year to year?] Unlike crab and salmon, groundfish are much longer-lived and therefore subject to depletion across years. Therefore, we modeled the groundfish population using a delay-difference model, described X.

Costs of fishing are divided into annual fixed costs that are automatically incurred every year (e.g., permits, boat and gear maintenance) and weekly variable costs that are only incurred if a vessel chooses to fish for a particular species in a given week (e.g., fuel, bait, labor). Fixed costs are constant for all participants, but variable costs vary by vessel according to a lognormal distribution in order to mimic variability in fishing efficiency. This allows for individual vessels to make different decisions through the season as to whether a particular population is profitable in a given week. We wished to ensure that in an average recruitment year, total costs (fixed and variable) would equal total revenue for a marginal fisher (95th percentile of variable costs) who might be considering entry into the fishery. We ensure this condition by using a root-finding routine that projects the fishery in an average year to solve for the mean variable cost given the profitability constraint, fixed costs, and catchability. This profitability constraint means it is a reasonable assumption that annual participation in the fishery and permit costs are both stable. To avoid monte carlo error during the root-finding phase, these vessel-specific variable costs are assigned based on quantiles from the inverse lognormal cumulative density function. For actual simulations, these costs are drawn randomly by vessel, but held constant over time. For simplicity, this variable cost calculation is done independently for each fishery (i.e., vessels do not have other fishing options during the calculations), and is based on a fleet consisting of the same number of vessels as hold permits for the fishery in the baseline scenario.

Fishers are assumed to have perfect knowledge of the available biomass each week, and catchability is held constant with no interference among vessels. Prices are also held constant for groundfish and salmon, so fishers also have perfect knowledge of the revenue and profit they will earn in a week for those populations. Revenue for a boat fishing for population *p* in week *w* of year *t,* *rp,t,w* is:

Where *qs* is catchability of stock *s* (proportion of the population harvested by one boat in one week) and *Ps* is the price per unit biomass of stock *s*. A linear demand function was built for the crab population to 1) better mimic the high level of depletion that occurs and 2) increase the temporal overlap between the realized crab and salmon fisheries. Prices for crab go up linearly once overall weekly catches fall below X% of average recruitment. Fishers use the prices paid for crab in the previous week to calculate expected revenue and profit for the upcoming week. In the first week of the year, X happens. Based on this information, each week each vessel calculates their expected marginal profits (expected revenue – variable costs) for each fishery that is open and for which they hold a permit, and either fish in the most profitable fishery or, if no fishery is profitable, do not fish that week. For vessels holding multiple permits, variable costs across fisheries are correlated (i.e., efficiency across fisheries is correlated for each vessel).

The groundfish population is simulated based on a Deriso-Schnute delay-difference model with a Beverton-Holt stock-recruit relationship. This allows for changes in age structure, an advance from simpler surplus production models, but restrictively assume selectivity and maturity are knife-edged and occur at the same age (Hilborn and Walters 1992, Quinn and Deriso 1999). Although biomass dynamics in this model can be simulated with a single complex equation, for ease, we equivalently modeled both abundance (*N*) and biomass (*B*). For comparability with the crab and salmon populations, we assumed these dynamics occurred at an annual time scale:

Where *st* is total per capita survival in year *t*; *α* and *ρ* are the intercept and slope, respectively, of a Ford-Walford plot (i.e., plot of weight at age vs. weight at age - 1); *wk* is the weight at age *k*; *k* is the age at both recruitment to the fishery and maturity; and *Rt+1* is the recruitment to the fishery in year *t+1*. We assumed a Beverton-Holt stock-recruit relationship, so that:

Where *h*, *R0*, and *B0* are steepness (percent of unfished recruitment occurring at 20% of unfished biomass), unfished recruitment, and unfished biomass, respectively, and *Ht-k* is the proportion of the biomass that was harvested in year *t-k*. This formulation presumes that reproduction occurs after fishing and before natural mortality. Unfished biomass is calculated based on equilibrium conditions as *R0*/*κ* where *κ* is the growth-survival constant:

The growth parameters *α* and *ρ* were calculated by taking the weight at age from the stock assessment’s age-length and length-weight relationships and estimating a linear regression through the resulting points (which are almost, but not exactly, linear). We fixed weight at recruitment (age 4), to 1, as with the salmon and crab.

Because the groundfish population dynamics respond to the fishery dynamics, tuning the fishery parameters was more complicated than for crab or salmon. First, catchability was set so that when all 200 vessels 40 weeks of the year, yield is equal to the level that leads the population to equilibrate at 40% of the unfished biomass. We then fixed the variable cost and solved for the fixed cost such that the 5th percentile vessel had no net profit when the population equilibrated at 40% of unfished biomass. In addition, we checked that the lowest quantile vessel would still cover its variable costs in the final week of the year, ensuring that all vessels would in fact fish every week.

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| Parameter | Definition | Value (if fixed) |
| *B* | Biomass |  |
| *N* | Abundance |  |
| *t* | Time (year) |  |
| *w* | Week |  |
| *s* | Total survival (includes natural and fishing mortality) |  |
| *M* | Natural mortality rate | 0.07 yr-1 |
| *α, ρ* | Intercept, slope, respectively, of Ford-Walford plot (i.e., weight at agevs. age - 1) | 0.459, 0.736 |
| *R* | Recruitment |  |
| *R0­, B0* | Unfished recruitment, biomass, respectively | *R0*: salmon=1, crab=1, groundfish=0.5 |
| *h* | Stock-recruit steepness (“resilience”) | 0.6 |
| *H* | Harvest rate |  |
| *r* | Revenue |  |
| *k* | Age at recruitment | 4 |
| *p* | Population (index) |  |

Results

More access:

1. Decreases average profits and revenue of individuals within a fleet: less fish per person
2. Decreases crab revenue because derby fishery floods markets, prices are low
3. Increases salmon and groundfish revenue because more permits means more fish caught
4. Increases variability of salmon and groundfish revenue (CV & SD)
5. Decreases inequality in mean revenue because more people have access to high value fishery
6. Decreases profit/revenue SD within a fleet for anyone who has a crab permit
7. Decreases revenue CV across all individuals (except also eliminates groundfish specialist hump near zero)
8. Decreases *spread* of revenue CV distribution for crab and crab/salmon fleets— decreases instances of high *and* low variability individuals/simulations (which?)
9. Complicated impact on total summed revenue/profits. No/minimal change in variability.

Asynchrony:

1. No impact on mean profit/revenue of individuals
2. No impact on mean or variability of profit/revenue by species
3. Decreases individual profit/revenue variability for those in fleets with crab & salmon in permit portfolio.
4. Decreases total summed profit/revenue variability