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Fishery participation and location choice model: the West Coast salmon troll commercial fishery

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Abstract

Random utility models have been widely used to model spatial choice within fisheries, but less attention has been paid to modeling participation and movement between fisheries. Fishers may switch fisheries in response to time closures or changes in profitability potentially creating management implications for those fisheries, as well as the fishery with the closure. We used a random utility maximization framework to model participation, fishery choice, and location choice for a large fleet of West Coast salmon trollers, many of which also participate in other fisheries. We used the model to demonstrate substitution effects across fisheries due to spatial policies implemented in the salmon fishery. Our work suggests that spatial management of a single fishery needs to take into consideration fishers' full choice set to predict behavioral responses to spatial policies. Our analysis also provides insights into how fishers construct multifishery harvest strategies that enable them to more fully use capital or adjust to closures or changes in relative profitability.

Key words: fishers' behavior, spatial behavior, fishery participation, ocean fisheries, fisheries management, random utility model

1. Introduction

Spatial policy instruments are frequently used to manage fisheries, which has motivated an extensive literature that explores how fishers' location choices respond to differences in profitability over space (Eales and Wilen 1986; Dupont 1993; Smith and Wilen 2003), changes in spatial policies (Curtis and Hicks 2000; Holland and Sutinen 2000; Hicks et al. 2004; Haynie et al. 2009; Haynie and Layton 2010), and regulatory constraints on bycatch (Abbott and Wilen 2009; Hicks et al. 2020). These studies have shown that fishers respond to profit differentials across space, a result consistent with seminal fisheries economic theory (Gordon 1954). However, fishers also exhibit inertia, tending to prefer fisheries or locations they have fished before (Bockstael and Opaluch 1983; Holland and Sutinen 2000; Smith 2005), and decisions are often affected by both financial and physical risk considerations (Dupont 1993; Mistiaen and Strand 2000; Smith and Wilen 2005; Pfeiffer and Gratz 2016).

Most fisheries behavioral models focus on only a single fishery in isolation of other fisheries, considering only location choice or, in a few cases, binary participation behavior (Ward and Sutinen 1994; Pfeiffer and Gratz 2016). There has been less consideration of whether fishers respond to regulations and profit differentials by switching to other fisheries. A few studies have looked at spillover issues caused by regulations that restrict fishery access or catch by estimating multispecies restricted profit functions (Asche et al. 2007; Hutniczak 2014; Squires 2016) or using difference-in-difference approaches to identify specific policy responses (Cunningham et al. 2016). These approaches are useful for understanding substitution induced by access and quota constraints but are arguably less suited to investigating impacts of time–area closures and changes in the temporal availability of different species that alter the underlying production possibilities fishers face (Reimer et al. 2017).

Random utility maximization (RUM) models offer an alternative way to model switching behavior that can identify how characteristics of fishing choices in combinations with attributes of fishers affect substitution behavior. The seminal RUM model applied to fisheries (Bockstael and Opaluch 1983) modeled annual fishery choice decisions in a discrete choice RUM framework, but it did not evaluate switching behavior within the year. Fishers' responses to profitability or regulations (e.g., spatial closures) in one fishery may spill over to, or be affected by, conditions in other fisheries within a fishing year, especially in cases where fishers switch between several fisheries on a seasonal or more frequent basis (Stafford 2018; Kroetz et al. 2019). Holland and Sutinen (1999, 2000) did consider simultaneous fishery and location choice, but they did not explicitly consider the decision not to fish, which can be important for predicting aggregate effort levels. Stafford (2018) compared a RUM model of participation in lobster and stone crab fisheries that included a no-fishing choice with a "naïve" model that groups stone crab participation with the decision not to fish at all. She showed that grouping these choices leads to biased parameters and incorrect predictions about response to policies in one fishery when conditions and participation in substitute fisheries are not explicitly modeled.

In our study, we utilized a model structure similar to Stafford's (2018), but we addressed a more intricate choice setting. This involved fishers making selections between fishing areas within a fishery, among fisheries, and with varying choices seasonally due to phenology, seasonal closures, and access privileges. To estimate a nested logit model of fishery participation and location choice (FPLC), we employed a static RUM framework that allowed for spatial movement within the West Coast salmon troll fishery, substitution to other fisheries, or temporary exit from fishing. The model characterizes observed salmon fishers' behavior on a weekly basis and assumes myopic behavior, where salmon fishers utilized recent and old revenue information, as well as available fishery and location alternatives to predict fishery participation and location choice behavior on a single time period, without forward-looking behavior. Through an empirical investigation, we sought to understand movement and switching behavior, and how spatial and temporal closures, intended to protect species in one fishery, might affect fishers' targeting behavior across space and different fisheries in a nondynamic framework.

Empirical results from the FPLC model were used to predict behavioral responses and compare predicted probabilities with observed choices. Further, the model was used to demonstrate how salmon commercial fishers respond to closures in specific salmon management areas. This research contributes to addressing concerns raised in the ecosystem-based fishery management (EBFM) literature, which call for shifting the traditional paradigm of single-species modeling and management to paradigms that recognize the existence of multispecies interactions at biological and economic levels. This work highlights the importance of recognizing that spatial linkages are dictated not only by biological systems, but also by economic conditions and fishers' targeting behavior (Smith and Wilen 2003; Kroetz et al. 2019; Caballero et al. 2023).

The remainder of this article is organized as follows. Section 2 provides background information about the West Coast salmon troll fishery, describes the fishery participation and location choice data used, and presents a behavioral model that characterizes the West Coast salmon fishery. Section 3 presents results of the FPLC model and evaluates the effect of closures in the salmon fishery on the behavior of fishery participation. Conclusions are summarized in Section 4.

2. Materials and methods

2.1. West Coast salmon fishery and alternative fisheries

In this subsection, we provide a brief description of the fishery, describe the management regime, and the participation behavior of salmon fishers. West Coast commercial salmon fishers target two main species of salmon—chinook (*Oncorhynchus tshawytscha*) and coho (*Oncorhynchus kisutch*)—using troll and gillnet gear methods.[1] Salmon fishers troll with a number of lures or baited hooks through the water using "cannon balls" and spreader rigs at depths of up to 80 fathoms (Commission 2000). The commercial fishing season typically runs from May to September/October each year, with variable opening and closure dates, annual and in-season closures are common due to concerns about Endangered Species Act (ESA)-listed stocks[2]. For example, in 2008, all management areas south of Cape Falcon were closed because of concerns about Sacramento River fall chinook and Klamath River fall chinook. In 2023, the Pacific Fishery Management Council (PFMC) mandated the seasonal closure of all California ocean commercial fisheries from the Oregon/California border to the US/Mexico border and limited fishing opportunities off the Oregon coast due to concerns on the same stocks.

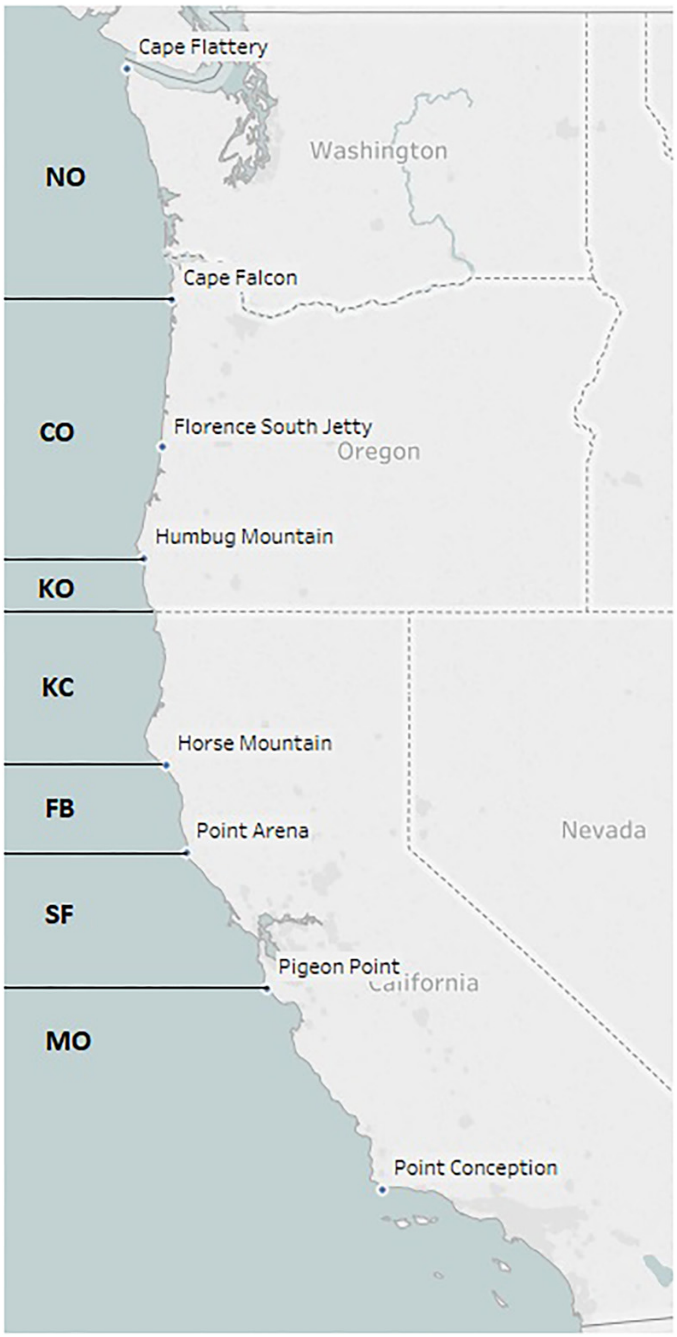
The PFMC manages the West Coast commercial ocean salmon troll fishery with state and tribal co-managers. The PFMC regulates fishing areas, seasons, quotas, gear, and landing restrictions for salmon taken in the US exclusive economic zone off the coast of Washington, Oregon, and California, to prevent overfishing and distribute the ocean harvest equitably among treaty Indian, nontreaty commercial, and recreational fisheries consistent with the Pacific Salmon Treaty (Council 2016). Commercial salmon fisheries management measures are developed for seven management areas from the US/Canada border to the US/Mexico border, with special measures to protect endangered stocks. Figure 1 displays management areas as defined in the salmon fishery management plan (Council 2016). For the reminder of the paper, we refer to each management area by the two-letter abbreviation listed in Fig. 1.

Many West Coast salmon troll fishers, the subjects of this study, also participate in other fisheries, including dungeness crab (*Cancer magister*), highly migratory species such as albacore tuna (*Thunnus alalunga*), and the multispecies groundfish fishery. The crab fishery begins in early December and lasts until August, but many fishers exit early as catch rates decline. Crab pots are used exclusively for commercial crabbing. Since 1995, the fishery has operated under a limited entry permit system that restricts the number of vessels and pots. The highly migratory fisheries use troll gear and spreader rigs similar to salmon trolling, and typically runs from July to early October. Although it is an open access fishery, only salmon fishers with larger, more mobile vessels tend to participate in this fishery. The groundfish fisheries target several species such as sablefish, cod, rockfish, sole, flounder, and Pacific whiting. The PFMC regulates the fishery, which has limited entry, catch share, and open-access sectors.

[1] Gillnet gear is only employed in the Columbia River by vessels with in-river permits. These vessels do not participate in Oregon ocean fisheries and were not part of this study.

[2] Current ESA-listed chinook (*Oncorhynchus tshawytscha*) includes Upper Columbia spring, Sacramento River winter-run (endangered), Snake River spring and summer, Snake River fall, Upper Willamette spring, Lower Columbia, Puget Sound, and California coastal (threatened).

Fig. 1. Non-Indian commercial salmon management areas. Management areas are abbreviated as follows: NO, US/Canada border–Cape Falcon; CO, Cape Falcon–Humbug Mt; KO, KMZ Oregon Humbug Mt–OR/CA border; KC, KMZ OR/CA border–Horse Mt; FB, Horse Mountain–Point Arena; SF, Point Arena–Pigeon Point; and MO, Pigeon Point–US/Mexico border. Source: Salmon fishery management plan (Council 2016).



Management measures include tradable quotas, trip and landing limits, area restrictions, seasonal closures, and gear restrictions. Open-access participants have small trip limits. Measures are adjusted routinely every 2 years. While it is known that salmon trollers participate in these fisheries (Commission 2000), there is no study that models salmon trollers' fishing behavior across fisheries.

2.2. Data

Our characterization of the participation and location choice behavior of west Coast commercial salmon troll rely on fish ticket (FT) data from the Pacific Fisheries Information Network (PacFIN).We obtained FT data with the permission of the California Department of Fish and Wildlife, Oregon Department of Fish and Wildlife, and Washington Department of Fish and Wildlife. FT information used in this analysis included the vessel identifier, landing date, landing port, species group identifier, quantity landed, unit price, and ex-vessel revenue. The data obtained from PacFIN corresponded to FTs associated with salmon trollers that landed 95% of the total salmon troll fishery ex-vessel revenue per year during the years of 2005 through 2014. The dataset consisted of 268 741 entries associated with 619 vessels. For this analysis, each individual FT was assumed to describe attributes of a single fishing trip that targeted species from a single fishery. In the dataset, only 6.5% of FTs recorded species from multiple fisheries, and entries from the species groups with the highest ex-vessel revenue were retained.[3]

We created a panel dataset by aggregating individual FTs weekly. The dataset records fishery participation for all vessels at the same time step and allowed for constructing a non-participation choice for any 1 week interval in which a vessel did not record a single FT. Using weekly fishery participation data also facilitated comparisons of expected revenues across fisheries with trips of different lengths[4]. Alternatively, we could have used days as time steps by dividing up multiple daytrips. However, daily choice occasions would not have provided a clear benefit because we tend to see little day-to-day switching between fisheries or areas and obtaining parameters of a nonlinear choice probability function would have greatly increased the computational burden.

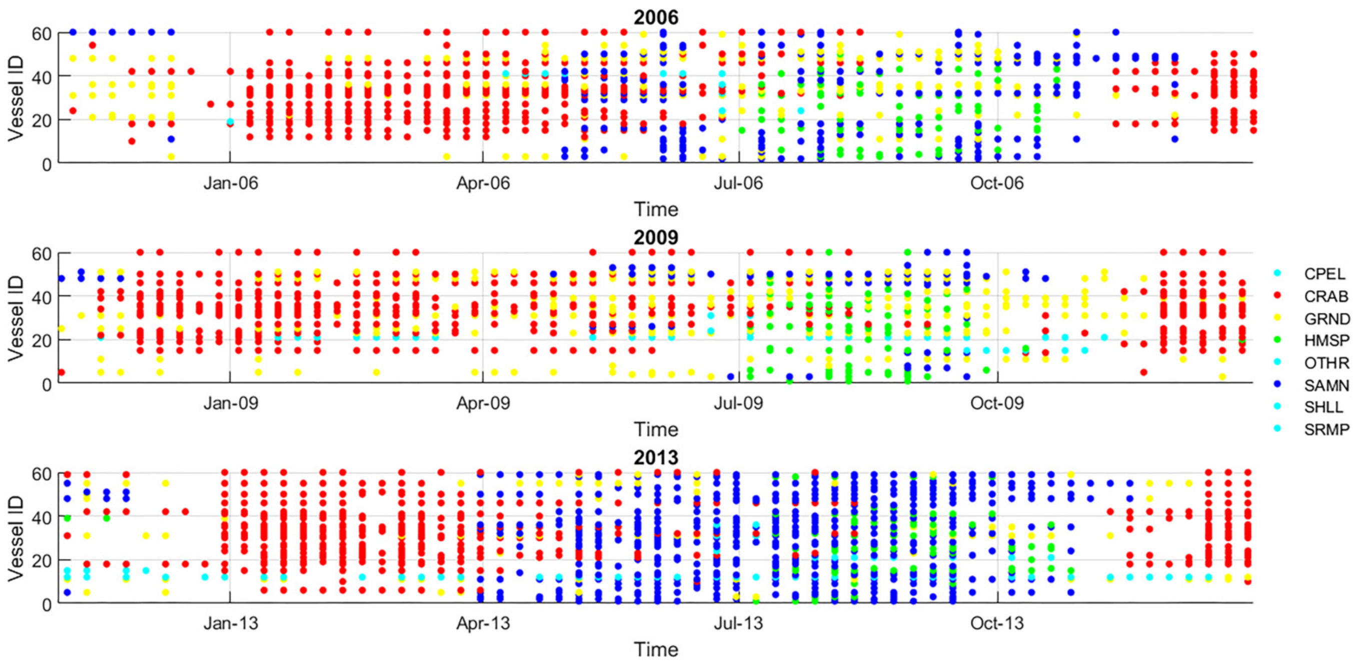
The data demonstrate heterogeneity in fishery participation behavior across several fisheries, including crab, groundfish, highly migratory species (mainly albacore tuna), coastal pelagic, shellfish, shrimp, and others. Figure 2 displays the weekly fishery participation for a random sample of 60 vessels over 3 arbitrary years. The figure shows that the annual fishing cycle of salmon fishers appeared to begin before the start of a calendar year, as they participated in the crab fishery in November or December[5]. The first significant switch by salmon fishermen occurred when fishers left the crab fishery and began participating in the salmon fishery in May. A second major switch occurred in July, when some salmon fishers started participating in the albacore tuna fishery. The switch between the salmon fishery and the groundfish fishery was less apparent and more intermittent. Another observation

[3] To justify this selection criterion, we assumed that the target species group of a fishing trip was the species group with the highest landing revenue; all other species landed were captured as bycatch.

[4] While crab, groundfish, and salmon trips have a mean of close to 1 day fished, albacore tuna trips have a mean of 5.8 days per week.

[5] Sometimes the crab fishery does not open until January.

Fig. 2. Weekly fishery participation across all fisheries. Each plot depicts weekly fishery participation for the same 60 randomly selected salmon troll vessels. Each dot represents fishery participation, where each fishery is represented by a different color. Labels: CPEL (coastal pelagic), CRAB (crab), GRND (groundfish), HMSP (highly migratory species), OTHR (other species), SAMN (salmon), shell (SHLL), and shrimp (SRMP). For comparison purposes and because of the low number of observations, CPEL, SHLL, and SRMP fisheries were aggregated into the OTHR category and colored in cyan.



from Fig. 2 is that nonparticipation behavior (represented by empty spaces) was highly recurrent among all vessels. The months of October and November appeared to be an idle period for most vessels.

The data also demonstrate that while some vessels solely targeted salmon, others engaged in two or more fisheries. Table 1 displays the percentage of vessels that participated in the most representative combinations of fisheries over the years. For example, only 14% of the vessels in the sample solely participated in the salmon fishery, whereas 23%, 16%, 11%, 9%, and 7% of vessels engaged in the following fishery combinations: salmon/highly migratory, salmon/highly migratory/crab, salmon/crab, salmon/crab/groundfish, and salmon/highly migratory/crab/groundfish. Figure 3 depicts the switching behavior of vessels that participated in two or three fisheries. The figure illustrates that, as the salmon season opened, fishers who also participated in the crab fishery started leaving it to join the salmon fishery. In some cases, fishers continued participating in the crab fishery after joining the salmon fishery, but this was a relatively small portion of the fleet. Fishers who participated in the highly migratory fishery followed a similar pattern, first participating in the salmon fishery early in the salmon season and then switching to the highly migratory fishery in early July. For vessels that participated in both the salmon and groundfish fishery, the switching behavior was more intermittent. Once a vessel began participating in the salmon fishery, it was likely to continue participating in the groundfish fishery as well. Although Fig. 3 shows the switching behavior of vessels in 2014, this behavior was consistent across all years in the sample.

FT data offer coarse scale catch information that varies across fisheries. Our dataset only indicates where the catch was landed, not where the trip originated. Since the catch-area information does not allow for distinguishing fine-scale fishing location choices common to all fisheries, the landing location served as a proxy for fishing location choices. In particular, we assigned each landing port and its corresponding fishing trips to a unique salmon management area that included the port area. This is a reasonable assumption provided that in most cases, though not all, there are management prohibitions in the salmon fishery that do not allow for landing outside of the management area where fish were caught. Furthermore, the Oregon Department of Fish and Wildlife internal studies using logbook data show that commercial salmon vessels that participate in the salmon fishery have very low probabilities of targeting fishing grounds greater than 25 miles from the landing port due to catch handling, vessel design, and management prohibition (Davis, personal communication). Although salmon management areas provide only a coarse-scale fishing location choice, they are the best available first-approximation choice for modeling salmon fishers' spatial behavior, since management areas are the most relevant scale to managers, and spatial policies are implemented at the management-area level.

2.3. Model

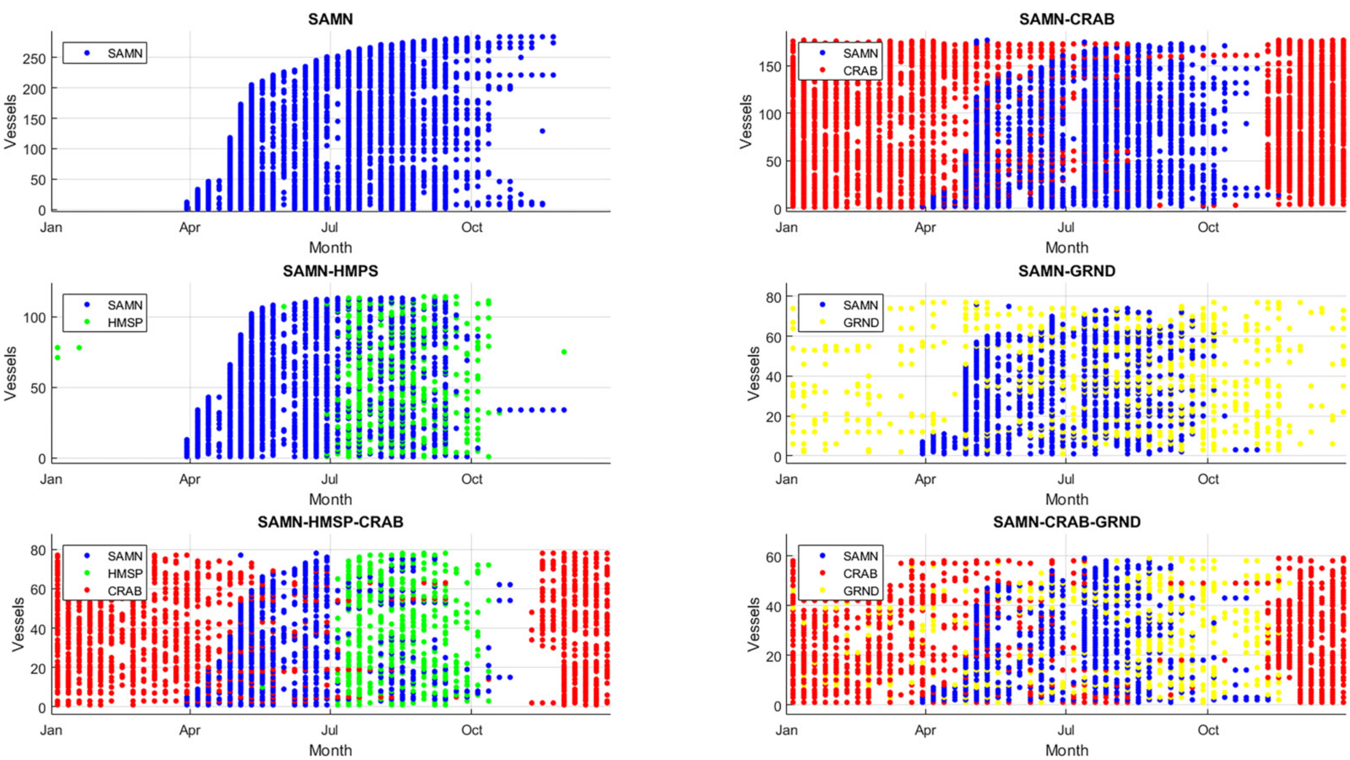
The West Coast salmon FPLC model captures the fishing choices made by fishers from a set of discrete fishing alternatives. The FPLC alternatives consist of not participating in any fishery, participating in the salmon fishery in one of the

Table 1. Proportion of vessel fishery participation for all years, 2005–2014.

Salmon	Highly migratory species			23.28%
Salmon	Highly migratory species	Crab		16.58%
Salmon				14.11%
Salmon	Crab			11.29%
Salmon	Crab	Groundfish		9.35%
Salmon	Highly migratory species	Crab	Groundfish	7.41%
Salmon	Highly migratory species	Groundfish		6.70%
Salmon	Groundfish			6.53%
Other				4.76%

Notes: Other category comprises all other possible fishery participation combinations. Percentages were calculated based on observed behavior across all years.

Fig. 3. Switching behavior across fisheries by portfolio of fisheries. Each plot depicts fishery participation of salmon troll vessels for the year 2014. Plot 1 (upper-left corner) shows participation behavior of vessels that participated exclusively in the salmon fishery. Plot 2 (upper-right corner) shows participation behavior of salmon troll vessels that also participated in the crab fishery, and so on. Vessels are listed according to the earliest date they participated in the salmon fishery. Color code: salmon fishery (blue), crab fishery (red), highly migratory fishery (green), and groundfish fishery (yellow).



management areas (NO, CO, KO, KC, FB, SF, and MO), or participating in an alternative fishery[6], such as the dungeness crab fishery, the highly migratory fishery, the groundfish fishery, or other fisheries; the other fisheries category includes participation in the shell, coastal pelagic, and shrimp fisheries. We formulated a representative utility for each alternative as a function of alternative-specific and individual-specific attributes, using FT data and vessel characteristics available from vessel registration data.

Although observed choices suggest that not all fishers participated in all fisheries, we included all alternatives in the choice set for all vessels. By doing so, we treated all fisheries and salmon management areas as potential choices for all vessels, regardless of their past behavior.[7] Additionally, our data showed that fishers' harvesting portfolios changed over time, indicating that non-observed choices in a given salmon season were latent alternatives chosen in later

[6] Location choices were defined only for the salmon fishery given management closures by region and the migratory behavior of the species.

[7] Alternatively, one can define an individual choice set based on observed past behavior. However, the recreation and transportation demand literature has shown that neglecting or mis-specifying individual choice sets may lead to biased parameter estimates in RUM models (Manski 1977; Parsons et al. 2000).

seasons. Although most of the fisheries we modeled required permits, they were transferable and could be acquired by a vessel owner through purchase or lease, despite some being costly. Therefore, we can assume that fishers' considerations for fishery participation between seasons are open to any available fishery.

Given the observations from our dataset, we assumed a nested choice set structure for salmon fishers grouping them into three levels of choices. At the first level, we model the choice of whether to participate in any fishery and the choice set is defined as $P = \{Nonparticipation, Participation\}$. If the choice is to not participate in any fishery, the alternative chosen is nonparticipation. However, if the decision is to participate, the fisher then selects one of the five fishery alternatives, and the second-level choice set is defined as $F = \{crab, groundfish, highly\ migratory, other, salmon, nonparticipation\}$. If the decision is to participate in the salmon fishery, the fisher chooses one of the seven salmon management areas, and the third-level choice set is defined by all 12 alternatives. This three-level choice structure has been used in previous literature on fishers' behavior (Holland and Sutinen 2000; Stafford 2018). The nested model specification is assumed for statistical reasons, but does not necessarily imply or require that these decisions are hierarchical and sequential.

2.3.1. The representative utility

Drawing on the extensive literature on modeling fishers' behavior (Bockstael and Opaluch 1983; Eales and Wilen 1986; Ward and Sutinen 1994; Holland and Sutinen 2000; Haynie and Layton 2010), we defined the representative utility as a linear function of alternative-specific variables, case-specific variables, and alternative-specific constant terms. Specifically, the fisher n's representative utility of choosing alternative j at time t can be written as:

$$V_{njt} = \alpha_j + \beta ER_{njt} + \sum_{i=1}^{I} \theta_i d_{njt,i} + \sum_{m=1}^{M} \mu_m Y_{n,m} + \vartheta MA_n + \epsilon_{nit}, \quad (1)$$

where the variable ER_{njt} denotes the expected revenue, which varies across fishers, alternatives, and time. $d_{njt,\,i}$ represents the i state dependence variable, which indicates the alternatives chosen in previous period. The total number of state dependence variables is denoted by I, and these sets of variables also vary across fishers, alternatives, and time. $Y_{n,\,m}$ represents the m vessel characteristic of vessel n, for a total of M vessel characteristics. MA_n is a variable that indicates the dominant management area chosen by the n vessel and serves as a proxy to capture lower travel cost associated with choosing a fishing location choice closer to home port.[8] ϵ_{njt} indicates the unobserved part of the utility, which varies across vessels, alternatives, and time. The parameter α_j represents alternative-specific constant. The parameters α_j, β, θ_i, μ_m, and ϑ are to be estimated statistically.[9]

2.3.2. The expected revenue

We modeled the expected revenue variable, ER_{njt}, as a function of coarse, fine, and finest scale information following the Abbot and Wilen (2011) rational expectations approach. A brief description of the estimation procedure is provided here, with a more detailed explanation in the accompanying supplementary materials (SM). To estimate the expected revenue variable, we used observed weekly revenues from aggregated FT data. However, using observed data from heterogeneous vessels (see Table S2), different fisheries, and different periods during a single fishing season can pose several issues. To address these issues, we first normalized observed weekly revenues using a translog revenue function based on vessel characteristics; Table S3 presents the results of the translog revenue function, while Table S5 and Fig. A3 provide a summary of statistics for different groups of vessels and their categorizations, respectively. Normalization enabled us to use observed weekly revenues from a particular vessel to predict expected revenues for a vessel with different characteristics using an standardization factor, see Fig. S1 (Holland and Sutinen 2000).

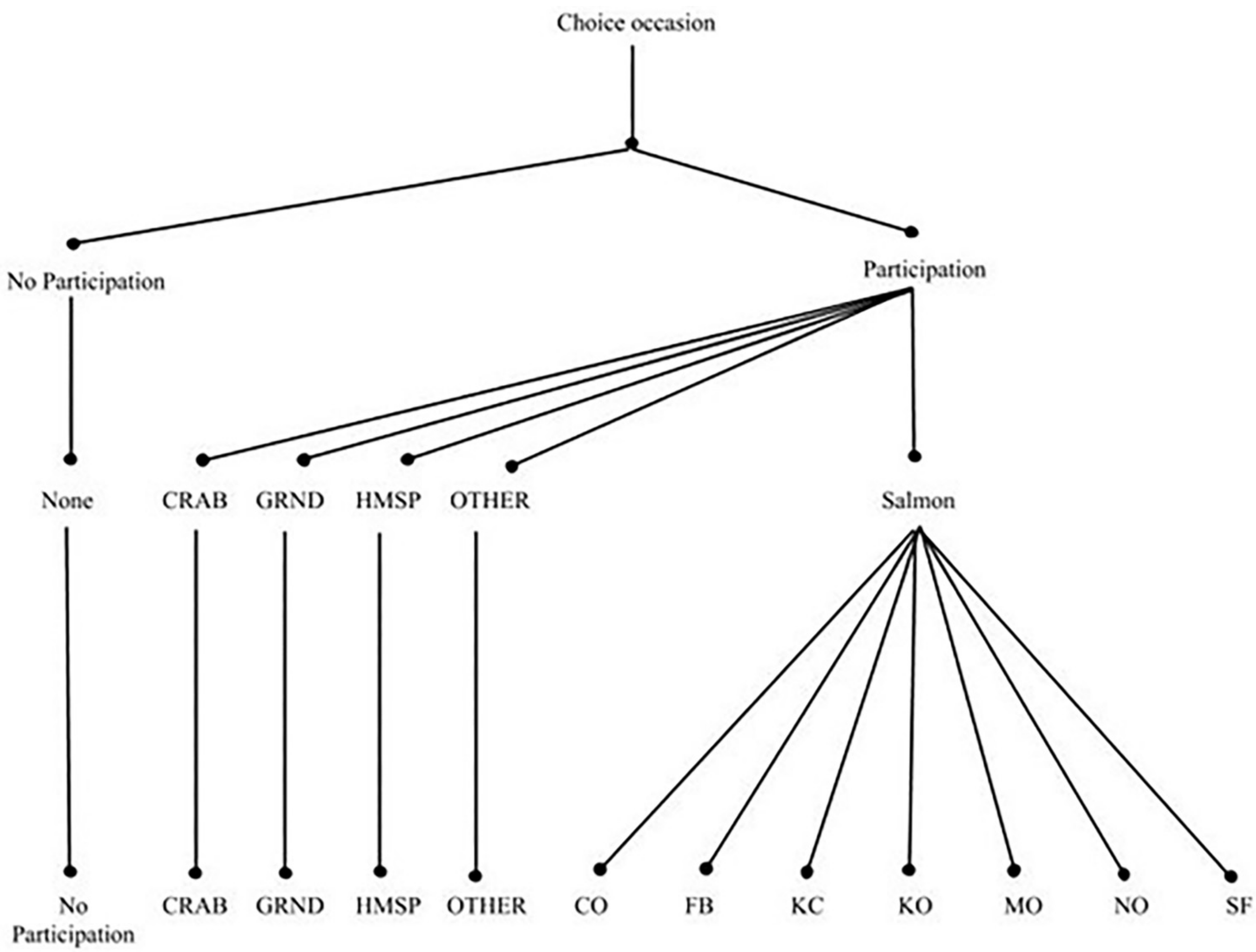
Normalized weekly revenues were used to estimate different sources of revenue information: coarse scale, fine scale, and finest scale. To calculate coarse-scale information, we estimated parameters of a fishery-specific linear regression mode that used observed weekly revenues as a function of time (number of weeks since the fishery opened), its quadratic term, and annual and spatial indicators; see equation S2 in the SM. Predictions generated by this estimated regression provide general trends in revenue that fishers can expect over the course of the fishing season, for each fishery and location; Table S4 and Fig. S2 display the estimated parameters of the coarse-information signal regression and the estimated revenue information for a single season, encompassing all fishery and location alternatives.

We calculated fine-scale information by averaging observed revenues from vessels with similar characteristics; see equation S3 in the SM. Vessels were classified into different groups based on their characteristics, ensuring that vessels in the same group were comparable. These groups were created using a k-mean clustering partition method that finds a partition in which vessels within each group are as close to each other as possible and far from vessels in other groups; see Fig. S3. Group average values were calculated for last-choice

[8] Due to the limited spatial information in our dataset, we could not incorporate a variable to gauge the spatial distance between a vessel's home port and all possible locations. In this case, the location choices have been determined at the management-area level rather than a more detailed spatial scale, like statistical areas. Even though this is not ideal, the main management-area indicator variable was introduced to take into account the expenses incurred when traveling to a management area other than the primary fishing location.

[9] Note that given the structure of the behavioral model, not all parameters enter the representative utility of all alternatives. Parameters α_j, β, θ_i, enter the representative utility of all alternatives under the first-level choice set, participation nest. On the other hand, parameters μ_m enter only in the representative utility of the alternatives under the second-level choice set while the parameter for the dominant management area indicator, ϑ, enters the representative utility of the alternatives under the third-level choice set.

Fig. 4. Tree structure of the nested logit specification. The nested logit specification was exclusively chosen to account for the correlation among alternatives within a nest. This figure illustrates the nesting structure of the model but is not intended to provide a behavioral characterization of salmon fishers. It does not necessarily imply that fishing choices are hierarchical and sequential though that may well be the case.



occasions and last-year-choice occasions for all alternatives at all time steps. The finest-scale information was calculated with vessels' own revenue history, as indicated in equation S4 in the SM. Therefore, this last piece of information was only used in estimating the expected revenue for the alternative previously chosen by each vessel.

To calculate expected revenues for all choices occasion, we account for the available information to each vessel; Table S1 list all possible information sets available to vessels. We calculated fine-scale and finest-scale information for the previous-choice and last-year choice occasions. This allowed us to estimate the expected revenue for all alternatives at all time steps for all vessels, which included coarse-scale, recent fine-scale, old fine-scale, recent finest-scale, and old finest-scale information. However, not all information elements were available for each alternative, for all vessels, or at all choice occasions. Therefore, we estimated a linear regression of observed weekly revenues as a function of the available information elements (Equation S5 in the SM). The estimates of the linear regression, see Table S6, were then used to estimate the expected revenues for every vessel's choice occasion for each alternative. These predicted expected revenues were then used to calculate the representative utility and estimate the parameters of eq. 1.

2.3.3. RUM estimation

Given the structure of the choice sets, a nested logit specification was used to estimate parameters of the representative utility to avoid violations for independence of irrelevant alternative (IIA) assumptions that could be caused by correlation of unobserved attributes of choices within nests. The nesting structure, as depicted in Fig. 4, allows for the unobservable attributes of alternatives within the salmon choice set to be correlated. For instance, our model does not account for salmon fishers' expectations on encountering low-abundance stocks, which is correlated with an increasing likelihood of a management-area closure. We assumed that fishers' expectations of catching low-abundance stocks are positively correlated between adjacent management areas but may be negatively correlated between management areas located far apart, because individual salmon stock follows seasonal migration patterns (Weitkamp 2010). Our nesting structure also allows for unobservable attributes of alternatives within the second nest to be correlated. For instance, we did not include variables that measure the variability of weather conditions such as wind speed and sea surface conditions. Presumably, these time-variant attributes, not included in the model, may affect the decision of fishers to participate in the salmon fishery and any alternative fishery, such as the albacore tuna fishery, thus creating a correlation across alternatives within alternatives in the second-level choice set.

We assumed that the errors in eq. 1 are distributed as Gumbel's multivariate extreme value distribution; thus, we estimated parameters of the representative utility for all alternatives with the generalized extreme value (GEV) choice probability, also known as a nested logit (Train 2009). The GEV choice probability accounts for the correlation of alternatives within the second- and third-level nests by estimating two dissimilarity parameters, λ_{fishery} and λ_{salmon}, respectively. The parameters of the representative utility and the dissimilarity parameters were estimated using full information maximum likelihoods (Green 2008) and implemented in Stata.

3. Results

3.1. RUM results

Estimation of the expected revenues for all fishery participation and location choice alternatives was carried out as described in the SM. Last-week choice and last-year choice were defined with dummy variables indicating the alternative chosen in the previous week and in the previous last year, respectively. The case-specific variables, vessel-specific tonnage, length, and horsepower are estimates for all alternatives under the fishery nest, and each alternative has a separate coefficient. Dominant management area is an indicator variable equal to 1 for the management area in which the fisher had the most landings. Dominant management area coefficients are estimated only for all alternatives under the salmon nest. Parameters of the model were estimated with weekly FT observations for the salmon season of every year.[10] Finally, when a salmon management area was closed, as reported in the PFMC reports, we removed the corresponding alternative from the choice set of all vessels.

Table 2 provides parameters estimated from the three-level nested logit specification. The estimated parameters of alternative-specific variables under the first-level choice set (expected revenue and state dependence) are significant at the 0.001 level. Only five alternative-specific constants are significant at the 0.05 level: highly migratory, other, and salmon at FB, KO, and MO. The alternative-specific constants account for the average effect of unobserved factors on the utility of each alternative relative to the nonparticipation alternative. The estimates suggest that the unobserved attributes are only significant for 5 of the 11 alternatives. The nested logit specification is a nonlinear model; thus, coefficients in Table 2 cannot be interpreted as marginal effects. However, the signs of the coefficients provide an interpretation in the direction of the effect of an individual variable on the probability of choosing an alternative. For instance, the positive sign in the expected revenues variable suggests, as expected, that salmon fishers are more likely to choose an alternative *j* when *j's* expected revenues increase. The positive coefficients in the dummy variables "last week" and "last year" suggest that fishers are more likely to choose the alternative that was chosen in the previous week and the previous year; this evidence of state dependence and sluggish behavior is consistent with findings from the literature (Bockstael and Opaluch 1983; Ward and Sutinen 1994; Holland and Sutinen 2000; Smith and Wilen 2005).

Case-specific estimates for vessel characteristics are not significant across all alternatives, indicating that vessel characteristics do not play a role in the probability of choosing a given alternative relative to the nonparticipation alternatives. The estimates of the dominant-area coefficient for alternatives within the salmon nest reflect the direction of the likelihood of choosing a given location with respect to the base case location, the SF management area. Table 2 shows that all dominant-area coefficients are positive and statistically significant at the 0.001 level. The positive value of the dominant-area coefficients, which serve as a proxy for travel costs, indicates that fishers tend to avoid the cost of moving to other areas without an offsetting benefit, and if a salmon management area is the dominant choice for a given vessel, the likelihood of choosing it increases compared to the SF management area. As suggested by the literature, distance from the home port has a significant power to explain fishing location choices (Holland and Sutinen 2000; Smith and Wilen 2003; Abbott and Wilen 2011).

Table 2 also shows the value of two dissimilarity parameters, one corresponding to the second-level nest, $0 \leq \lambda_{\text{fishery}} \leq 1$ and the other corresponding to the third-level nest, $0 \leq \lambda_{\text{location}} \leq 1$. In each case, the dissimilarity parameters measure the degree of independence among alternatives within the same nest; as the value of the parameters approaches 1, the independence among alternatives increases, indicating a lower degree of substitution among alternatives within the nest (Train 2009). The dissimilarity parameter for the salmon nest is equal to 0.414, indicating a low degree of independence and high degree of substitution among fishing location choices at the management-area level. The dissimilarity parameter of the fishery nest is equal to 0.379, indicating a relatively lower degree of independence and higher degree of substitution among fisheries alternatives. Note that $\lambda_{\text{fishery}} < \lambda_{\text{location}}$ suggests that the fishery substitution effect is greater than the location substitution effect. That is, the propensity to substitute across fisheries when a fishery alternative is removed is greater than the propensity to substitute a location choice when a management area is closed. Further, our model allowed us to explore yet another

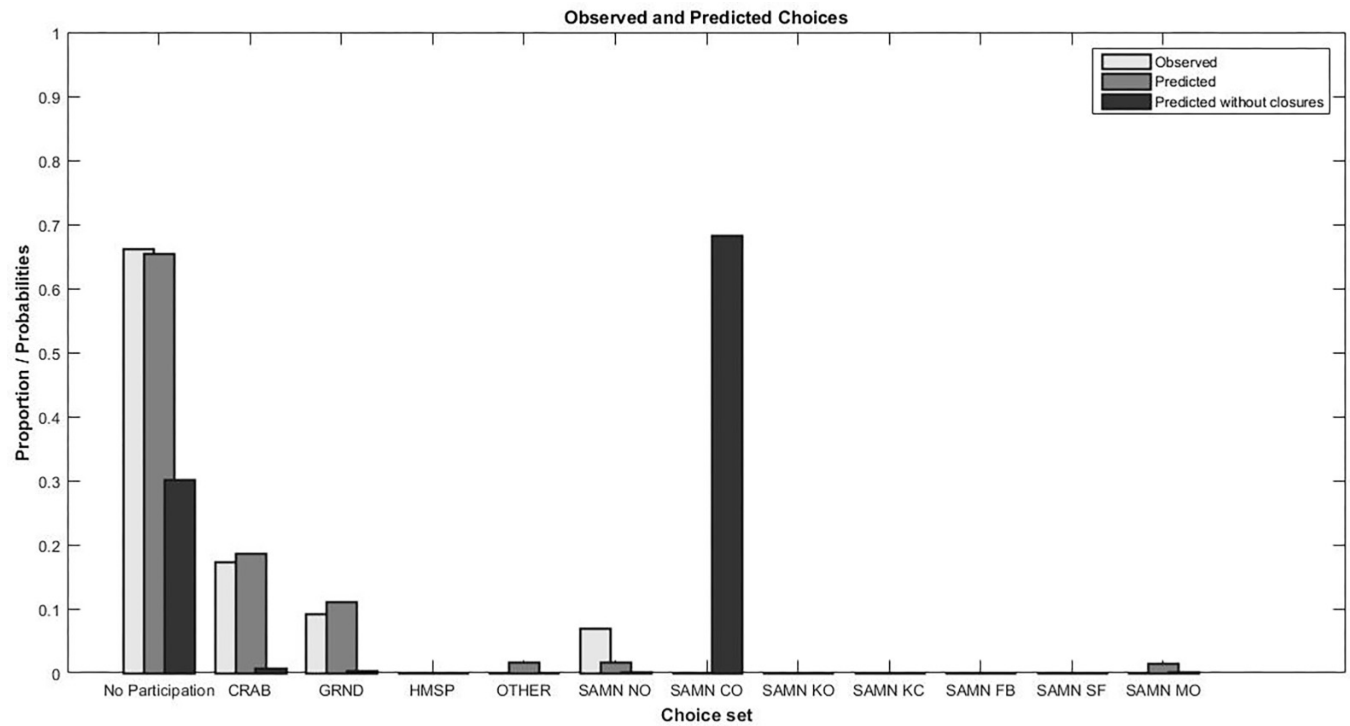
[10] We defined the beginning of the salmon season as the week when the first salmon management area opened. Likewise, the end of the salmon season was defined as the week when the last salmon management area closed according to the summary of commercial non-Indian salmon troll fishing regulations, which are published by the Council in its yearly SAFE documents and are found at https://www.pcouncil.org/stock-assessments-and-fishery-evaluation-safe-documents/.

Table 2. RUM model results.

	Estimate	Standard error
Alternative-specific variables		
Expected revenue	0.0001368***	1.95E−05
Last-week choice	1.124***	0.088
Last-year choice	0.449***	0.072
Variables per alternative		
Nonparticipation	Reference choice	
Crab	−1.041	0.696
Constant	−1.041	0.696
Length	−0.004	0.021
Tons	−0.018	0.017
Horsepower	0.001	0.001
Groundfish		
Constant	−1.231	0.787
Length	−0.005	0.025
Tons	−0.018	0.018
Horsepower	0.002	0.001
Highly migratory species		
Constant	−1.204*	0.609
Length	0.002	0.017
Tons	−0.014	0.013
Horsepower	−0.001	0.001
Other		
Constant	−1.844*	0.974
Length	−0.011	0.028
Tons	−0.032	0.026
Horsepower	0.003*	0.001
Salmon		
Length	−0.033**	0.014
Tons	0.002	0.012
Horsepower	0.001	0.001
Salmon at CO		
Constant	−0.244	0.429
Dominant area	0.487***	0.178
Salmon at FB		
Constant	−1.420***	0.522
Dominant area	1.176***	0.330
Salmon at KC		
Constant	−0.773	0.484
Dominant area	0.791***	0.244
Salmon at KO		
Constant	−2.981***	0.574
Dominant area	0.818***	0.251
Salmon at MO		
Constant	−1.000*	0.529
Dominant area	0.804***	0.248
Salmon at NO		
Constant	−0.871	0.503
Dominant area	1.302***	0.364
Salmon at SF		
Constant	−0.846	0.481
Dissimilarity parameters		
Fisheries nest, $\lambda_{fishery}$	0.379	0.067
Salmon nest, $\lambda_{location}$	0.414	0.076

Notes: Standard errors in parentheses $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Fig. 5. Observed and predicted choices in the second week of May 2006.



substitution effect—location–fishery substitutability, which is the propensity to substitute a salmon fishing location with participation in a different fishery when one of the salmon management areas is closed. We discuss the location–fishery substitutability effect in the next subsection by simulating fishers' behavioral responses to closures of a salmon management area.

3.2. Observed versus predicted choices

To evaluate the model, we compared in-sample observed outcomes with predictions from the FPLC model. We chose an example from the 2006 salmon season when both total and partial closures of management areas south of Cape Falcon Oregon took place, including CO, KO, KC, FB, and MO. The 2006 ocean salmon fishery season was constrained by three salmon stocks: the ESA-listed Sacramento River winter chinook, Klamath River fall chinook, and the threatened Snake River and lower Columbia River natural tule fall chinook.

Figure 5 shows observed and predicted choices for the second week of May in 2006. In 2005, the NO, CO, KO, and MO management areas were open before the first week of May, while the KC, FB, and SF management areas were closed. However, during the same week in 2006, the CO, KO, KC, FB, and SF management areas were closed.[11] We used the 2006 closure in the CO management area during May to explore the behavior of salmon vessels that participated in the salmon fishery at the CO management area the previous year. Figure 5 shows the observed choice behavior in the second week of May 2006. A total of 86 vessels were included that satisfied the following conditions: (1) they participated in the salmon fishery at the CO management area in the second week of May in 2005 when the management area was open, and (2) the vessel's dominant management area was CO. All vessels that satisfied these conditions were included regardless of their characteristics.

Figure 5 illustrates the choices made by vessels during the second week of May 2006 when the CO management area was closed. Out of the 86 total vessels, 66% chose not to participate in any fishery. The remaining 34% participated in one of three fisheries: crab, groundfish, or salmon. The light grey bars in the figure show the observed proportions of choices: nonparticipation (66%), crab (17%), groundfish (9%), and salmon at the NO management area (7%).

The FPLC model accurately predicted salmon fisher participation behavior during the second week of May 2006, as evidenced by the similarities of predicted choices and observed choices. We used the estimated parameters presented in Table 2 to calculate the predicted probabilities for the second week of May 2006, replicating the conditions of the observed choices. To achieve this, we excluded five of the seven management areas (CO, KO, KC, FB, and SF) from the choice set to mirror the closures at the beginning of the salmon season in 2006. We also excluded the highly migratory fishery alternative from the choices set since does

[11] In 2006, only the NO and MO management areas opened on May 1. The KO and KC management area were closed for the season. The CO, FB, and SF areas partially opened after June. In 2005, however, four management areas were open before the first week of May; these management areas were NO, CO, KO, and MO. The KC area was closed for the 2005 season, while the FB and SF areas partially opened after July.

not operate during this time of the year. Figure 5 displays the predicted probabilities with dark grey bars, which align closely with the observed choices as demonstrated by the light grey bars. Specifically, the model predicted a nonparticipation probability of 65%, which is marginally lower than the observed proportion of vessels that chose the nonparticipation alternative. Similarly, the probabilities of participation in the crab and groundfish fisheries (19% and 11%, respectively) closely matched the observed proportion of vessels that selected those alternatives (17% and 9%, respectively). However, the model overestimated the participation in the alternative “other” which includes coastal pelagic, shellfish, and shrimp fisheries. Furthermore, the model predicted very low levels of participation in the salmon fishery at the two open management areas (NO and MO), while the observed choices showed a somewhat higher percentage of landings from the NO management area. Despite these differences, the comparison of observed and predicted choices suggests that the model reasonably predicted the fishery participation and location choice behavior of salmon fishers. As such, we utilized the model predictions to evaluate fishers' responses to fishing location choices.

3.3. Location–fishery substitution effect

Figure 5 also illustrates the predicted probabilities assuming that the salmon fishery in the CO management area had opened earlier during the 2006 salmon season. To calculate these probabilities, we used the same independent variables as in the predicted probabilities that replicate observed choices. However, we modified the choice set to include the alternative for the CO management area if it had remained open. The black bars in the figure represent the predicted probabilities of selecting each alternative. The figure reveals that the probability of participating in the salmon fishery at the now-open CO management area is 69%, while the probability of not participating is 30%. This probability is much lower than the scenario that replicates the actual conditions in 2006. Furthermore, the probability of participating in the crab fishery also decreased from 19% to 1%, and the probability of participating in the groundfish fishery also decreased from 11% to 0%. Under the assumption of an open CO management area, there is an increase in the probability of choosing this management area and a slight decrease in the probability of choosing one of the alternative management areas.

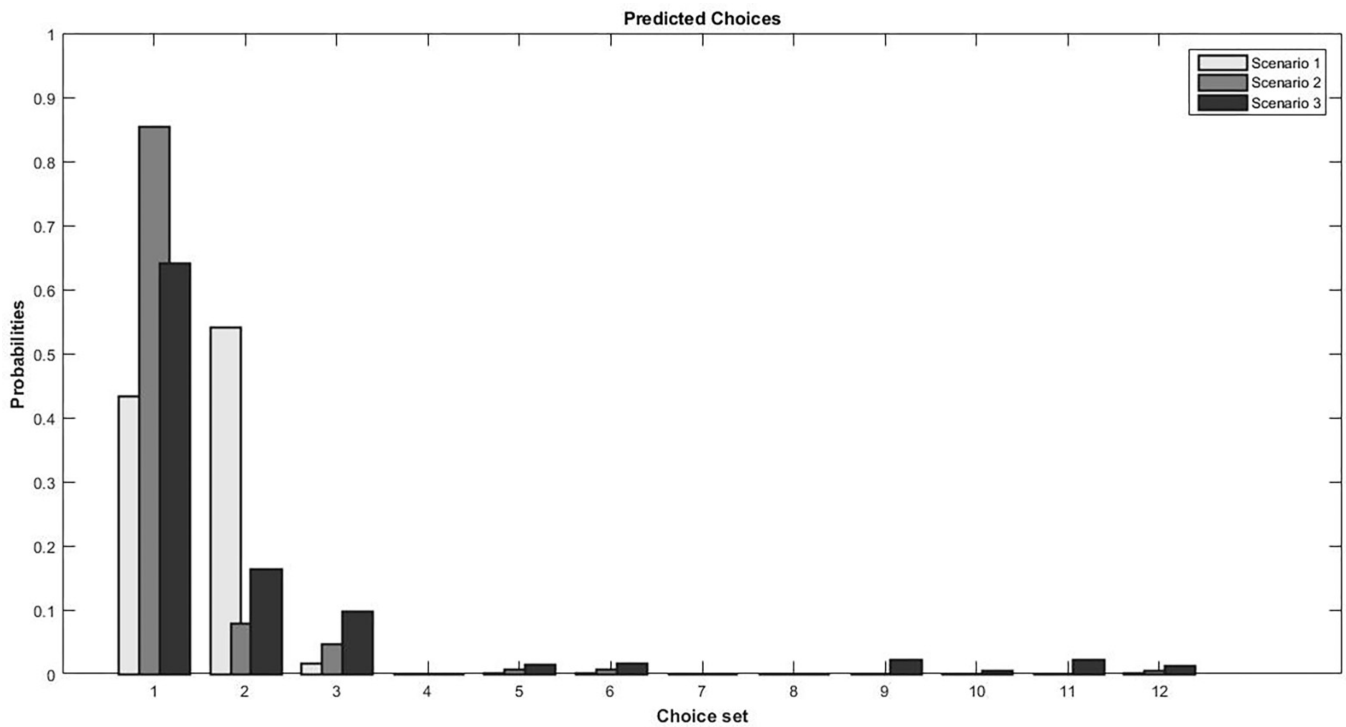
The above results suggest that the closure of the CO management area did not lead primarily to a redistribution of effort to open salmon management areas, but instead to a redistribution of effort to other fisheries. In the absence of a closure, only 1% of vessels that traditionally target salmon in the CO management area switched to targeting crab. However, due to the closure, 19% of vessels that typically target salmon in the now closed management area participated in the crab fishery instead. Figure 5 also shows that if the CO management area were to open early in the season, there would be almost zero probability of reallocating effort across all other management areas. According to our model, the substitution of a management area with a fishery alternative is greater than the substitution of a management area with an alternative location; note that the results of the same closure later in the year might have been quite different because alternatives would differ (for example, albacore might be available while crab is not).

To further explore the impacts of spatial closures in the salmon fishery and understand how and why results may vary across vessels, we calculated the probabilities for three additional vessel-specific scenarios that are illustrated in Fig. 6. In Scenario 1, we used the same independent variables and choice set as in Fig. 5 to replicate observed choices, but we assigned the crab fishery as the alternative chosen in the previous-choice occasion. Scenario 2 also used the same independent variables and choice set as Scenario 1 but assigned nonparticipation as the choice in the previous week. Scenarios 1 and 2 are intended to replicate vessels that participated in the salmon fishery at the CO management area in the previous season but chose to participate in the crab fishery or not to participate in the previous week because their preferred area was closed. Finally, Scenario 3 used the same independent variables as Scenarios 1 and 2 but assumes that salmon fishing in the CO area was chosen in the previous choice occasion and included all salmon management area alternatives except for CO, which was assumed to remain closed.

Figure 6 depicts the predicted probabilities for Scenarios 1 (light grey), 2 (dark grey), and 3 (black). Not surprisingly, the choice fishing in the crab fishery made in the previous-choice occasion (Scenario 1) or not having fished the previous choice occasion (Scenario 2) is a strong predictor for current choice. However, when a salmon alternative chosen in the previous choice occasion is no longer available because of a closure (Scenario 3), the probability of continuing to participate in the salmon fishery at an available management area is still lower than the probability of switching to an alternative fishery or the nonparticipation alternative. For instance, the probability of remaining in the salmon fishery is approximately 8%, while the probabilities of the nonparticipation, crab, groundfish, and other alternatives are approximately 64%, 16%, 10%, and 1%, respectively. Overall, this additional exercise suggests that fishers are likely to respond to closures in the salmon fishery by switching to other fisheries instead of continuing to participate in the salmon fishery in the available management area. Possible explanations for these results are that costs of moving to other areas are higher than for switching fisheries or that fishers may lack knowledge and skills needed to fish effectively in other areas.

Although we only examined the closure of the CO management area at the beginning of the 2006 salmon season, our model is capable of exploring the impact of closures in different years and at various points along the salmon season—for example, when the highly migratory fishery is available or after the crab fishery is closed. We did not explore other scenarios in this study, but our results suggest that several substitutability mechanisms take place in fishers' behaviors, including substitution among fishing locations, substitution across fisheries, and nonparticipation. Moreover, fishers' behaviors can vary depending on the timing of closures, the open opportunities, and their experience in fishing alternative fisheries or areas.

Fig. 6. Predicted choice in the second week of May 2006.



3.4. Ignoring location–fishery substitution effect

Stafford (2018) demonstrates that failing to consider fishers' participation behavior across fisheries when evaluating area-temporal closures for a specific fishery can result in misleading policy predictions produced by discrete choice models. We illustrate the policy implications of our findings by comparing the observed choices under an area-temporal closure to the predicted choices made by two types of policymakers: one well-informed and one naïve.

The well-informed policymaker employs a model that fully characterizes the utility function for all alternatives (including non-participation, alternative fisheries, and salmon management areas). In contrast, the naïve policymaker ignores the utility function of alternative fisheries. Figure 7 displays the observed choices (light grey), predictions from a well-informed policymaker (dark grey), and prediction for a naïve policymaker (dark) for the second week of May in 2006, similar scenario as Fig. 5.[12] Figure 7 demonstrates that the naïve policymaker overestimates the non-participation behavior of salmon fishers. By ignoring the multitargeting behavior of fishers, the naïve policymaker assigns a probability of 83% to nonparticipation and a 17% probability of remaining in the salmon fishery at a different management area. These probabilities are notably higher than the predicted probabilities of a well-informed policymaker, which closely resemble the observed choices, 66% and 6%, respectively. As depicted in Fig. 7, characterizing the complete behavior of fishers is crucial for estimating meaningful policy predictions regarding their behavior.

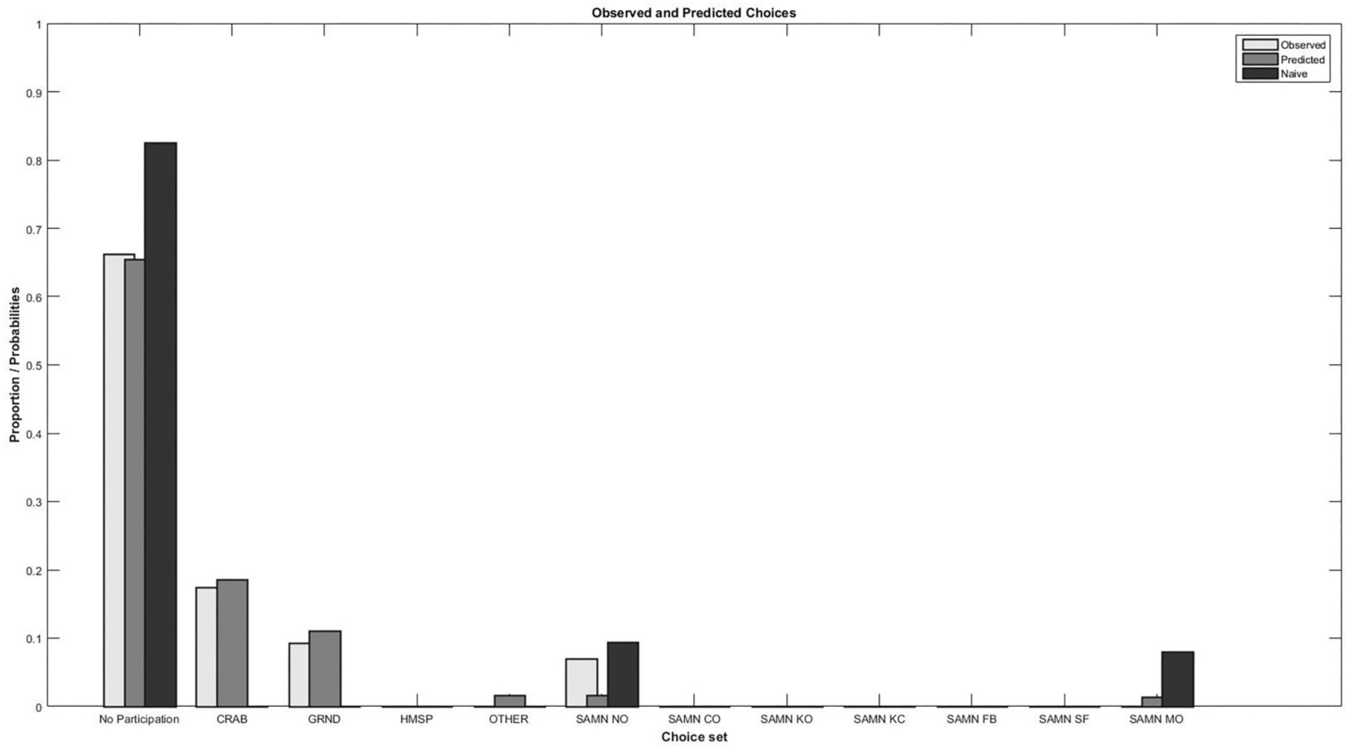
4. Conclusion

Studies have shown that fishers alter fishing locations in response to profit differentials across location alternatives and that models of spatial behavior can be useful for predicting responses to management measures that close areas or change profitability over space. Spatial measures that are intended to protect stocks in one fishery may also have spillover effects on other fisheries if fishers switch fisheries rather than simply switching fishing locations or exiting the fishery. Understanding interconnections between fisheries associated with fishers' switching behavior in response to regulatory changes and other exogenous shocks is critical for implementing EBFM approaches (Richerson and Holland 2017; Kroetz et al. 2019).

Our model demonstrates how RUM models can be used to explore substitution effects across alternative fisheries and across space within a fishery. We modeled fishery participation, fishery choice, and location choice in a single model and showed that West Coast salmon troll fishers' responses to changes in profitability and closures extend to decisions to switch fisheries and spatial movement within a fishery. Our results suggest that spatial regulation in the commercial salmon troll fishery can have significant impacts on other

[12] Unlike Stafford (2018), we do not estimate two distinct models (true and naive models) to generate the predicted probabilities in Fig. 7. Instead, we assume that a naive policymaker possesses accurate parameters for the non-participation and salmon location choice utility function. However, the naive policymaker disregards the utility function associated with participation in other fisheries due to their inadequate understanding of salmon fishers' behavior.

Fig. 7. Ignoring the location–fishery substitution effect. This figure presents the observed choices (depicted in light grey) alongside the predictions made by a well-informed policymaker (represented in dark grey) and a naïve policymaker (shown in dark) for the second week of May in 2006, corresponding to a scenario similar to that depicted in Fig. 5.



available fisheries, thus creating linkages across species due to fishers' behavior. In the broader context of EBFM, our results suggest that spatial fishery regulations, such as selected openings and closures, should account for the potential effects of, and on, other fisheries.

Our work relies on a meticulous treatment of landing observations of salmon trollers. We used all fisheries targeted by all salmon fishers to create a uniform choice set across all vessels, but the choice sets considered by those vessels undoubtedly vary. The composition of permit portfolios that may restrict choices for some fishers almost certainly plays a role in the substitution effect between fishing location and fishery participation. We proxied this imperfectly with our state dependence variables (e.g., participation in the prior year likely means the vessel holds that permit the following year). It would be preferable to explicitly model permit portfolio choice, although doing so may be challenging due to the lack of data on permit prices. Nonetheless, our model can offer valuable insights into how and why choice behavior may differ for individual fishers, or clusters of fishers, given different constraints on the alternative fishing opportunities.

Many interesting questions concerning how and why fishers assemble permit portfolios affect the potential for spillover between fisheries and the need for managers to consider other fisheries when designing management actions. Of particular interest is the construction of portfolios with complementary fisheries that occur during different seasons versus substitute fisheries that allow a fisher to move to the more profitable fishery in each season. The former may allow for fuller utilization of both physical and human fishing capital, while the latter may provide a hedge against inter-annual variation in profitability and regulatory actions such as closures. Our analysis not only identified both types of portfolios but also showed that the distinction between complements and substitutes is complex. As shown in Fig. 3, participation in the crab fishery rapidly decays before the beginning of the salmon season so that participation in the salmon fishery usually will act as a complement to participation in the crab fishery. However, with closures in the salmon fishery, fishers may delay their exit from the crab fishery such that crabbing acts as a substitute for salmon fishing. Targeting salmon and albacore tuna requires minimal fishing gear transition and the seasons overlap, so these fisheries act more clearly as substitutes, although some fishers may choose to fish one and then the other over the season, making them appear to be complements.

We recognize some limitations of our modeling approach due to lack of data. Comparing fishing location choices across different fisheries requires data at similar or compatible spatial scales. Because of data limitations, we are only able to use large management areas to delineate fishing location choices. Substitution between fishing location choices and fisheries may be more relevant when considering broad management actions that affect fisheries over large areas. When spatial regulations are established at a fine spatial scale, we might expect more spatial substitution within the same fishery and less switching of fisheries, and our model would not be well suited to modeling impacts of such closures.

A second limitation of our model concerns the temporal scale of choice and the significance of long-term expectations. We acknowledge that an area closure at time t may also have a ripple effect on the rest of the fishing season, and fisheries managers should consider these effects when designing spatial policies (Hicks and Schnier 2006). Our model focuses on weekly choices and we do not explicitly model forward-looking behavior. It is plausible to assume that the substitution between locations and fisheries can vary over temporal scales and may be influenced by expectations beyond the modeled choice period. A fisher's decision to change areas, participate in a different fishery, or quit fishing may depend heavily on the known length of the closure of their preferred management area. As our modeling approach is not forward looking, we can only assess the influence of a closure at time t on the choice probabilities during the same time period. To model choices in subsequent periods would necessitate simulating choices of vessels sequentially to generate state dependence variables and would also require simulating how expected utility across choices evolved. Modeling choices when closed areas re-open presents a particularly difficult problem, regardless of whether state dependence is included in utility since there it is unclear how fishers would formulate expectations about revenues in the reopened areas. However, we do find that choices made the prior year are good predictors or behavior and these would tend to increase the predicted probability of choices in reopened areas if they had been opened the previous year. Despite these limitations, the static ROM model is valuable for helping to understand fisher behaviors in a complex multi-fishery setting of the salmon fishery, and we leave the development of a dynamic fishery participation and location choice model for future work.

Our study is primarily focused on providing empirical evidence for substitution effects across different fisheries and spatial locations within the salmon fishery, making it primarily positive in nature. However, we did not use our findings to conduct welfare analysis or provide policy options to address the impacts of closures in the fishery. We also did not aim to evaluate the potential impacts of future fishery closures. Instead, our approach is based on a careful analysis of available data and the application of the RUM to characterize the observed behavior of salmon fishers. We obtained our results by comparing observed and predicted choices within our sample using FTs from 2005 to 2014 that include observed closures. Estimating the welfare effect of future fishery closures using our approach is beyond the scope of this study, and we leave it to future research. We expect that our modeling approach will help guide others interested in modeling multispecies fisheries and those seeking empirical evidence to demonstrate the need for EBFM approaches that coordinate management of different fisheries that are connected by cross-participation.

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The data used in this manuscript are the property of the California Department of Fish and Wildlife, Oregon Department of Fish and Wildlife, and Washington Department of Fish and Wildlife. Due to proprietary restrictions, the data generated or analyzed during this study are not available for public access.

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Supplementary material

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