Natural Resource Modeling WILEY

An agent-based model to optimize transboundary management for the walleye pollock (*Gadus chalcogrammus*) fishery in the Gulf of Alaska

Benjamin C. Williams | **Keith R. Criddle** | **Gordon H. Kruse**

College of Fisheries and Ocean Sciences, University of Alaska Fairbanks, Juneau, Alaska, USA

Correspondence
Benjamin C. Williams, NOAA Alaska Fisheries Science Center, Auke Bay Laboratories, Juneau, AK, USA.
Email: ben.williams@noaa.gov

Abstract

Because fish stocks often straddle state, national, and international boundaries, there is a need to coordinate fishery management across jurisdictions. This is particularly important when the abundance or spatial distribution of the stock varies through time. This is best achieved when management objectives and strategies align, and there is coordinated decision-making and catch accounting among jurisdictions such that each fish stock is managed over its full geographic range. However, legal constraints or differing management objectives may not permit such coordinated decision making and policy development. This study introduces a framework for effectively simulating fleet dynamics, fishery quota allocation, and the implications of alternative management strategies while allowing for determination of economically optimal management approaches at the community level. As a case study, an agent-based model (ABM) was developed to examine the interplay between transboundary management scenarios on the economic viability of a nascent Alaska

state-waters trawl fishery for walleye pollock (*Gadus chalcogrammus*) in the Gulf of Alaska, given a longstanding federally managed fishery. Under conditions characteristic of the recent past, the management strategy that produced the best overall improvements, relative to status quo, involved a scenario that allows for community-based cooperatives in federal-waters and an open access strategy in state-waters. This case study allows us to demonstrate more generally how using an ABM allows for quantifying the impacts of and informing managers on anticipated, and novel, results of alternative management strategies for complex socio-ecological systems before implementation.

Recommendations for Resource Managers

- Agent-based modeling provides a method to realistically simulate fleet behavior within a fishery.
- The approach enables a quantitative analysis of the effects of alternative management scenarios under consideration by policymakers.
- "Best practices" for fishery management should include simulation analysis of management alternatives before selection of the preferred alternative for real-world implementation.

KEYWORDS
agent-based modeling, fisheries management, transboundary fish stock

1 | INTRODUCTION

The imperative to coordinate fishery management across jurisdictions arises from tele-connections of marine ecosystems and their constituent stocks, which often straddle state, national, and international jurisdictions. Theoretical and empirical considerations of the management of fugitive and transboundary resources evoke the advantages of cooperative strategies and the characteristics of management systems and decision-making processes that often drive those resource systems to ecologically and financially disadvantageous non-cooperative solutions (Kaitala, 1986; Levhari & Mirman, 1980; McKelvey, 1997; Munro, 1979). Cooperative strategies are most easily obtained when there is coordinated decision-making and catch accounting among jurisdictions and an alignment of management objectives and

strategies. However, when legal, social, or political considerations lead to differences in management objectives or management strategies it can be difficult to coordinate decision-making (Munro, 1991; Scholtens & Bavinck, 2014). Even in such cases of divergent management, certain combinations of management strategies increase the likelihood of achieving the management objectives of each jurisdiction. Making and changing management strategies is time-consuming and costly, so it is important to provide managers with good information on the potential consequences of alternative management strategies before implementation. Quantitative models can play a role in identifying likely trade-offs before policy implementation.

One approach that can be used to quantify management scenario decision outcomes is agent-based modeling (ABM). ABMs are "bottom-up simulation models" (Lamberson, 2002) that simulate the actions of "agents" (i.e., individuals or groups) with defined behaviors that may interact with each other and their environment (Gilbert, 2008). Each agent is governed by simple rules that respond to the environment in a particular fashion, given the location of the agent within the environment. The environment can be designed to represent the real world or some stylized version thereof (i.e., virtual world) and may be designed to be spatially explicit. Such models are commonly used in ecology, where they are often referred to as individual-based models (Grimm et al., 2005). ABMs are often implemented to explore how individual agent actions are expressed as "emergent" properties (Heckbert et al., 2010) or patterns that emerge in the larger simulated system.

Many types of ABMs have been successfully developed to examine ecological, social, or socioecological systems (Grimm et al., 2010). Some ABMs explore biological relationships such as moth infestations and controls (van Vuuren et al., 2017), or the effects of size-selectivity on salmon population characteristics (Bromaghin et al., 2011). Other ABMs have been used to explore fishing fleet dynamics (Holland & Sutinen, 1999) and fishery stability (Helu et al., 1999). A case has been made for utilizing ABMs to inform policy development for human–environmental systems (An, 2012; Bailey et al., 2019).
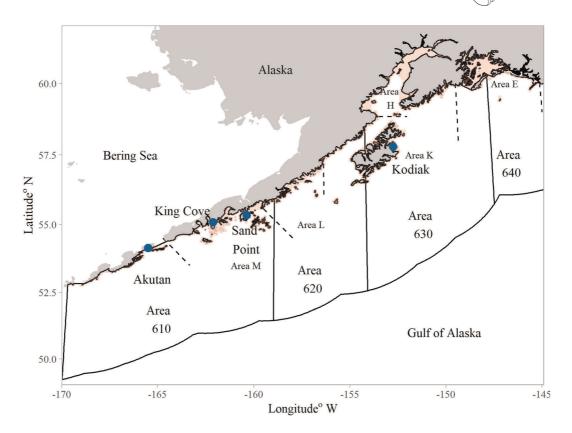
Fisheries are complex social-ecological systems (Glaser, Fogarty, Liu, et al., 2014; Glaser & Glaeser, 2014) and our understanding of these systems can be improved through the process-based understanding provided by ABMs (An, 2012). Recent research has shown that understanding the impacts of policy changes in fisheries management requires a thorough comprehension, derived in part through modeling, of the underlying technological structure of the fishery and responses to both market and institutional constraints (Reimer et al., 2017). While management of shared fish stocks are often characterized as cooperative or non-cooperative games (Criddle & Strong, 2014; Hannesson, 2013a, 2013b; Levhari & Mirman, 1980; McKelvey, 1997) jurisdictional managers may not be motivated by a suite of social and political objectives that are readily reduced to competition over shares of sustainable catches. On this basis we developed an ABM to explore the implications of parallel and divergent management strategies in a system where a fish stock straddles jurisdictional boundaries. For our purposes parallel management is defined as strategies that may be adopted across jurisdictions, whereas divergent strategies cannot be reconciled due to legal, social, or political constraints. These parellel or divergent strategies could nevertheless be implemented in a coordinated or un-coordinated fashion. Our model incorporates relevant biological, social, and economic factors to simulate the trade-offs and implications of alternative management strategies while allowing for determination of economically optimal management approaches at the community level. For illustration of this generalized approach, we parameterized our model to reflect stylized aspects of state and federal fisheries for walleye pollock (*Gadus chalcogrammus*; hereafter pollock) in the Gulf of Alaska (GOA). Given the extent of scenarios available for such a

simulation analysis we limited the scope of this examination to a single proposal put forward to the Alaska Board of Fisheries (BOF), the state management body that promulgates regulations for fisheries in state waters off Alaska.

2 | CASE STUDY

The GOA pollock fishery is currently managed under a License Limitation Program (LLP) in federal waters (3–200 nmi offshore) and as a parallel, open access fishery in state waters (0–3 nmi offshore). In managing the parallel pollock fishery the State of Alaska has adopted most federal rules and regulations in state waters except for the LLP, that is, the fishery is open access in state waters. In federal waters, the North Pacific Fishery Management Council (Council) has been exploring alternatives to LLP management as a means of reducing the incidental catch of prohibited species (especially Pacific salmon *Oncorhynchus* spp. and Pacific halibut *Hippoglossus stenolepis*) in the fishery (DiCosimo et al., 2015; Witherell et al., 2000). In state waters, the BOF has considered changes to regulations for this fishery to expand economic opportunity for coastal communities adjacent to the fishing grounds.

Stakeholder interest in developing new fisheries in state waters led to the submission of a proposal to the BOF in 2013 to establish a state-managed pollock fishery in state waters of the GOA. Proposal 44-5 AAC 28.36X, if approved, would allocate 25% of the combined total allowable catch (TAC) from federal reporting Areas 620, 630, and 640 to state waters in the Prince William Sound (PWS, state fishery management area E), Cook Inlet (CKI, area H), Kodiak (KOD, area K), and Chignik (CHG, area L; Figure 1). Kodiak is the largest port in the region with eight shoreside processors in 2015 (Fissel et al., 2016), and annual average groundfish landings of 80% of the GOA delivered volume; the other ports each have one primary processor. Annual groundfish landings in Sand Point are about 12% of the GOA delivered volume (Dorn et al., 2016); King Cove and Akutan have reduced delivery volumes relative to Sand Point, with Akutan having the lowest volume. Accurate catch accounting by port cannot be reported here due to data confidentiality restrictions that prohibit reporting catch statistics for three or fewer fishermen or processors.

Some management strategies available for Council consideration in federal waters are not legally permissible in state waters. For example, the Council could adopt a management strategy that distributes exclusive durable shares of the TAC to fleet sectors or community-based entities. Additionally, several sectors of federally managed fisheries in Alaska have the option to develop fishing cooperatives. However, the Alaska Supreme Court (1980) has found that, with few exceptions, Article VIII of the Alaska Constitution bans state resource management agencies from issuing exclusive entitlements to shares of common-property fishery resources (see Alaska Supreme Court, 2005, 2006; Criddle & Shimizu, 2014; Knapp, 2008). The Court has allowed an equal quota-share management system (i.e., all entities are entitled to an equal percentage of the TAC regardless of vessel size, catch history, and other factors) in the state-waters Southern Southeast Inside and PWS subdistrict sablefish (*Anoplopoma fimbria*) fisheries. Thus, there is very limited precedent for individual fishing quotas (IFQs), sector allocations (cooperatives), or community quotas (CQs) in state waters. Consequently, if the Council adopts IFQs, cooperatives, or CQs for the GOA pollock fishery in federal waters based on individual fishing histories, it is highly unlikely that the state would be able to adopt a parallel management strategy for state waters.

FIGURE 1 Map of federal and state waters fishing areas in the Gulf of Alaska. Federal management authority (solid lines) extends from 3 to 200 nmi from shore. Federal management Areas 630, 620, and 610 were included in the model as Areas 1, 2, and 3, respectively. State management authority in Areas E, H, K, L, and M (separated by dashed lines) extends from 0 to 3 nmi from shore (red shading). The fishing ports (blue dots) of Kodiak, Sand Point, King Cove, and Akutan, were included in the model as Ports 1–4, respectively

Because management actions adopted by the Council may create spillover effects into state-water fisheries and vice versa, the Council's and BOF's preferred management alternative may depend on what measures are adopted by their counterpart. That is, the choice of preferred management strategies is a choice made under conditions of a non-cooperative game, the solution of which is complicated not only by the lack of coordination, but also the challenge that state and federal managers are tasked with differing sets objectives (e.g., the 10 National Standards for federal fisheries and the plurality of objectives for resource management stipulated in Article 8 of the State Constitution). Additionally, the adoption of new strategies to address management concerns may have unintended consequences. Proposal 44-5 prescribes limits on vessel size, gear type, the duration between landings, and maximum delivered weight per landing; these provisions were intended to extend benefits to fishers on small vessels that are mostly home-ported in coastal communities. Proposals such as Proposal 44-5 arise from a wish to create an opportunity for new entrants with small vessels in state waters, but that opportunity would come at the cost of reduced opportunity for current participants, such as those with large fishing vessels. Conversely, federal catch-share programs may be beneficial to many current participants and provide for better control of harvest (Branch, 2009; Criddle, 2012; Hannesson, 1996; Wilen, 2005), but they may decrease the resilience of

fishery-dependent communities and fishing operations that have limited catch history, such as small vessels (Adasiak, 1979; Carothers, 2010; Copes & Charles, 2004; Criddle, 2012; Himes-Cornell & Hoelting, 2015; Lowe, 2008; McCay, 2004).

The objectives of this case study were to: (1) develop an ABM that uses a discrete, static, stochastic simulation-optimization framework to estimate the local economic impacts of combinations of federal and state management strategies, and (2) compare the simulated economic outcomes of the management strategies across stock levels consistent with historical (1998–2014) fishery catch data. We employed the ABM to examine four federal management strategies (IFQs, catch-share allocations to community fishing associations, LLPs with the ability to form cooperatives, and bycatch/prohibited species catch [PSC] allocations) in combination with four state management strategies (open access, limited entry, limited entry with super-exclusive registration (Natcher et al., 1996), and limited entry with equal catch shares). For comparison, we also evaluated a no action (status-quo) strategy. We anticipated that each combination of management strategies would have differing economic impacts on individual fishers and fishery-dependent communities. For the purpose of this case study, we define the best alternative management strategy as the scenario that maintains or increases harvest and revenue to the four communities, relative to status quo.
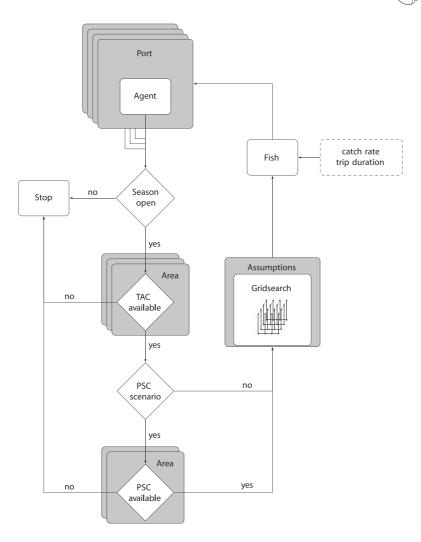
2.1 | Model overview

In this model, agents are individual vessels that behave in response to state variables conditioned on a combination of an individual vessel's historical participation in the fishery and the specifics of the management scenarios being evaluated. Agent behavior is generalized by season and vessel size-class, using metrics such as historical average catch and trip duration. The model includes federal management Areas 630, 620, and 610, denoted in the simulation as Areas 1–3, respectively. The model includes four fishing ports to represent Kodiak, Sand Point, King Cove, and Akutan, denoted in the simulation as Ports 1–4, respectively. The four fishing seasons represented in the model follow established management regulations (GOA pollock seasons). The four vessel size-classes represented in the model were based upon the Alaska Commercial Fisheries Entry Commission (CFEC) fishery codes (CFEC vessel permits) for otter trawl vessels (<18.2 m, 18.2–27.3 m, 27.4–38.1 m, and >38.1 m).

State variables such as season length, available TAC, anticipated exvessel price, and expected fuel price are defined at the start of each simulation and invariant throughout time, though the model framework allows for time-varying state variables. Agents are assumed to select a fishing strategy that maximizes their expected net revenue. Each agent originates from a "home" port and determines where to fish based upon a grid search routine provided that the season is open, whether there is TAC or IFQ available (area dependent), and whether bycatch/PSC quota (area dependent) is available. The grid search is based upon an assumed catch, catch rate, exvessel value, and anticipated fuel costs, the outcome of which informs an agent of the area to fish and the port of delivery. This cycle is repeated until either the season is closed, all quota in all areas available to be fished has been caught, or the bycatch/PSC quota has been reached. All areas are closed to fishing when the duration of a season is reached.

When the ABM simulation is initialized, all vessels begin fishing. The general decision matrix for each agent is shown in Figure 2. The number of vessels for a métier, a grouping of similar vessels, in a given season and port that fish in an area was based upon historical data collected by the CFEC. A vessel's starting or home port of call was designated as the starting

FIGURE 2　Agent-based model flow chart. Each agent originates from a port, checks whether the season is open, whether TAC is available (area dependent) and whether bycatch/PSC quota part of the current management routine and if so whether quota is available. A grid search routine is based upon user inputs of assumed catch, catch rate, exvessel value and fuel price with the output informing an agent of the area to fish and the port of delivery. This cycle is repeated until either the season is closed, all the TAC in all areas has been caught, or the PSC quota, if relevant has been reached. PSC, prohibited species catch; TAC, total allowable catch

port of highest historical frequency for the first trip of each season from 2006 to 2014. If the management scenario being examined does not permit a vessel the flexibility to fish in multiple areas, then the location was determined by the scenario rules, otherwise a vessel has access to any area. The time step advances by day through the course of a season. The probability that a vessel participates on a given day is based upon the average historical participation of the vessel during a given season. Days remaining in a season and remaining quota for a given area or vessel/area combination are decremented throughout the season.

　　Catch and quasi-rent (short-term net revenues) vary depending upon the management strategy implemented. The model is structured so that substantive differences in total catch and revenue by port are due to changes in management strategy rather than gross changes in

individual behavior. Specifically, individual behavior includes stochasticity, but the underlying behavior is consistent. Agents may not adapt behavior over time and are only capable of "sensing" exvessel price, anticipated trip durations, and fuel costs. However, they may join a cooperative and allocate their quota per a predefined strategy (see Supporting Information Material) to another vessel if the scenario permits cooperative strategies. Agents have been designed to have limited and restricted interactions, with the only meaningful interaction being the cessation of fishing due to the completion of a season or after all quota has been harvested.

Several elements in the ABM are stochastic. For each trip, a binomial draw determines a vessel's participation on a given day of a season, with a probability based upon historical vessel activity. Each vessel was assigned a distribution draw of catch based upon port, season, and individual catch history. Similarly, the duration of a trip was drawn from a distribution of previous trip lengths by port, season, and individual. Trip duration was considered independent of vessel catch per trip; a review of historical catch by trip duration showed catches to decline slightly with trip duration, though catch distributions were consistently uniform to be deemed equivalent for the purposes of our examinations (see Supporting Information Material). These stochastic elements were utilized to produce variability in processes within the model to reflect the inherent variability of this social-ecological fishery system.

Collectives, groupings of agents that have similar behavior, were created for some simulations for example, small vessels may have state waters quota only, while larger vessels have a federal quota, or a collective may have quota for only a specific area. Collectives are a key component of some of the management strategies and were anticipated to affect results substantively. Submodels that will influence collectives such as TAC allocation to management areas, IFQ allocation to individual vessels, and CQ allocation to ports are fully detailed in the Supporting Information Material.

In overview, this ABM was structured with a set of simple behavioral rules that drive the choice of fishing location and port of delivery. Agents' realized earnings are conditioned on their choice of fishing location, the fishing location choices of other agents, and on the realizations of draws from stochastic distributions for catch and variable costs. The simulation was explicitly designed to reflect the particular characteristics of the Central and Western GOA fishery for pollock.

Specifically, for each trip l, an agent i from métier j ($j = 1$–4, corresponding to four distinct vessel size classes in the fishery) selects the fishing location k ($k = 1$–3) and delivery port d ($d = 1$–4) that maximizes expected short-run profits or net revenue ($E(NR_{i,l})$), given their port of origin a ($a = 1$–4):

$$E(NR_{i,l}) = E(p_d) \cdot E(q_{j,k}) - C(E(\tau_{a,d,j,k}), E(o), E(f_j)). \tag{1}$$

Expected gross revenue for each trip l and agent i (first part of Equation 1) was calculated as the product of expected exvessel price ($E(p_d)$) for each delivery port and expected catch ($E(q_{j,k})$) in area k for métier j. Costs C (second part of Equation 1) are a function of trip duration ($E(\tau_{a,d,j,k})$), which is dependent upon the port of origin a, port of delivery d, métier j, and area fished k, the observer costs ($E(o)$) and fuel costs ($E(f_j)$)). Métier is important as, for instance, vessels in the larger size classes ($j = 3$–4) have greater average catch per unit effort, greater operating range, and greater operating costs than vessels in smaller size classes. They are also more likely to be based in Kodiak, the largest regional port. Fuel consumption was estimated following Tyedmers (2001) using an assigned horsepower by métier (500, 750, 1000, and 1500 hp), based upon average horsepower as reported in the Alaska Fisheries Information Network vessel horsepower database (http://www.akfin.org/). Observer costs were specified as

0.0625% of gross revenue per current federal regulations (Observer fee collection North Pacific groundfish and halibut fisheries). We assumed that the BOF would implement an onboard observer program for state waters at the same rate.

Equation (1) was constrained to preclude solutions where the sum of all agents' catches exceeds the TAC for any area during a fishing season and to reflect the attributes (e.g., where fishers can fish, where they can deliver, how the TAC is partitioned among métiers, whether fishers operate under a quota system or fish on a common pool) of various combinations of federal and state management strategies. The fishing location and delivery port that maximize $E(NR_{i,l})$ were found using the Numerical Methods and Optimization in Finance (NMOF) package (Gilli et al., 2011) in R v.3.4.2 (R Core Team, 2017).

Once fishing location and delivery port were determined, we treated an individual agent's realized (observed) catch q for métier $j = 2$–4 (all vessel size classes except the smallest) as a stochastic variable drawn from a truncated normal distribution parameterized on historical catches by fishing season s reported to the CFEC: $q \sim N(\mu, \sigma^2), q \in [\alpha, \beta]$, where the minimum catch was $\alpha = 0\,t$ and the maximum was $\beta = 140\,t$. The small vessel métier ($j = 1$) had trip catch drawn from a truncated lognormal distribution, $\ln(q) \sim N(\mu, \sigma^2), q \in [\alpha, \beta]$, to reflect observed historical catches (see Supporting Information Material). Average variable costs were modeled as a function of métier with trip duration τ drawn from a truncated normal distribution of historical CFEC data observations of starting port a, delivery port d, métier j, and area k, $\tau \sim N(\mu, \sigma^2), \tau \in [\alpha, \beta]$, where $\alpha = 0$ days and $\beta = 7$ days.

After each simulation, the realized net revenue of a vessel's single trip was calculated as:

$$NR_{i,l} = p_d \cdot q_{j,k,s} - C(\tau_{a,d,j,k}, o, f_j). \tag{2}$$

Simulated catch and revenue corresponding to the optimal solutions obtained for each combination of state and federal management strategy were summed by port of delivery, and conditions (i.e., exvessel price, fleet size, and fuel costs) to characterize likely regional economic impacts. Projected revenues were expressed by their coefficient of variation and absolute revenue values for each port, vessel-size class and management scenario.

2.2 | Model performance

Model performance was evaluated using comparisons of simulated catch to observed catch using the status quo management scenario. This metric was chosen because emulating modeled gross revenues to observed gross revenues is difficult due to varying market forces and the presence of multinomial exvessel prices per individual delivery in the CFEC data set. Three representative years (2006, 2010, and 2014) at the beginning, middle, and end of the CFEC data set were chosen for examination of model performance. Simulated catch was compared by season and port of delivery using aggregate (2006–2014) average behavior by vessel size-class. Additionally, an "out-of-sample" evaluation was made simulating catches in 2014 using aggregate behavior from 2006 to 2013. To account for stochasticity in the ABM, 10 simulations were performed for each year. The TAC for these simulations was based upon the total catch observed in the CFEC data set for each year. The CFEC catch was used to account for any discrepancies that may exist between the CFEC data and the TAC set by the Council for the years examined. The ABM used for this evaluation reflected the current parallel management structure (status quo, described

below). This model is not structured to fully capture the variability for a given year, but rather to describe the general underlying dynamics of the fishery. To this end, if simulation results were produced on a scale similar to observed values the model structure would be deemed sufficient to capture structural differences in management strategies.

2.3 | Management scenarios

Management scenarios for consideration were based upon status quo and the four federal and four state management strategies presented in Table 1. Five "bounding" scenarios (Table 2) were considered; these scenarios were used to examine extreme cases of the available strategies.

The bounds were based upon a subjective judgment as to whether they represented the outer margin of available management strategies, for example, IFQ implemented in federal waters and equal catch shares implemented in state waters, combined these scenarios represent an "extreme" case of share allocation. Six "likely" scenarios (Table 2) were simulated; it is anticipated that federal and state managers will choose a combination of strategies for GOA pollock fishery management that is similar to one of these hypothetical pairings based on their historical management decisions for other fisheries. These scenarios were also compared relative to a status quo management scenario (LLP in federal waters, open access in state waters). The status quo model was also used for the model performance examination described previously.

For this study, the following stipulations were adopted for each of the scenarios (see Supporting Information Material for full descriptions):

1. Vessels were not required to return to their port of origin for delivery, except for IFQ, catch-share community allocation, or limited entry-super exclusive scenarios;
2. IFQ excludes the smallest vessel size class; a vessel needed to catch 100 t per year by fishing area and port of delivery to be allocated IFQ. The fishing behavior of individual permit holders was averaged by port and season;
3. Prohibited species allocations were set at 25,000 Chinook salmon *O. tshawytscha* with 18,316 allocated to Areas 620 and 630 at a catch rate of 0.66 salmon/ton of pollock and 6684 allocated to Area 610, at a catch rate of 0.32 salmon/ton of pollock (see Chinook Salmon Prohibited Species Catch in the Gulf of Alaska Non-Pollock Trawl Fisheries). The LLP framework was used as the underlying model for this scenario;
4. LLP with the ability to form cooperatives was simulated with 85% of the catch and vessels (randomly drawn from all vessels) included in cooperatives. Vessels in a

TABLE 1 Management scenarios considered for simulation analysis

Federal	State
1. IFQ	A. Open access
2. Catch-share community allocation	B. Limited entry
3. LLP w/ability to form cooperatives	C. Limited entry—super exclusive
4. Bycatch/prohibited species catch allocations	D. Limited entry—equal catch shares

TABLE 2 Management scenarios presented in this study

Bounding	Likely
1C	2A
1D	2B
3A	2C
4C	3A
4D	3B
	3C

Note: See Table 1 for federal and state scenario designations, numbers identify federal strategies, and letters identify state strategies. "Bounding" scenarios are those scenarios that represent the outer margins of available management options. "Likely" scenarios are strategies anticipated to be more likely chosen by managers.

cooperative had an increased probability of fishing (i.e., the quota was more likely to be caught), whereas vessels out of the cooperative fished per their average fishing behavior. The vessels in the cooperative with marginal profits below the 0.05 quantile of the fleet's marginal profits did not participate in the fishery (i.e., other vessels fished their quota).
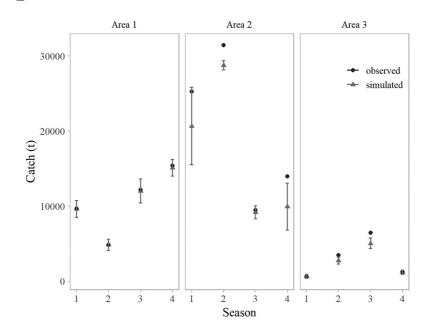
2.4 | TAC inputs

Two separate TAC inputs were evaluated. In the first examination, the TAC was set at 200,000 t and simulated 40 times for each management scenario to account for stochasticity in the model and to remove the effect of variable population abundance from the results. The number of simulations was selected as a balance between observed stochasticity during model development, and the runtime per simulation. The second TAC input was a range between 20,000–236,000 t in 6000 t increments; this range reflects historical variability, each simulation was replicated five times to incorporate model stochasticity for each management scenario. The range of TAC values allows for a sensitivity analysis of variable population sizes.

The grid search routine was optimized for anticipated revenue, based upon an expected exvessel price of US \$220/t (\$0.10/lb.), a fuel price of \$0.80/l, and an observer cost of 0.065% of gross revenue. The exvessel and fuel prices can be varied within the model but were held constant for this analysis. Each vessel began a trip with the assumption that they would harvest 50 t of pollock in 2.5 days of fishing, regardless of vessel size. The assumption of 50 t seems reasonable given historical average catches by vessel size-class (see Supporting Information Material).

3 | RESULTS

3.1 | Model performance

Graphical examinations show that model outputs produce realistic catches on a scale similar to observed values. The out-of-sample examination (Figure 3) shows accurate catch estimates for
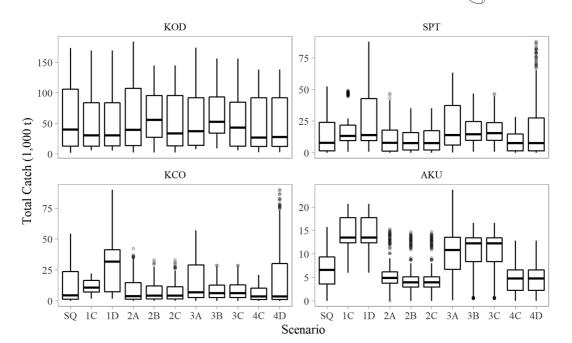
FIGURE 3 Out of sample comparison of 2014 allocated total allowable catch to simulated catch using average vessel behavior from 2006 to 2013. The simulation was replicated 10 times to account for stochasticity in the model structure

Area 1, with slightly lower than observed catches in Areas 2 and 3 during some seasons. Additional examinations using all years of data to inform vessel behavior show bias in 2006 and 2010 for Area 3, though Areas 1 and 2 are generally equally divided above and below the replacement line (Supporting Information Material). The 2014 simulations exhibit less biased results relative to the observed catch. For our current analysis we deemed this model to reflect observed fisher behavior at an acceptable level for contrasting the relative differences in outcomes under the alternative scenarios.

For presentation purposes select output results are shown to highlight specific points, full model outputs are available in the Supporting Information Material. Substantive differences in total catch were observed between ports (Figure 4) and for vessel size-classes by port (Figure 5) by management scenarios. Similar to the current fishery, there is a general trend whereby the majority of catch is returned to Kodiak, with the second and third vessel size-classes harvesting most of the fish. Sand Point, King Cove and Akutan receive less of the overall catch, respectively. However the smallest vessel size-class captures more of the harvest for some ports in a number of the scenarios (Figure 5). That is, some of the scenarios favor the preservation or development of a small-boat fleet based out of local ports. Relative to the status quo, some scenarios have greater total catches for all ports, for example, Scenarios 1D and 3A, or reduced catches, for example, Scenario 4C (Figure 4).
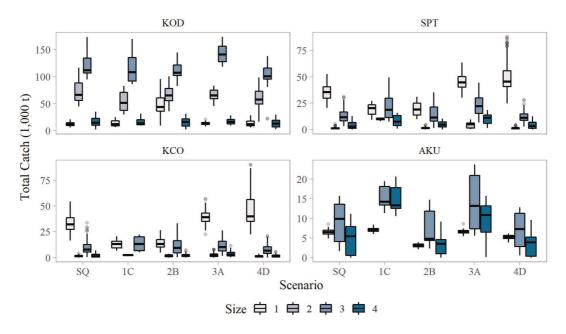
Because this model was not implemented with substantive changes to fisher behavior over time, it is effectively examining the short-term implications of a change in management strategies. Therefore, each simulation is utilized as a replicate. Also, given the short-term nature of the projections, these analyses have not been inflation adjusted. When the CV of catch is considered, some management scenarios have better properties
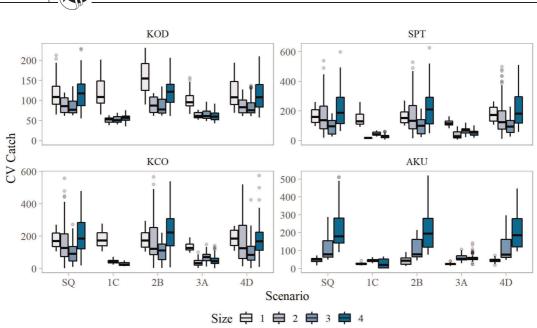
FIGURE 4 Total simulated catch delivered to each port for 40 replicates of each management scenario. Management scenario descriptions are available in Table 1

(lower CV) than do others (Figure 6). The scenarios that allow for IFQ or cooperatives in federal waters tend to reduce catch variability, though this trend is less evident for the smallest vessel size-class. These are anticipated results as IFQ and cooperative type scenarios are, in part, intended to increase the efficiency of the fleets. Scenarios based upon

FIGURE 5 Total simulated catch delivered to each port for 40 replicates of select management scenarios, by vessel size-class. Management scenario descriptions are available in Table 1
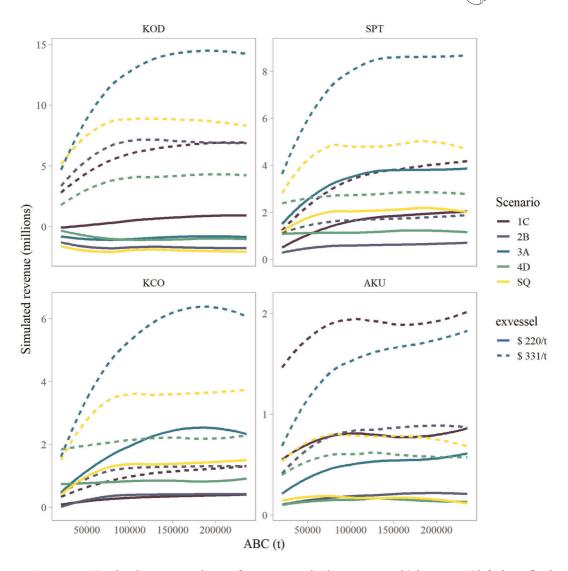
FIGURE 6 The coefficient of variation of simulated total catch delivered to each port for 40 replicates of select management scenarios. Note the different scales

catch-share community allocations or bycatch/PSC allocations tend to have greater variability in catch or are similar to the variability observed in the status quo scenario.

Exvessel value and fuel costs have substantial impacts on simulated revenue across all management scenarios (Figure 7). The influence of exvessel price is most readily noted for Kodiak. There is a strong positive relationship between price per ton and net revenue. The inflection point for positive revenue for Kodiak is slightly higher than an exvessel value of ~$220/t at a fuel price of $0.80/l. A similar threshold is observed for the other ports, though the change in net revenue is greatly reduced, primarily due to fleet characteristics. The influence of fuel costs is less dramatic than that of exvessel values (Figure 8), though it remains a significant factor for determining positive or negative net revenues. There are far more large-sized vessels that home port in Kodiak; these larger vessels have substantially higher modeled operating costs than those assigned to the smaller vessels typically home-ported in Sand Point and King Cove. Akutan is the home port to few vessels that fish the GOA and therefore receives limited revenues from GOA pollock. If fuel costs are high and exvessel prices are low, the CVs of revenues are low (see Supporting Information Materials), because each trip is of low value. This CV behavior is also observed when fuel costs are low and exvessel prices are high, because individual trips are of consistently high value. CVs have different trends between different state variables and ports due to the previously mentioned differing revenue inflection points for different fleets by port.

Given the input characteristics of these simulations, the management strategy that produces the best overall improvements relative to status quo is Scenario 3A. In this scenario, the federal waters are managed under an LLP with the ability to form cooperatives while state waters are managed in parallel as open access. This scenario produces generally higher net revenues for all ports (Figures 7 and 8) and has revenue CVs in line with status quo (Supporting Information Material), but has catch CVs that are reduced from status quo (Figure 6).
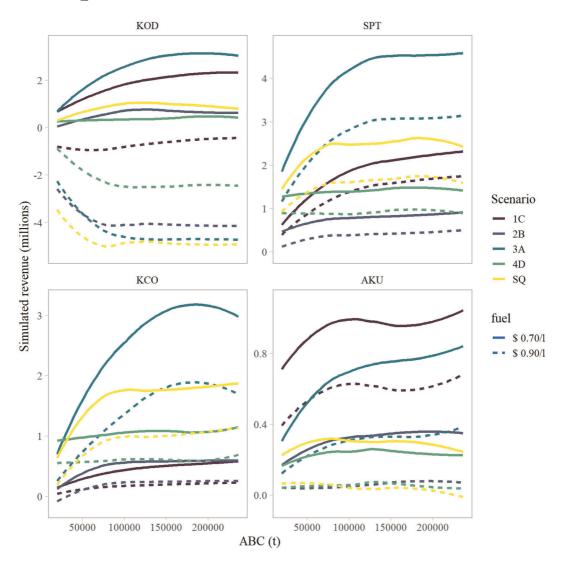
FIGURE 7 Simulated net revenue by port for two exvessel values, across multiple quotas with fuel cost fixed at $0.80/l. Note the variable *y*-axis scale. Scenario 1C = IFQ in federal waters and super exclusive, limited entry in state waters; 2B = Catch-share community allocation in federal waters and limited entry in state waters; 3A = LLP w/ability form cooperatives in federal waters and open access in state waters; 4D = Prohibited species catch allocations in federal waters and equal catch-shares, limited entry in state waters; SQ, status quo

4 | DISCUSSION

This ABM has been built in a compartmentalized manner for flexibility to facilitate future incorporation into other sociobiological or economic models. For instance, if further examinations of IFQ type scenarios were desired this model can be coupled with a dynamic catch-share trading model, such as the IFQ trading scenario presented in Little et al. (2009). This ABM could also be incorporated into, or draw from the results of, management strategy evaluations (Punt et al., 2016) to examine potential biological and economic impacts from changes in the environment or management strategies (e.g., Francis, 1992). Further, it would be possible

FIGURE 8 Simulated net revenue by port for two fuel values, across multiple quotas with the exvessel value fixed at $220/t. Note the variable *y*-axis scale. Scenario 1C = IFQ in federal waters and super exclusive, limited entry in state waters; 2B = Catch-share community allocation in federal waters and limited entry in state waters; 3A = LLP w/ability form cooperatives in federal waters and open access in state waters; 4D = Prohibited species catch allocations in federal waters and equal catch-shares, limited entry in state waters; SQ, status quo

to couple this type of model with discrete individual events such as those presented in Watson and Haynie (2016) as a method to more accurately account for costs by incorporating travel and fishing time based upon vessel speed.

Fishery management, from a modeling perspective, is a complex endeavor as quantifying the motivations of individual fisher behavior is nigh on impossible. For example, fishers adapt their behavior to the perceived situation, whereas this model does not. Differences in simulation results and observed catches in this model are due to the generalization of fisher behavior, for example, average behaviors are used as model inputs, which will by definition not capture distinct behaviors in a given year, season, or area. To address this the model calibration

was examined at an emergent behavior level (e.g., catch by season/area) rather than discrete individual catches. Alternative fisher behaviors could be examined using pattern-oriented modeling (Grimm et al., 2005, 2006) or simple adaptive rules (Carrella et al., 2020). Such an approach would be warranted if the management purpose or question was explicitly based upon behavior of individuals or if additional information on fisher behavior was identified through socioeconomic analyses.

While the identified "best strategy" 3A may be the best option for the management target of revenue by port, the objective of our examination, it may not be the strategy that meets other management objectives. For instance, it is highly desirable that the pollock fleet in the GOA keep PSC to a minimum and Proposal 44-5 was initially brought forward to increase, or at least retain small vessel participation in the fishery. While these objectives have not been evaluated directly within this strategy, it is entirely possible to evaluate the impacts of PSC management strategy using the LLP with cooperatives framework in federal waters as the underlying management strategy or to compare the potential for small vessel participation by port using this current framework. Alternatively, if managers identified these types of examinations as desirable, they could be rapidly addressed with small changes to the simulation structure. Such flexibility is a function of the compartmentalized aspect of this model. There are numerous factors in play when evaluating a fishery, such as the potential to enter other fisheries, seasonal exclusions, catch, and fleet behavior that managers need to consider that may not be addressed within a single framework. Additionally, there are base assumptions that can be evaluated, for example, all catch allocated to state waters by area and season is available to be caught. Spatial examinations of historical catch trends may show that such assumptions are invalid or overstated.

5 | CONCLUSIONS

Managing natural resources across jurisdictions often leads to intricate interactions between governing bodies. Attention to these interactions is likely to increase as managers incorporate ecosystem-based fishery management practices (Harvey et al., 2017; Link & Browman, 2017) and further recognize that coupling complex underlying processes is necessary for exploring policy effects (Bailey et al., 2019, Reimer et al., 2017). The need for a framework for exploring non-cooperative management strategies is likely to grow as the abundance or spatial distribution of fished stocks vary through time under climate forcing (Miller & Munro, 2004). The primary purpose of this exercise was to develop an ABM in a framework that is flexible enough to be of utility to managers for examining alternate management strategies of fishery resources. This objective has been met with the development of a modular framework that is readily adaptable to alternative management scenarios, can be utilized in conjunction with other models of stock allocation or vessel interactions, and has been developed in a widely utilized coding language. Further, this type of model is adaptable to resource allocation issues outside of fisheries.

While the hypothetical fishery presented in this paper is grounded in recent fisher behavior, it is not necessary to have such a developed input structure to address management questions such as those presented throughout this paper. An ABM could easily be adapted for data-limited management scenarios (Fitzgerald et al., 2018), utilizing different métiers and informing input parameters with expert opinion. Coupled with sensitivity analyses such

examinations can produce dynamic model outputs, thus providing managers another tool to help guide decision making.

Bioeconomic models are not regularly used to inform fishery policy making (Carrella et al., 2020) though the capability to produce these models and inform policymakers is increasing (Nielsen et al., 2018). As with any modeling venture, ABM is a not a panacea for marine policy and resource utilization issues and we would not recommend their use as the sole deciding factor in establishing policy. There are social, political, and ecological aspects that may not be adequately addressed by such simulations. However, a reasonable argument can be made for the utility of ABMs, particularly given their ability to inform managers on the trade-offs present in complex and diverse policy decisions.

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AUTHOR CONTRIBUTIONS

Benjamin C. Williams: conceptualization (equal); formal analysis (lead); methodology (lead); validation (lead); visualization (lead); writing original draft (lead); writing review and editing (lead). **Keith Criddle**: conceptualization (equal); funding acquisition (equal); supervision (equal); writing original draft (supporting); writing review and editing (supporting). **Gordon H. Kruse**: conceptualization (equal); project administration (lead); supervision (equal); writing original draft (supporting); writing review and editing (supporting).

ORCID

Benjamin C. Williams http://orcid.org/0000-0001-7295-2076
Keith R. Criddle https://orcid.org/0000-0001-9347-2944
Gordon H. Kruse https://orcid.org/0000-0001-6925-1308

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