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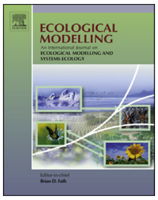

An adaptable agent-based model for guiding multi-species Pacific salmon fisheries management within a SES framework

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ABSTRACT

Informing fishery management decisions using coupled socio-ecological systems (CSES) models requires model construction that captures the systems interactions with high precision. Ecological uncertainty in fishery models is easily reduced using existing scientific literature, but social drivers are often poorly defined or understood. The lack of knowledge about fishermen behavior results in inaccurate models of questionable utility for fishery managers. We designed and constructed a high fidelity agent based model (ABM) using the socio-ecological framework that reduces social system uncertainty by capturing complex behaviors using data-driven bounded rationality and feedback. The resulting generalized ABM of CSES dynamics was instantiated to Pacific salmon fisheries at Kenai river in Upper Cook Inlet, Alaska. The data-driven model construction fuses multiple data-sets for classification of social and ecological fishery regimes into stochastic distributions; the agent behaviors were generalized by evolving parametrized equations using data-driven machine learning; multiple non-trivial metrics on multiple scales verified model's accuracy and predictive capacity. The verified model of CSES dynamics at the Kenai river revealed recent instability in the dipnet fishery coupled dynamics, historic instability in the drift gillnet fishery coupled dynamics due to a compensatory and aggressive fishing strategy, and in the future the model will be used for scenario-based studies to understand the outcomes of alternative management strategies.

1. Introduction

Fishery models are a key tool to inform management decisions to minimize the chance of stock collapse and maximize fish harvest (Schlueter et al., 2012). The Ricker model (Ricker, 1958) and the Beverton–Holt model (Beverton and Holt, 1957) are two commonly used stock–recruitment (S–R) models to manage industrial scale fishing stocks (Limburg, 2017). Fisheries began using these scientific models for assistance in management decisions shortly after they were introduced. After the Ricker curve was developed, single-species S–R models, biomass-based production models, and age-structured pool models formed the scientific basis for management guidance (Schlueter et al., 2012) (e.g. Fleischman et al.'s use of an age-structured S–R state-space model for Pacific salmon Fleischman et al., 2013). These models reduce uncertainty associated with ecological aspects of fisheries management. More recently, social–ecological (SE) models are proposed to incorporate complex social interactions and feedbacks within and across both the social and ecological systems (Schlueter et al., 2012).

Human behavior in fishery science and management has been identified as a complex source of uncertainty requiring additional data collection, analysis and modeling (Schlueter et al., 2012; Garcia and Charles, 2008; Fulton et al., 2011). Resource users often behave differently from management and scientific expectations due to bounded rationality, autonomy, and complex decision patterns (Fulton et al., 2011). Unexpected behavior might result from implementation of a management strategy with unanticipated outcomes of social systems (Schlueter et al., 2012). The uncertainty propagates through the couplings between social and ecological systems and can result in compound unpredictability of outcomes in ecological systems. Despite this realization, most research focuses on reducing uncertainty of the exploited resource in an ecological system alone (Fulton et al., 2011). Reducing uncertainty in the social system may be complicated by poorly understood social drivers or lack of data for model design, whereas economic and biophysical drivers are well defined (Fulton et al., 2011; Degnbol and McCay, 2007; Symes and Phillipson, 2009).

Recent landscape and bio-economic fishery models incorporate social complexity and uncertainty to capture varying levels of complexity. Bayesian methods (Ives and Scandol, 2013) and systematic

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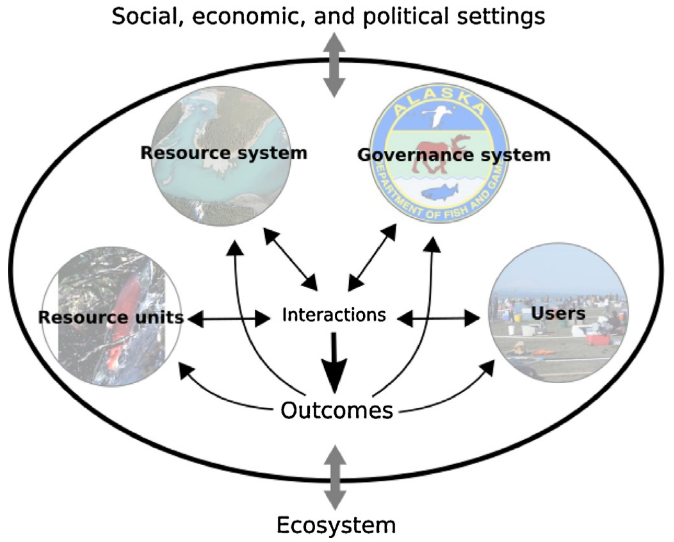

Fig. 1. Adaptation of Ostrom's framework for developing an agent based model of CSES of Alaska Fisheries. Photo credit: Sockeye salmon: Sockeye salmon jumping over beaver dam Lake Aleknagik, AK by Kristina Ramstad 1997. All others: Photos obtained from the Alaska Department of Fish and Games website.

variation of angler behavior (Hunt et al., 2011) techniques quantify uncertainty as probability or choice utility maximization or random utility theories. Agent-based models (ABMs) with complex social dynamics using bounded rationality and variation in individual behavior have been proposed to study coupled social–ecological systems (CSES) in other problem domains than fisheries scenarios (Schlueter et al., 2012). Building ABMs to inform fisheries policy on different scopes and issues cannot be done using single assessment dimensions as would occur in neo-classical economics models or biomass transfer models. On the other hand, decision rule-based ABMs for fisheries modeling allows for implementation of complex social behaviors and feedbacks of CSES modeling. Ostrom proposed the general SES framework that consists of resource units, resource system, users, and governance system subunits (Ostrom, 2009) and allows implementation of multiple social–social, social–ecological, and ecological–ecological feedbacks occurring in fisheries. Fig. 1 shows a conceptual adaptation of Ostrom's framework for salmon fisheries with salmon, fishermen, watershed, and fishery management subunits interacting to produce outcomes that then loop back to the original subunits themselves. Subunits influence both the ecosystem and social, economic, and governance settings and vice versa.

Our ABM was built to support scenario-based fishery studies within Ostrom's framework for SES. Agent-based models employing Ostrom's framework are expressive enough to capture the desired complexity of human behavior in fisheries models and incorporate social uncertainty by allowing for interactions between the different SES subunits. Scenario-based studies allow fisheries managers to test the outcomes of a new management policy or study the impact of climate change on CSES dynamics. We use CSES metrics that incorporate interactions between social and ecological components as the primary model construction tool to ensure we capture the coupled system dynamics. The utility of this approach is demonstrated by successful construction of a high-fidelity model, the model validation on multiple scales and across multiple coupled metrics, and the model's predictive capacity. The use of CSES metrics for model construction and validation is a novel and necessary approach to accurately capture the coupled interactions between ecological and social system subunits.

2. Background

Alaska salmon fisheries are a major economic driver that annually produce an ex-vessel value exceeding $400 million a year (ADFG, 2016). In 2009 alone, Alaska salmon fisheries generated more than $1.3 billion in ex-vessel revenue and resulted in 80,800 direct, indirect, and induced jobs (Marine Conservation Alliance, 2011). In addition to employment and economic impacts, 32% of the wild food harvest for subsistence in rural areas consist of salmon (Fall, 2014). Subsistence patterns of harvesting seasonal salmon runs and preserving fish by smoking or drying for winter continue to be a part of the cultural identity for Alaska Natives (Alaska Native Heritage Center Museum, 2011). Active management is necessary to ensure ecosystem stability of these fisheries due to salmon harvest by various users. The maximum sustained harvest principle of salmon returns of many of Alaska's salmon stocks further justifies management for ecosystem resilience to maintain stock productivity.

Alaska salmon fisheries are managed with two goals: (1) ensure adequate numbers of salmon are allowed to spawn or *escape* and (2) simultaneously allocate fish to different user groups based on Board of Fisheries (BOF) management guidelines (see AAC Title 5) (Woodby et al., 2005; AAC, 2016). Alaska fisheries managers predominantly use S–R models to establish escapement goals (Piccolo et al., 2009). The BOF manages fisheries by issuing pre-season regulations including season openings and closings, quotas, allowed fishing areas, and gear specifications. The Alaska Department of Fish and Game (ADFG) enforces these regulations in addition to collecting scientific data including salmon life history statistics, escapement, stakeholder effort, and stakeholder harvest. To meet escapement goals, the ADFG uses *emergency orders* to either limit or increase in-season harvest through fishery openings, closures, gear limitations, and allowed fishing areas (Sechrist and Rutz, 2014). While the escapement goals are well understood and calculated using watershed carrying capacity, the management of Alaska salmon fisheries uses fishermen groups to meet the ecological objectives. Alternative management scenarios of meeting escapement goals are needed to avoid sometimes harsh management decisions that cause conflict among the stakeholders and management.

The ADFG management decisions for the Upper Cook Inlet fisheries use a combination of different models including genetic stock identification (GSI), test fishing, in-river salmon sonar counts, analysis of commercial effort and harvest, salmon age composition studies, and mark-recapture studies (Barclay et al., 2017; Shields and Dupuis, 2015). Collected data is analyzed by technicians and used by managers along with years of observed human management decisions and personal experience to make management decisions. Our ABM is designed to be used as a decision support tool for fisheries resource managers to allow for governing CSES (Wood et al., 2015; McLane et al., 2011) that incorporates both social and ecological drivers. Our constructed ABM is used for scenario-based studies to understand the potential outcomes of simulated or observed changes to the social or ecological systems.

The advantage of spatially explicit ABMs is that they allow capturing of landscape heterogeneity in SES (Filatova et al., 2013). The downside of spatially explicit models is that they fail to generalize SES interactions and make the model difficult to alter to study different watersheds. Over-fitting the model to a spatially explicit landscape degrades its ability to make reliable predictions of coupled dynamics and understand the nature of interactions between agents and landscape. A spatial model (not spatially explicit) does not sacrifice spatial heterogeneity where space simply limits the scope of agent interactions. This cardinal notion of space allows for simulation of complex dynamics in site-specific models, reliable predictions of CSES dynamics by collecting statistics from multiple