Participatory place-based integrated ecosystem assessment in Sitka, Alaska: Constructing and operationalizing a socio-ecological conceptual model for sablefish (*Anoplopoma fimbria*)

Judith Rosellon-Druker [a,*], Marysia Szymkowiak [b], Kerim Y. Aydin [c], Curry J. Cunningham [a], Emily A. Fergusson [b], Stephen Kasperski [c], Gordon H. Kruse [a], Jamal H. Moss [b], Melissa Rhodes-Reese [b], Kalei S. Shotwell [b], Ellen Spooner [d], Ellen M. Yasumiishi [b]

[a] *College of Fisheries and Ocean Sciences, University of Alaska Fairbanks, 17101 Point Lena Loop Rd, Juneau, AK, 99801, USA*
[b] *Alaska Fisheries Science Center, NMFS, NOAA, 17109 Point Lena Loop Road, Juneau, AK, 99801, USA*
[c] *Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way NE, Seattle, WA, 98115, USA*
[d] *Office of Science and Technology, NMFS, NOAA, 1315 East-West Highway, Silver Spring, MD, 20910, USA*

ARTICLE INFO

ABSTRACT

An integrated ecosystem assessment (IEA) is a framework that organizes science to aid in the transition from traditional single-species management towards ecosystem-based management. Within the Gulf of Alaska, we started a small-scale IEA framework with active engagement of local stakeholders in the fishing community of Sitka. The initial step of this framework was the development of conceptual models. Here, we present a co-produced conceptual model using data gathered from participatory focus groups and a literature review of ecosystem attributes driving the abundance of sablefish (*Anoplopoma fimbria*). We then assembled a qualitative network model (QNM), a mathematical representation of a conceptual system in which perturbations of individual components can be assessed for their qualitative effect. Simulations were conducted to test different biophysical scenarios, while evaluating tradeoffs across ecological and human dimension components. In contrast to large adult sablefish, juvenile and small adults responded similarly to most biophysical conditions. In general, human dimension components responded negatively to the tested scenarios. These results highlight the potential need for management strategies that differentiate between small and large adults, particularly if current sablefish stock assessment trends persist, such as the lack of older fish contributing to spawning biomass and uncertainties in estimates of year-class strength.

1. Introduction

An Integrated Ecosystem Assessment (IEA) is a formal synthesis involving both a qualitative and quantitative analysis of information related to natural, social, and economic factors that are relevant to specific ecosystem management objectives (Levin et al., 2009). An IEA can inform management decisions in an ecosystem-based fishery management (EBFM) framework. A primary IEA goal is to inform and engage natural resource managers, policy makers, scientists, stakeholders, and other citizens (Levin et al., 2009). IEAs have been established in several coastal regions of the United States (NOAA IEA Program, https://www.integratedecosystemassessment.noaa.gov/) and abroad (Dickey-Collas, 2014). The size and scope of an IEA varies depending on the number of participants, size of the ecosystem investigated, and stakeholder and management needs. However, there are many commonalities in the process involved in establishing and conducting an IEA. This process involves defining ecosystem-based goals and targets, developing indicators, assessing ecosystem status, analyzing uncertainty and risk, and evaluating management strategies (Levin et al., 2009).

A place-based IEA is one that is focused on a place or community within scientifically defined and distinctive socio-ecological subregions that addresses the concerns of stakeholders. Fishing villages and coastal communities in Alaska are, by definition, placed-based, and are protected under National Standard 8 of the Magnuson-Stevens Fishery Conservation and Management Act, which highlights the importance of fishery resources to fishing communities and establishes a requirement

---

to provide for the sustained participation of such communities, and to the extent practicable, minimize adverse economic impacts on those communities (NMFS, 2007).

Sitka, Alaska is a coastal community in Southeast Alaska located on the west coast of Baranof Island (Fig. 1) where commercial, subsistence and recreational fishing are the most important economic, social, and cultural activities (Himes-Cornell et al., 2013). In 2017, Sitka ranked 10th among all US ports in terms of total landed fishery value (US$75 million; SEDA, 2019) despite a population size under 9000. Compared with other Southeast Alaska fishing communities, Sitka is the largest with respect to the number of active vessels and number of federal and state fishing permits (Fey et al., 2016).

The Southeast Alaska sablefish (*Anoplopoma fimbria*) fishery is the oldest and one of the most lucrative groundfish fisheries in Alaska (Carroll and Green, 2013; Fissel et al., 2019), and is important to the commercial, sport, and personal use sectors of Sitka (Himes-Cornell et al., 2013). The commercial sablefish fishery is prosecuted by fixed gear (longline and pot) in the Bering Sea, Aleutian Islands, and Gulf of Alaska (GOA), including within both state- and federally-managed fisheries. Since 1995, the federal directed sablefish fishery has been managed under an Individual Fishing Quota (IFQ) program, through which fishermen have a transferable fishing privilege (quota share) that translates into an individual annual harvest allocation (pounds) based on the total allowable catch. Hereinafter, the commercial sablefish fleet is referred to as the sablefish IFQ fleet for simplicity.

Large recruitment events of Alaska sablefish occur episodically. Two such events occurred recently with large 2014 and 2016 year classes (Hanselman et al., 2019). The 2014 year-class was initially estimated to be extremely large, but estimates have declined with the addition of new age data in more recent assessments. The 2016 year-class is currently estimated to be 2.5 times larger than any other observed year-class (1977 to date), but it is possible that it is also overestimated as were initial estimates for the 2014 year-class (Hanselman et al., 2019).

Dockside price per pound for sablefish is positively correlated with fish size, categorized by weight ranges (1–2 lbs; 2–3 lbs; 3–4 lbs; 4–5 lbs; 5–7 lbs; 7 lbs and greater). On average the next biggest size class results in a 16% increase in the average dockside price, and prices for the largest size class (7 lbs and up) are on average 35% greater than the smallest size class that is typically captured by the sablefish IFQ fleet

(3–4 lbs), based on prices from 2012 to 2017 (NPFMC 2018; NPFMC 2019). Therefore, to the extent practicable, the IFQ fleet targets larger-sized fish primarily through larger hook sizes and greater fishing depths. A larger percentage of smaller fish are being landed in recent years as the 2014 year-class has entered the commercial fishery and the current retention policy does not allow fishermen to discard small fish (i. e. high-grading). Increased harvests of smaller fish are putting downward pressure on the price of small fish as well as increasing the price margin between small and large fish, further reducing average prices (Hanselman et al., 2019). Therefore, despite increasing allowable harvests, revenues decreased 22.5% to $92.4 million from 2017 to 2018 as ex-vessel prices fell 30% (Hanselman et al., 2019).

Additionally, several recent observations have raised concerns regarding the population dynamics of this stock. Although recent strong year classes are clearly positive signs and help reverse decades-long declines in sablefish biomass, the lack of older fish contributing to spawning biomass, below average body condition (i.e. lighter fish for a given length), uncertainties in estimates of the strengths of the 2014 and 2016 year classes, and uncertainty about rapid, ongoing changes in environmental conditions in the GOA in recent years lead to concerns about the future condition of this stock (Hanselman et al., 2019). Over the short-term, spawning biomass is projected to increase rapidly from 2020 to 2022 as the 2014 and 2016 year classes continue to mature, after which spawning biomass is expected to stabilize (Hanselman et al., 2019).

To better understand the social and economic consequences of these changes in the sablefish population, a series of participatory focus groups were held with community members and resource stakeholders in Sitka to co-produce a socio-ecological conceptual model. These type of models are representations of systems that allow for the integration of intrinsically linked social, environmental and biological components, capturing in turn the scientific understanding of an ecosystem and promoting engagement of stakeholders via the incorporation of diverse types of knowledge (Levin et al., 2016). The sablefish socio-ecological model serves then as a communication tool to describe connections between the ecosystem, sablefish, and humans in the community of Sitka based on the amalgamation of both local ecological knowledge (LEK) and scientific knowledge. The incorporation of LEK (i.e. day-to-day observations and practical experiences) into science is
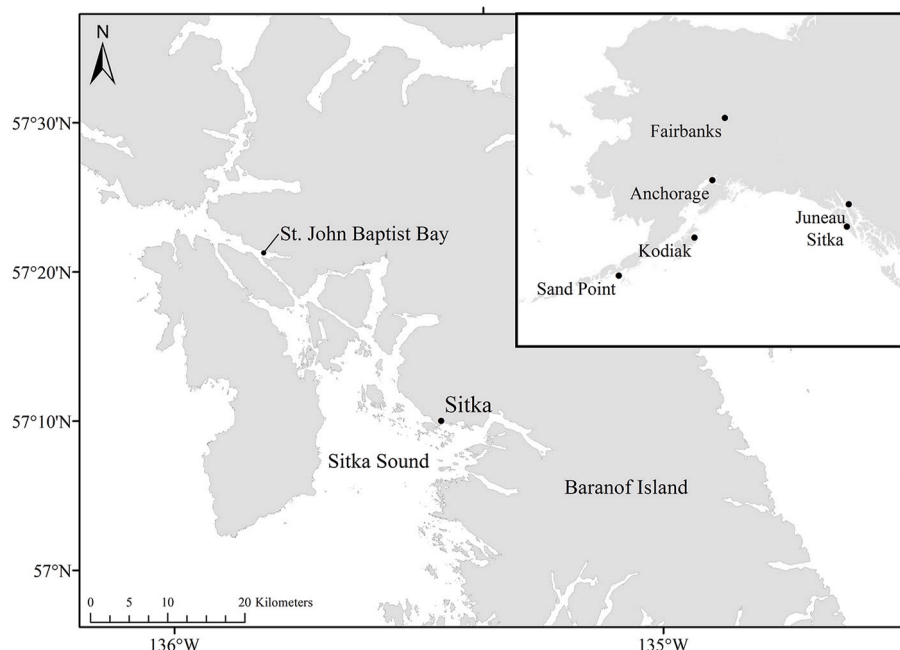

Fig. 1. Study site map. Locations shown are Sitka, Sitka Sound and St. John Baptist Bay, an important sablefish nursery area in Southeast Alaska.

needed to achieve sustainable, effective, and equitable management of fisheries at local scales (Palacios-Agundez, 2013; Wadsworth et al., 2014; Raymond-Yakoubian et al., 2017).

Here we develop a Qualitative Network Model (QNM), a mathematical representation of a conceptual model, to advance an IEA for Southeast Alaska that promotes an EBFM approach of the sablefish fishery. We begin by describing the process of co-developing a socio-ecological model for sablefish between scientists from the Alaska Fisheries Science Center (AFSC) of the National Marine Fisheries Service (NMFS), University of Alaska Fairbanks (UAF) and stakeholders from the Sitka community. This co-produced model summarizes the main biological and environmental factors driving the abundance of sablefish and the economic well-being associated with this commercial fishery in Sitka. Through QNM perturbation scenarios, we predicted qualitative changes in the abundance of sablefish and how these resulting predictions are determined by intertwined ecosystem processes that might explain present and future changes of the stock at an ecosystem level.

2. Methods

2.1. Development of the conceptual model

We followed a five-step process to develop a co-produced socio-ecological model for sablefish (Fig. 2; Rosellon-Druker et al., 2019). First, we undertook a comprehensive literature review to determine relevant biological and environmental aspects driving the abundance of sablefish. Key components within and linkages among environmental and biological components were identified. We documented peer-reviewed publications and agency technical reports for each link. Link directions (i.e. positive, negative, or unknown) and link descriptions (i.e. summary of the interaction) were recorded (Appendices A and B). Sablefish life stages were selected based on two sources: 1) the most recent stock assessment (Hanselman et al., 2019) and 2) ontogenic differentiation by depth (e.g. Norris, 1997; Saunders et al., 1997; Sogard and Berkeley, 2017).

Second, information obtained from the previous step was used to develop a preliminary conceptual model, which included the following nodes: a) life stages of sablefish (eggs and larvae, juveniles, small adults, and large adults); b) environmental features (oceanographic properties and intra-decadal patterns of climate variation); and c) biological components (primary and secondary producers, prey, predators and competitors).

Third, we conducted two participatory focus groups in Sitka with local residents in April and November 2018 (Rosellon-Druker et al., 2019; Szymkowiak and Kasperski, 2020). These meetings involved fishery and social scientists and local participants including commercial, subsistence, and sport fishermen, harvester representatives and fishery managers, community health and well-being educators and leaders, Alaska Natives with cultural ties to local resources and representatives from the resources department at the Sitka Tribe of Alaska, and researchers with expertise in the local ecosystem. The focus groups were divided into two sections: a) ecological connections in the local ecosystem and b) human dimensions of local fisheries.

The ecological connections section centered on the identification of biological and environmental factors that influence the abundance of focal fisheries (e.g. Chinook salmon (*Oncorhynchus tshawytscha*), Pacific halibut (*Hippoglossus stenolepis*), Pacific herring (*Clupea pallasii*) and sablefish) over time and the direction of connections between these factors, as well as current knowledge gaps about species' biology and ecosystem dynamics, based on personal experiences, knowledge, and *in situ* observations (i.e. LEK components) by Sitka residents. Workshop participants were encouraged to draw, or otherwise describe, their own sablefish conceptual model. Following this individualized exercise, participants were shown the pre-constructed model and asked to complement it with their own written or drawn elements.

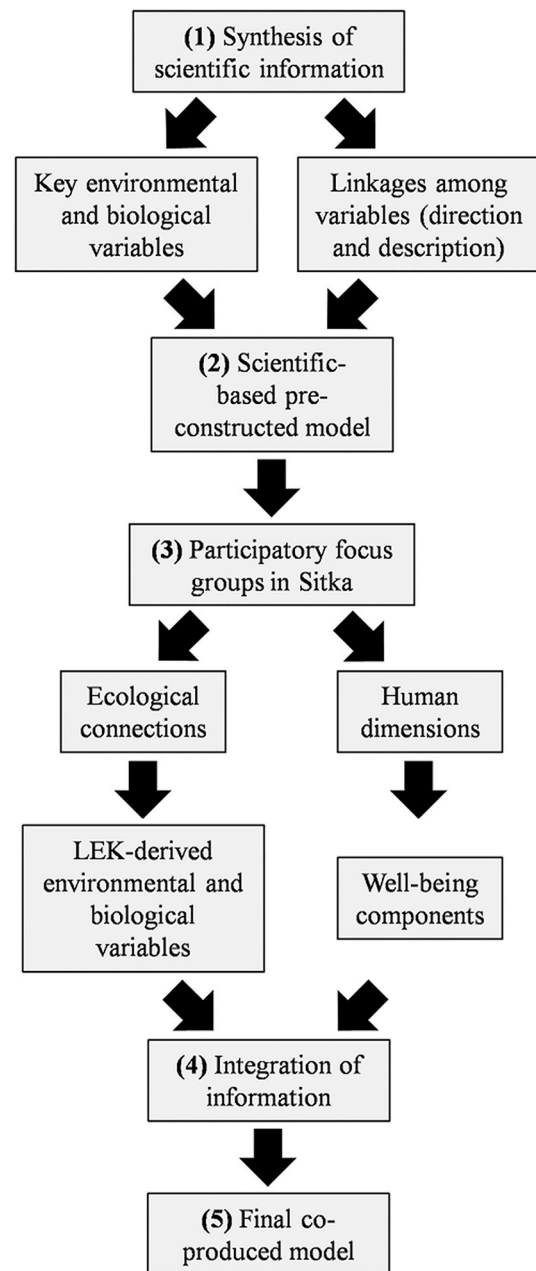The human dimensions section examined how residents interact with

Fig. 2. Flow diagram illustrating the development of the co-produced conceptual model for sablefish.

their local fisheries and how those interactions may affect community well-being. The discussion during this focus group illuminated the multifaceted nature of how a community derives well-being from fisheries participation, including economic welfare, family connection to cultural values and traditions, and the psychological benefits of a connection to the water (Rosellon-Druker et al., 2019; Szymkowiak and Kasperski, 2020). Here, we explored the linkages between sablefish and community well-being in Sitka, focusing only on economic welfare, in terms of livelihood and income security, due to the substantial dependence of the local commercial fleet on sablefish in terms of their fishing portfolio, the comparatively lower reliance of the local sport and subsistence users on this resource (Sill and Koster 2017), and to maintain model tractability.

Fourth, the focus groups were followed by an immediate debriefing process whereby researchers discussed and summarized the major themes that emerged of the discussion. The environmental and

biological components provided by Sitka participants were co-referenced with the components already identified during the literature review process. Last, the science-based pre-constructed model, LEK-generated components, and human dimension components were combined into one unifying model, which is described in more detail in the Results section.

2.2. Qualitative network models

The structure of socio-ecological systems can be described through qualitative models (Puccia and Levins, 1985; Dambacher et al., 2009). These models are represented by signed diagraphs that depict all variables of interest as well as links and link direction (+, -, neutral or unknown) among those variables. A signed diagraph can be also represented as a matrix of interactions (i.e. community matrix **A**; Levins, 1974) and a set of simultaneous differential equations (Puccia and Levins, 1985):

$$\frac{dx_i}{dt} = f_i(x_1, x_2, \ldots, x_n; c_1, c_2, \ldots, c_n),$$

where the rate of change in variable x_i is a function f_i of the other n – 1 variables and their rate parameters c (Harvey et al., 2016). The community matrix **A** is composed of a_{ij} elements (i.e. interaction coefficients) that indicate the direct effect of variable j on variable i (Dambacher et al., 2009) and is defined as the partial derivative $a_{ij} = \frac{\partial f_i}{\partial x_j}$ evaluated at equilibrium (Raymond et al., 2011; Reum et al., 2015). In a press (sustained) perturbation of one or more rate parameters c, the system approaches a new equilibrium and the response variables can experience a shift of direction. Predictions of these shifts are obtained from the inverse of the community matrix ($-A^{-1}$).

A probabilistic QNM approach was used to determine the sign outcome of system variables to a press perturbation (Reum et al., 2015). This simulation approach can be summarized as follows: 1) a community matrix **A** is generated with the signs specified in the conceptual model. Additionally, negative "self-effects" (i.e. -1 on the diagonal of the matrix) are added to increase overall stability (Puccia and Levins, 1985) although these negative self-effects were not considered for further analysis; 2) absolute values of each a_{ij} element are randomly drawn from uniform distributions spanning 0.01 to 1 or -0.25 to -1 for the diagonal of the matrix; 3) the resulting matrix is evaluated against system stability criteria (i.e. feedback of the whole system is negative) (Dambacher et al., 2009) and if stable, the final sign response is calculated. If unstable, the community matrix is discarded, and a new matrix is generated restarting the simulation approach. We repeated this process until obtaining at least 1000 stable matrices for a given analysis. Raymond et al. (2011) considered a sign consistency threshold of 70% meaning that a model component response was considered highly positive or negative (i.e. high sign consistency) if it was positive or negative, respectively, in ≥70% of the total number of simulations (10,000). Model components with positive or negative responses in <70% of the total simulations were considered ambiguous.

We then identified linkages with the strongest relative influence on the sign outcome of target variables (i.e. sablefish life stages and human dimension model components with a non-ambiguous sign response) using a Generalized Boosted Regression (GBR) where the simulated responses (i.e. signs) of the target variables were treated as a response variable and the simulated interaction strengths between each linkage were treated as a predictor variable (Melbourne-Thomas et al., 2012; Harvey et al., 2016). GBR models resemble additive regression models in which individual terms are simple trees, fitted in a stage-wise fashion (Melbourne-Thomas et al., 2012). All analyses were run in R language using the "QPress" package (Melbourne-Thomas et al., 2012) and the "dismo" package (Hijmans et al., 2017).

2.3. Press perturbation scenarios

To determine press perturbation scenarios, we performed exploratory Pearson correlations to evaluate possible relationships between sablefish recruits (age 2) and sablefish total biomass (age 2+) and a suite of environmental and biological variables. We also incorporated LEK into these scenarios, based on the responses given by Sitka residents during the participatory focus groups. Yearly sablefish recruitment and biomass data were obtained from the 2019 sablefish stock assessment (Hanselman et al., 2019). Years analyzed were 2000–2018, a span for which observations on all variables were available. Environmental and biological variables were obtained from six different sources (Table 1) and are described in detail below. Although we prioritized data from Sitka Sound (i.e. Southeast Alaska), data sets from this region were not commonly available, so we considered data from other regions of the GOA. For the exploratory analysis, strong (r ≥ 0.50) and moderate (0.30 ≥ r ≤ 0.50) correlations were considered for further analysis (Cohen, 1988) (Table 1). To obtain p-values, all dependent and independent variables were log base 10 (x+1) transformed to meet assumptions of heteroscedasticity (Zar, 1999). Given the exploratory nature of this analysis, correlations with p-values < 0.10 were selected as final candidates for press perturbation scenarios (Tables 1 and 2).

The first data source used to determine perturbation scenarios were report cards from the Ecosystem Status Reports (ESRs), which are produced annually by the AFSC to summarize biological, environmental, and social information about the status of the Alaska marine ecosystems via ecosystem indicators. Further details about these reports and contained information is provided in Zador and Yasumiishi (2018) and https://access.afsc.noaa.gov/reem/ecoweb/Index.php. We analyzed the following ecosystem indicators from the eastern GOA: rhinoceros auklet (*Cerorhinca monocerata*) chick mean growth rate, Steller sea lion (*Eumetopias jubatus*) abundance (non-pups), herring mature biomass, motile epifauna biomass (i.e. eelpouts, octopi, crab, sea stars, brittle stars, sea urchins, sand dollars, sea cucumbers, snails, and hermit crabs), copepod community size index, zooplankton density in Icy Strait, and a multivariate ENSO index (MEI) for December–January. We also analyzed two indicators from the western GOA: freshwater discharge from Resurrection Bay and capelin (*Mallotus villosus*) in prey composition from various piscivorous seabird and groundfish species, due to their relevance to sablefish abundance and recruitment (Shotwell et al., 2014; Coutré et al., 2015; Coffin and Mueter, 2016).

The Southeast Coastal Monitoring (SECM) annual survey started in 1997 to identify the relationships between year-class strength of juvenile Pacific salmon (*Oncorhynchus* spp.) and biophysical variables that influence their habitat preferences, growth, and biological interactions. Further details of this survey can be found in Fergusson et al. (2018). We explored chlorophyll-a (Chl-a, μg/L) concentrations estimated from water samples. In a study of potential indicators for age-2 sablefish recruits as estimated by annual stock assessments, Yasumiishi et al. (2015) found that the best-fitting general linear model included chl-a concentrations. Strom et al. (2016) found that higher chl-a concentrations were related to diatom-dominated spring blooms in the GOA, so we used chl-a as a proxy for primary production (phytoplankton).

The AFSC conducts annual longline surveys to estimate sablefish and other groundfish species' abundance on the continental slope of the eastern Bering Sea, Aleutian Islands, and GOA (AFSC, 2020). A detailed description of this survey and gear used is found in Sigler and Lunsford (2016). Besides determining relative abundance, size composition, and migration patterns of sablefish, the survey also records depredation by killer (*Orcinus orca*) and sperm whales (*Physeter macrocephalus*) when gear damage or removal of fish from the hooks is observed (Sigler and Lunsford, 2016). We explored the sperm whale depredation variable for Southeast Alaska (Table 1). Sperm whale world-wide population has grown at about four percent a year since 1986 (i.e. moratorium went into effect) (ADFG, 2020) while depredation on sablefish and other species has increased since the implementation of the IFQ program

Table 1
Data sources (with temporal and spatial scales) for QNM press perturbation scenarios and exploratory Pearson correlations to determine those variables correlated with sablefish recruits and biomass. P-values are only reported for moderate to strong correlation coefficients ($\geq$0.30) and (*) represent significant p values ($<$0.10) for log10 transformed data. NA indicates that no correlations were performed for LEK components.

Data source	Scenario #	Temporal and spatial scales	Component	Correlation coefficients (biomass)	p-value	Correlation coefficients (recruits)	p-value
ESR Report cards	1	Southeast Alaska (2000–2016)	Rhinoceros Auklet Chick Growth	−0.26		−0.54	0.02*
ESR Report cards		Southeast Alaska (2000–2017)	Steller Sea Lion Non-pups	0.31	0.21	0.40	0.10
ESR Report cards		Southeast Alaska (2000–2018)	Herring Mature Biomass	−0.27		−0.23	
ESR Report cards		Southeast Alaska (2003, 2005, 2007, 2009, 2011, 2013, 2015, 2017)	Motile Epifauna Biomass	0.27	0.35	−0.04	0.24
ESR Report cards		Southeast Alaska (2000–2018)	Copepod Community Size	0.32	0.28	0.33	0.19
ESR Report cards		Southeast Alaska (2000–2018)	Zooplankton Density	0.14		−0.20	
ESR Report cards	4	Tropical Pacific (2000–2018)	Multivariate ENSO Index	0.14		0.56	0.01*
ESR Report cards	1	Western Gulf of Alaska (2000–2013)	Freshwater Input	0.48	0.08*	0.31	0.27
ESR Report cards	1	Central and Western GOA (2000–2018)	Capelin (as prey in seabirds and groundfish)	−0.36	0.02*	−0.31	0.01*
SECM survey	1	Southeast Alaska (2001–2018)	Chlorophyll-a concentrations	0.15		0.45	0.06*
AFSC Longline survey	3	Southeast Alaska (2000–2018)	Whale depredation	0.43	0.06*	0.04	
NCEP/NCAR model	1, 4	Southeast Alaska (2000–2018)	Modeled surface temperature	0.27		0.43	0.06*
Fisheries and Oceans Canada Government	4	North Pacific (2005–2015)	ALPI Index	0.42	0.19	0.54	0.09*
LEK (Sitka community)	2	Sitka Sound (2015–2018)	Pyrosomes and squid blooms	NA	NA	NA	NA

Table 2
Summary of QNM scenarios evaluated for the sablefish co-produced model: (1) local ecosystem change, (2) increased cephalopods/jellies, (3) whale recovery, and (4) atmosphere-ocean warming.

Variable	Scenario	Press perturbation
Temperature	1	+
Freshwater input	1	+
Primary production	1	+
Seabirds	1	-
Capelin/Sand lance	1	-
Gelatinous zooplankton	2	+
Cephalopods and jellyfish	2	+
Whale depredation	3	+
Aleutian low, ENSO, the Blob	4	+

(Wild et al., 2020).

The National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) Reanalysis Project began in 1991 to produce a 40-year record of global analyses of atmospheric fields. This project uses a frozen state-of-the-art analysis/forecast system and performs data assimilation using data from 1957 to the present (Kalnay et al., 1996). Reanalysis information and selected output is available online (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surfaceflux.html). We analyzed a time series of modeled daily sea surface temperature from a single Southeast Alaska position (56.5°N, −138.0°W) located ~160 km offshore Sitka Sound (Table 1).

Since 1993, the Pacific Biological Station (Department of Fisheries and Oceans Canada, DFO) has produced an index of the relative intensity of the Aleutian Low (Aleutian Low Pressure Index, ALPI). The ALPI describes decadal-scale changes in North Pacific climate-ocean conditions (Surry and King, 2015) and is calculated annually and available from https://open.canada.ca/data/en/dataset/4bb821ce-bef7-46d3-95d2-064065f1bda4 and explored here as another environmental variable (Table 1).

Finally, direct LEK contributions from Sitka community members were used to construct another press perturbation scenario (Table 1). In the first focus group held in Sitka in April 2018, participants stressed the unusual presence of pyrosome (*Pyrosoma* spp.) blooms in recent years. In that same focus group, as well as in the one held on November 2018, participants also highlighted the abundant presence of market squid (*Doryteuthis opalescens*) in Sitka Sound. Blooms of these gelatinous species in recent years (2015–2018) have also been scientifically documented (e.g. Cavole et al., 2016; Archer et al., 2018; Brodeur et al.,

2018). Gelatinous zooplankton and a corresponding increase of jellyfish and squid abundance (important prey of sablefish; Yang and Nelson, 2000 and Hanselman et al., 2019) were thus selected as the last set of variables.

For the press perturbations, based on exploratory correlation results, we used four scenarios that characterize recent or expected future ecosystem conditions (Table 2). First, we imposed a positive press perturbation to sea surface temperature, freshwater input, and primary production (diatoms and picoplankton), and a negative press perturbation to seabird depredation and capelin abundance. We nicknamed this scenario, "local ecosystem change" which describes relevant local or regional biophysical conditions in the last decade (Zador and Yasumiishi, 2018). Second, we imposed a positive press perturbation to gelatinous zooplankton, cephalopods and jellyfish abundance (nicknamed, "increased cephalopods/jellies") which is based on LEK. Third, we imposed a positive press perturbation to whale depredation (nicknamed, "whale recovery"), one of the most important sources for stock variation over time (Hanselman et al., 2019). And fourth, we imposed a positive press perturbation to intra-decadal patterns of climate variation: Aleutian Low, ENSO, and The Blob (i.e. a large mass of warm water over the North Pacific Ocean with water temperatures 3 °C above the long-term (1982–2014) average), which we nicknamed, "atmosphere-ocean warming". For each scenario, shifts in community equilibrium were calculated using the simulation algorithm explained above. Scenarios 1, 2 and 4 capture various facets of climate change (e.g. Brodeur et al., 2018; Zador and Yasumiishi, 2018; Yang et al., 2019) whereas scenario 3 largely represents ongoing recovery of whales in the Northeast Pacific as a result of cessation of commercial whaling (Hanselman et al., 2018).

3. Results

3.1. Sablefish conceptual model

The sablefish co-produced model included a total of six environmental components (rectangles), sixteen biota components (triangles), and five human dimension components (diamonds) (Fig. 3 a). Lines between model nodes indicate either a positive (arrow head) or negative (dot head) effect on the terminal group (Fig. 3 a).

Model components and link directions determined during the scientific literature review process remained unaltered by Sitka community members during the focus group activities. About 80% of biological and environmental model components and link directions determined

during the scientific literature review process were also identified by stakeholders, where the missing components were related to a few prey and predator species. This high concurrence displays the expert-like knowledge that stakeholders possess on their surrounding ecosystem based on observational experience. Participants also added other components to the model such as anthropogenic impacts on the ecosystem and the importance of nursery habitats (e.g. fjords). All the LEK-generated components were grouped into four topic groups (Table 3): 1) Anthropogenic impacts on ecosystems; 2) Biological interactions; 3) Miscellaneous; and 4) Knowledge gaps. Only some of these components were included in the final model (yellow highlighted components; Fig. 3 a), based on the following selection criteria: 1) components with a direct effect on the abundance of sablefish, their prey, or predators (i.e. first and second-order interactions); and 2) components that have a potentially quantifiable effect on the abundance of sablefish. The motivation for the aforementioned criteria was model simplicity to keep the model tractable and interpretable across different stakeholder groups to facilitate its use as a communication tool. The sablefish co-produced model was illustrated to engage a broader audience and this image is expected to be used for teaching, outreach, and tourism (Fig. 3 b).

All the prey-predator interactions identified by focus group participants were considered for the final model and added to a correspondent biota node (Appendix B; Fig. 3 a) as they were cross-referenced with diverse diet composition studies. For example, rockfish (shortspine thornyhead; *Sebastolobus alascanus*) was identified by Sitka participants as an important commercial species consumed by sablefish (Yang et al., 2006) and also as a potential competitor and predator (Gaichas and Ianelli, 2005; Aydin et al., 2007). Rockfish were considered inside the "Other prey/predator" nodes of the model (Appendix B). Another interesting example was the observation by some participants of "greenish algae/matter" in sablefish stomachs. This might refer to a high content of terrestrial leaf litter, which is consumed by juvenile sablefish (Coutré, 2014). These components were also considered inside the "Other prey" node (Appendix B).

The connection between ecological and human dimension components in the sablefish co-produced model was specified through economic drivers between small and large adults and average price, fishing effort, harvest, and gross revenue. The human dimension components represent participation in the commercial sablefish fishery only, focusing on how the changing fish size composition in the fishery is affecting prices, effort, and revenues. Thus, we omit the subsistence sablefish fishery from our analysis (herein meaning fishing for the purposes of personal consumption rather than under a permit specified as subsistence), which is small in Sitka (and throughout Alaska) due to the difficulty of harvesting this deep-water resource relative to other subsistence fisheries (Sill and Koster, 2017). For simplicity, the conceptual model also assumes that the Sitka community well-being components derived from commercial fisheries participation are constrained to livelihood and income security, through the positive link with gross revenue, which is consistent with other conceptual models of GOA fisheries (Zador et al., 2017). This allows for assumptions of a unidirectional and constant link between gross revenue and community well-being. Incorporating other well-being components would necessitate more complex linkages and feedback loops than were feasible for the purposes of exploring ecological scenarios, which were the focus of this study. Other well-being components associated with commercial and subsistence participation in the sablefish fishery for Sitka stakeholders are described in Rosellon-Druker et al. (2019).

The human dimension components of the sablefish conceptual model reflect the basic economic relationships between earnings expectations and fishing behavior, as well as the economic components of well-being derived from fisheries as reflected in discussions with Sitka community stakeholders during participatory focus groups. The size-based pricing for sablefish is reflected in the links between small adults (negative) and large adults (positive) and these combine to produce an average price received for the sablefish landed. The relationship between earnings

expectations and fishing effort is captured through the positive link from average price to fishing effort. Fishing effort drives the total harvest of sablefish, within the bounds of the total allowable catch (TAC). The link between small adults and fishing effort captures the negative effect of the smaller average size composition of the stock on effort due to lowered earnings expectations associated with both lower average prices as well as increasing fishing costs due to greater use of bait, fuel, and time to harvest one's full quota, as well as other behaviors to avoid small sablefish. In contrast, large adult sablefish have the opposite effect on fishing effort due to increased earnings expectations. Price multiplied by harvest volume yields gross revenue. In this conceptual model, this relationship is captured through positive links from average price and catch to gross revenue, omitting the multiplicative component due to the formulation of conceptual models with only positive and negative linkages. Gross revenue, in turn, positively contributes to community well-being through its association with livelihood and income security (Breslow et al., 2016). The negative links between catch (volume) and small and large adult sablefish reflect the removals of fish from the population.

3.2. Sablefish responses across perturbation scenarios

For all scenarios, the socio-ecological model configuration responded strongly to the selected perturbations, although with highly variable sign consistency among model components (Fig. 4). Scenario 1 (local ecosystem change) resulted in a positive response of sablefish juveniles and small adults (73% and 72%, respectively) and an ambiguous response in large adults (59%). In the case of other model components, positive responses with high sign consistency (100%) were observed in picoplankton, small copepods, and gelatinous zooplankton as well as in the abundance of cephalopods and jellyfish. Positive responses with high sign consistency were also observed in herring, Pacific cod (*Gadus macrocephalus*), and pollock (*Gadus chalcogrammus*) (75%), and other sablefish prey (85%) (Fig. 4 a).

Scenario 2 (increased cephalopods and jellyfish) resulted in positive responses with high sign consistency in juveniles and small adults (97 and 99%, respectively), while large adults had an ambiguous response (67%). Negative responses with high sign consistency were observed in fishing effort and average price (94% and 87%, respectively) (Fig. 4 b).

Scenario 3 (whale recovery) resulted in mostly negative responses across all model components. In the case of the sablefish life stages, large adults and juveniles had high sign consistency (81% and 77%, respectively) while small adults had an ambiguous response (67%). Other relevant results include a high sign consistency in gross revenue (80%) and total harvest (94%) (Fig. 4 c).

Finally, in scenario 4 (atmosphere-ocean warming), the socio-ecological system responded in different directions. In the case of life stages, positive responses with high sign consistency to the press perturbation were observed in both juveniles (70%) and small adults (71%) while in large adults the sign response was ambiguous (62%). Other positive responses with high sign consistency (100%) were observed in picoplankton, small copepods, and gelatinous zooplankton as well as in abundance of cephalopods and jellyfish (Fig. 4 d).

In the local ecosystem change scenario, according to the GBR model, the positive sign response of juveniles was mainly attributed to three links: capelin/sand lance – juveniles, temperature – primary production (diatoms), and pollock – capelin/sand lance (Fig. 5 a). These linkages explaining the sign response of juveniles accounted for 17.9% of the explained deviance by the GRB model. The positive sign response of small adults was influenced by the links between capelin/sand lance and different life stages of sablefish (Fig. 5 a). These two linkages explaining the sign response of small adults accounted for 14.9% of the explained deviance by the model.

In the increased cephalopods/jellies scenario, the positive sign response of juveniles was mainly attributed to the interactions of different sablefish life stages as well as the fishing effort – harvest,
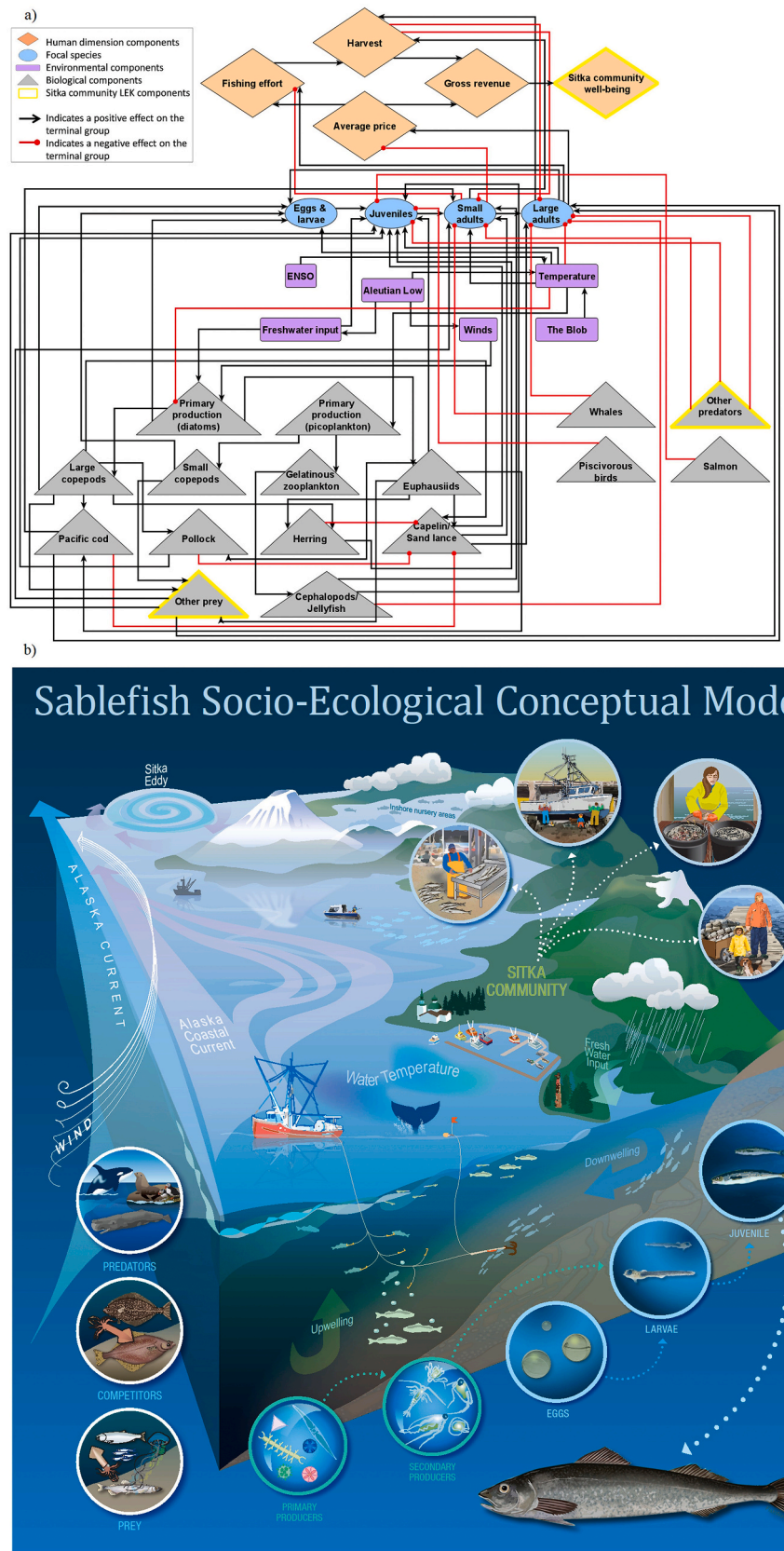
Fig. 3. a) Sablefish socio-ecological co-produced model; b) communicative tool representing the socio-ecological model (illustrated by Paul Irvin; reproduced with permission of NOAA-NMFS).

Table 3

Topic groups and sablefish model components provided by Sitka community members during a participatory focus group (LEK-generated model components).

Anthropogenic impacts on ecosystem	Biological interactions	Miscellaneous	Knowledge gaps
Pollution	Predators/Competitors Squid† Skates† Spiny dogfish† Grenadier† Rockfish† Halibut†	Conservation and health of fjords	Pyrosome/squid blooms†
Logging	Prey/Food source Rockfish (thornyheads)† Algae and terrestrial leaf litter† Lantern fish†		Empty stomachs as possible sign of starvation
Fishing gears			Diet at different depths
Bycatch			Vertical and horizontal movement patterns
Ocean acidification			Spawning ground habitat characteristics
			Modification of the microbial loop
			Interactions with aquaculture

Note: † reflects components that were incorporated into the final model.

cephalopods/jellyfish – juveniles, and small adults – harvest links (Fig. 5 b). These six linkages accounted for 52.1% of the explained deviance. The positive sign response of small adults was mainly attributed to the fishing effort – harvest link, followed closely by the links corresponding to all different sablefish life stage interactions (Fig. 5 b). These five linkages accounted for 37.6% of the explained deviance. In regard to human dimension variables, the negative sign response of fishing effort was attributed to the small adult – large adult and the harvest – large adult links, followed closely by three more links (Fig. 5 b). These five linkages accounted for 50.9% of the explained deviance. The negative sign response for average price was mainly attributed to the small adult – average price link, seconded by the large adult – average price, small adult – fishing effort, and small adult – large adult links (Fig. 5 b). These four linkages accounted for 57.6% of the explained deviance.

In the whale recovery scenario, the negative sign response of juveniles was mainly attributed to the whale depredation – small adult, harvest – small adult, and whale depredation – large adult linkages (Fig. 5 c). These three linkages accounted for 53.7% of the explained deviance. The negative sign response of large adults was mainly attributed to five links: harvest – small and large adults, fishing effort – harvest, and whale depredation – small and large adults (Fig. 5 c). These linkages accounted for 37.9% of the explained deviance. In the case of human dimensions, gross revenue negative sign response was mainly attributed to the small adult – average price link, followed closely by the whale depredation – small and large adults, along with three more links (Fig. 5 c). These six linkages accounted for 59.6% of the explained deviance. Harvest negative sign response was influenced by five links: whale depredation – small and large adults, small adults – large adults, fishing effort – harvest, and small adults – fishing effort (Fig. 5 c). These linkages accounted for 30.1% of the explained deviance.

Last, in the atmosphere-ocean warming scenario, the juveniles positive sign response was mainly determined by the temperature – primary production (diatoms and picoplankton) as well as the capelin/sand lance – juvenile links (Fig. 5 d). These three linkages accounted for 16.6% of the explained deviance. The sign response of small adults was also influenced by the temperature – primary production (diatoms and picoplankton) as well as the capelin/sand lance – small adults and primary production (diatoms) – euphausiid links. These four linkages accounted for 19.1% of the explained deviance.

4. Discussion

4.1. Interpreting QNM results

4.1.1. Local ecosystem change and atmosphere-ocean warming scenarios

These two scenarios represent recent ongoing changes in regional biophysical conditions, as well as global intra-decadal patterns of climate change. In both cases, an ambiguous sign response occurred in large sablefish in contrast to a high sign consistency observed in juveniles and small adults. The positive sign response of juveniles and small adults under these two scenarios was influenced by links related to the abundance of capelin/sand lance and different sablefish life stages, as well as the relationship between temperature and primary (picoplankton and diatoms) production. The relative low deviance (<20%) explained by the model in these two scenarios might be related to the inherent complexity of both, reflected by the large number of interactions and the presence of countervailing feedback loops within the system when several press perturbations occur simultaneously.

In general, when the GOA is cold and well-mixed, nutrients are high and phytoplankton abundant and commonly dominated by diatoms (Strom et al., 2016). A high abundance of diatoms supports a zooplankton community dominated by large calanoid copepods and euphausiids. Such a community sustains a nutritionally rich food web (due to a higher lipid content and greater efficiency of energy transfer to higher trophic levels), supporting large numbers of fish, seabirds, and marine mammals (Liu and Hopcroft, 2008; Chiba et al., 2015; Simonsen et al., 2016; McKinstry and Campbell, 2018). In contrast, under warm, stratified, and stable water conditions, nutrients are usually low and the phytoplankton community, with lower production rates, is dominated by picoplankton and flagellates. These conditions result in a zooplankton community dominated by gelatinous zooplankton (e.g. salps, doliolids, ctenophores, cnidarian medusae) and small copepods (Simonsen et al., 2016; Strom et al., 2016; McKinstry and Campbell, 2018), that represents a nutritionally poor food web of low nutritional quality and inefficient energy transfer, supporting a smaller biomass of higher trophic levels (Richardson, 2008). In general, these conditions were replicated with press perturbations in scenarios 1 and 4. However, there seems to be some model feedbacks countering the expected net negative effect of these scenarios on primary production (diatoms), secondary production (euphausiids), and capelin/sand lance.
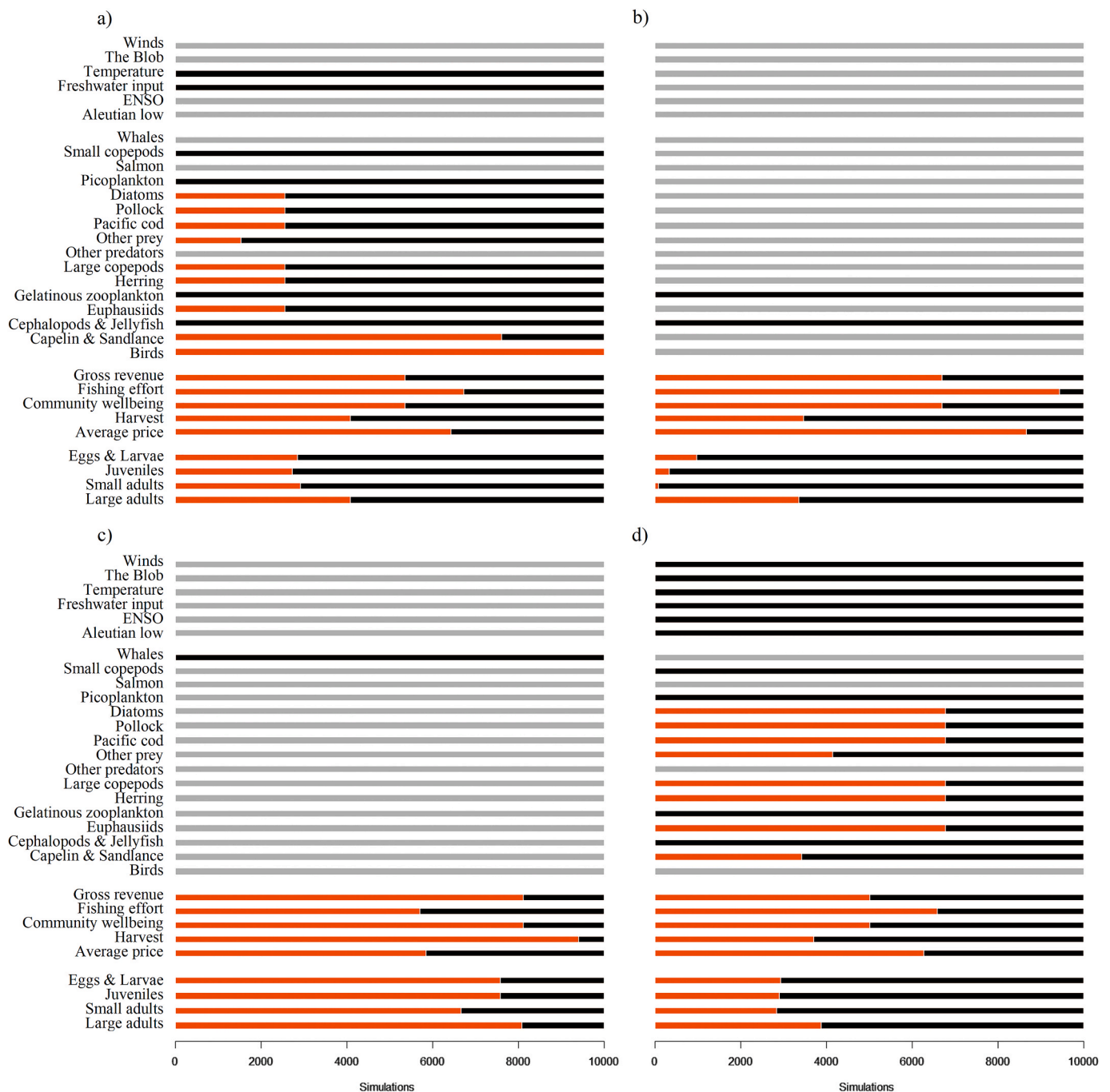
Fig. 4. Responses of the sablefish socio-ecological model to four press perturbation scenarios; a) Scenario 1 (local ecosystem change); b) Scenario 2 (increased cephalopods/jellies); c) Scenario 3 (whale recovery), d) Scenario 4 (atmosphere-ocean warming). Bars indicate the number of simulations (from a total of 10,000) where the response was of a given direction: Grey, no response; black, positive response; red, negative response. Sablefish life stages are shown in the bottom of each panel. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

In the local ecosystem change scenario, one of the press perturbations included an increase of primary production (picoplankton and diatoms) which resulted in an overall positive response of secondary production by euphausiids, which in turn favored capelin/sand lance. This also explained a positive response in other groundfish species such as herring, pollock and cod. Further, the freshwater input (e.g. glacial runoff, precipitation) variable increased either as a direct press perturbation (scenario 1) or as a response to other variables (i.e. Aleutian low; scenario 4). Glacial runoff modifies turbidity, temperature, stratification, nutrients, and distribution of phytoplankton (Arimitsu et al., 2016). In our model (Fig. 3 a), this variable produces a positive response

on primary production (diatoms) and therefore on euphausiids and capelin/sand lance. Our results suggest that capelin/sand lance are important for early stages of sablefish either as a direct prey or as a food source for other species that are also part of the sablefish diet. It is worth noting that capelin were abundant from 2008 to 2013 in the GOA but declined during the warm years of 2015–2016 and continue to be minimal in recent years (Zador and Yasumiishi, 2018). In contrast, abundance of sand lance increased in the GOA during warm periods. An apparent tradeoff between sand lance (warm conditions) and capelin (cold conditions) exists and may explain the importance of these forage fish in the system for commercially relevant fisheries (Zador and
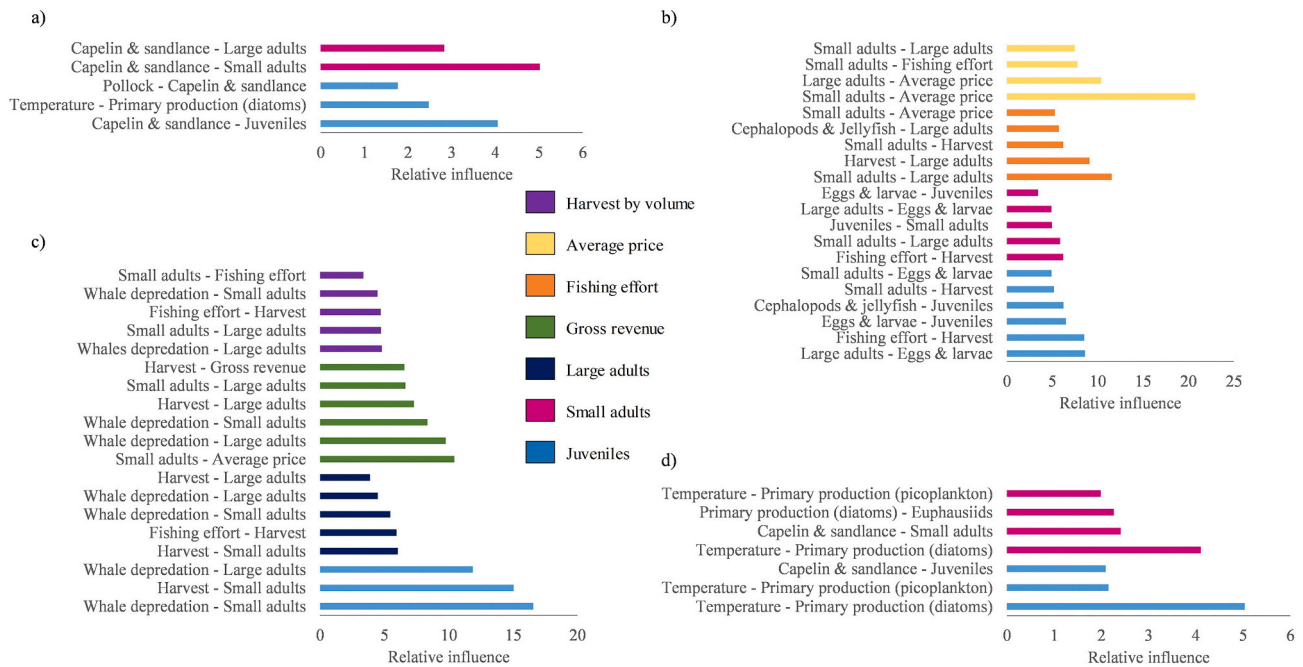
Fig. 5. Relative influence of linkages on the sign response of target variables for each of the four press perturbation scenarios; a) Scenario 1 (local ecosystem change); b) Scenario 2 (increased cephalopods/jellies), c) Scenario 3 (whale recovery), d) Scenario 4 (atmosphere-ocean warming). The relative influence is unitless and the sum of all the model linkages (n = 108) for a given scenario sums to 100. Standardized values above 2.5 standard deviations from the mean were selected as the number of linkages accounting for the highest relative influences.

Yasumiishi, 2018).

The ambiguous response of large sablefish to these two scenarios may be due to a negative influence of temperature on large adults in comparison with other life stages. Such differential temperature effects would not be surprising given the diverse habitats occupied by sablefish during their life history: adults spawn at depths of 300–500 m along the continental slope edge (Mason et al., 1983), eggs develop at depth but larvae develop near the surface far offshore (Wing, 1997), and young juveniles are found in inshore waters (Rutecki and Varosi, 1997). Different temperature responses due to size-specific horizontal and vertical movements could explain some of the disparity between small adults and large adults. Temperature is an important factor affecting the early development and maturation of fish. Larvae and age-0 sablefish experiencing warm temperatures (>14 °C) have higher physiological rates, which favor faster growth and survival (Sigler et al., 2001; Doyle and Mier, 2016; Lee et al., 2017). This suggests that juvenile sablefish can thrive at increased temperatures, when sufficient food supply is available (Sogard and Olla, 2001). Further, there is an ontogenetic shift downward in the optimal temperature for growth in sablefish and many other fish species (Sogard and Olla, 2001), thus tolerance for elevated temperatures in juveniles differs from that in adults. Krieger et al. (2019) observed a shift in thermal performance with size, with larger fish performing better at colder temperatures compared to smaller fish. Shallow and deep-water sablefish have significant differences in external morphology, mean weight-at-length, mean length and age at depth, physiological properties, and histological characteristics (Norris, 1997). Fish experiencing food deprivation, which is a common occurrence in deep benthic habitats, have a clear motivation to reduce body temperature and conserve energy when foraging success declines (Sogard and Olla, 2001).

Above average recruitment of sablefish appears to be associated with above average sea surface temperature anomalies (i.e. the Blob) (Sigler et al., 2001; Sogard and Olla, 2001). However, it is important to emphasize that there is a steep decline of both growth and survival in juvenile sablefish outside the boundary between highly favorable (>8 °C) and highly unfavorable (>20 °C) temperatures (Sogard and Olla,

2001; Krieger et al., 2019). As sea surface temperatures keep increasing and Blob-like warming events occur more frequently (Frölicher et al., 2018), year-class success may decline for sablefish.

In contrast with scenario 1, the resulting biophysical conditions in the atmosphere-ocean warming scenario, such as the shift in abundance from large, lipid-rich copepods to small, lipid-poor copepods, had a general negative effect on the system (Fig. 4 d) that mirrors the real situation for many stocks in the GOA in recent years. For instance, fish apex predator biomass during NOAA trawl surveys in 2017 was the lowest observed over the 30-year time series, largely due to severe declines in Pacific cod and arrowtooth flounder (*Atheresthes stomias*) (Zador and Yasumiishi, 2018). The recent Blob and associated environmental conditions in the GOA appear to be the main drivers of these recent declines. These downward trends act synergistically with those we explored for sablefish not only on Sitka but also on other fishing-dependent communities in the eastern GOA. The implications of downward revenue trends in any one species are compounded when they are concurrent with revenue declines in other fisheries that comprise the suite of harvesting or access privileges within a fishing portfolio (Tuler et al., 2008; Hall-Arber et al., 2009; Murray et al., 2010), and may increase income variability and risk for fishers (Kasperski and Holland, 2013). In addition to additive effects on revenue declines, these sorts of changes can have severe psychological implications due to how declines across species within a fishing portfolio can negate one of the chief adaptive mechanisms by which fishermen adjust to revenue declines, that is fisheries diversification (Murray et al., 2010; Lord, 2011).

4.1.2. Increased cephalopods and jellyfish scenario

This LEK scenario was based on workshop participants' observations relating to the presence of pyrosome and squid blooms in recent years. An increase of these gelatinous organisms resulted in positive responses for both juveniles and small adults and an ambiguous response in large sablefish. The positive sign response of juveniles and small sablefish was influenced by the positive feedback between different sablefish life stages and by the net negative effect that human dimension variables experienced under this scenario. The high deviance explained by the

model in this scenario suggests that the composition of zooplankton and the abundance of gelatinous organisms-based food supply is important to explain the dynamics of sablefish.

Sablefish larvae, juveniles and adults consume gelatinous zooplankton, jellyfish and squids (Yang and Nelson 2000; Hanselman et al., 2019). It is plausible that sablefish are able to switch easily from a fish to a gelatinous organism-based diet. In the case of juveniles, the increase of cephalopods and jellyfish was one of the most influential links explaining the positive response of this life stage under this scenario. However, a diet mainly based on these organisms may explain the ambiguous response in large adults and why the current body condition of mature sablefish is below average (Hanselman et al., 2019). Focus group participants were concerned that a perceived increasing proportion of empty adult sablefish stomachs in recent years may be a sign of starvation. Although observations of empty stomachs from sablefish caught in longline surveys are not new and might result from regurgitation upon gear retrieval or a rapid digestion rate (Sasaki, 1985), this LEK component might also be an indication of a poor diet. The "soft or mushy" flesh condition, present in sablefish and other commercially harvested species, is associated with several causes, including a lipid-poor diet (Karinen et al., 2010; Jones et al., 2018), gonad maturation matching low food availability, low temperatures and low oxygen levels (Norris, 1997). Shenker and Olla (1986) documented an example of prey quality influence on sablefish growth in which faster growth occurred with a diet of mysid shrimp compared to a diet of brine shrimp. Mysids promote sablefish growth primarily due to their higher dry-to-wet weight ratio in comparison to brine shrimp. Older, larger sablefish might survive on a squid/jellyfish based-diet but their poor-lipid, high-water content could have a measurable impact on the meat quality and potentially lead to starvation and subsequent death.

Driven by the response of sablefish (i.e. increased juveniles/small adults and a dampened effect on large adults), human dimension components such as fishing effort and average price responded negatively to this scenario. There is a substantial price premium for large sablefish that provides for positive revenue trends. Increases in juvenile and small sablefish abundance drive down average prices for sablefish resulting in lowered revenues. Under nutrient-limited conditions, wherein there are relatively fewer large, fat fish entering the large adult size class due to their reliance on gelatinous organisms for food, the continued prosecution of this adult class seems to contribute to its lower abundance (i.e. harvest – large adults link).

4.1.3. Whale recovery scenario

An increase in whale depredation under this scenario resulted in negative responses for juveniles and large sablefish. These responses were influenced by the negative effect of whale depredation on the entire sablefish life history. This scenario also indicated that the joint dynamics of fishing and whale depredation have a more pronounced reduction of the abundance of sablefish, which is reflected as a net negative effect in harvest and gross revenue. The ambiguous response in small adults might be then explained by the more intense prosecution of larger sablefish by the fishery, consequently reducing part of the negative influences on this life stage.

Whale depredation on longline gear has been occurring throughout Alaskan waters for decades (Peterson and Carothers, 2013). Sperm and killer whales are the main predators, with sperm whales accounting for the majority of depredation in the central and eastern GOA (Peterson and Hanselman, 2017). The estimated reduction in sablefish catch rate due to depredation is approximately 15% suggesting a significant impact on commercial harvests, survey abundance indices in terms of reduced accuracy, and increased costs for the commercial fishery (Hanselman et al., 2018). Fishermen can also incur additional operating costs due to changes in fishing behavior intended to avoid whales, such as increased distances between sets, shorter soak times, and fishing in deeper waters which are generally further offshore. Further, in response to high levels of whale depredation, in 2015, the North Pacific Fishery Management

Council (NPFMC) implemented new management actions intended to reduce depredation by allowing fixed-gear fishermen in the GOA to use pots (traps), which deter whales from consuming captured fish (Peterson and Hanselman, 2017; Hanselman et al., 2018). All of the above reflects the significance of whale depredation for this stock, which also becomes evident in the high explained deviances observed under this scenario.

4.2. Sablefish conceptual model as part of a place-based IEA framework for Southeast Alaska

We demonstrated an example of how a conceptual model can be transformed from an illustrative communication tool to a simulation modeling tool that represents a local ecosystem structure. The socio-ecological sablefish model represents a steppingstone of an IEA pilot approach for Southeast Alaska. As such, it is a tool that helps to identify and link social and ecological components of this local ecosystem and evaluate how biophysical stressors might impact fisheries resources and well-being of a community to inform future management actions. For example, our results indicate that certain biophysical conditions seem to be more favorable towards recruitment and abundance of juvenile sablefish while that same positive effect is somewhat dampened in older sablefish. A strong desire to reduce or avoid interactions with small sablefish have led to changes in fishing behavior, which are in turn increasing operating costs. Over the last two years, these costs have been coupled to lowered revenues due to smaller fish sizes, decreasing overall profits for the fleet (Hanselman et al., 2019), and highlight the need for potential new management strategies. The gap between small and large sablefish was the basis of a discussion paper presented to the NPFMC by stakeholders and managers in 2019 exploring the possibility to allow discarding of small sablefish in the IFQ sablefish fishery (NPFMC, 2019). Although this is not considered in the short-term, several management options are currently being explored including the ability to produce species- and gear-specific discard mortality rates, different discarding rules depending on stock abundance, likelihood of achieving TAC, effect of discards on whale depredation, and gear modifications to avoid small sablefish, among others (NPFMC, 2019).

Conceptual models are valuable tools in communicating complex systems, identifying knowledge gaps, and making information accessible to a variety of different audiences, however, they also present disadvantages that are worth noting. Conceptual models are simulations of ecosystem dynamics that simplify complex interactions. During this simplification process, assumptions need to be made and, because of this, many known and unknown linkages are not included (e.g. LEK-generated components such as anthropogenic impacts on the ecosystem or ecological processes like changes in the microbial loop structure; Table 3). Further, the heterogeneity of human responses is greatly reduced. Humans have both instant and long-term adaptations that may not be readily incorporated into a simplified model structure due to the longer time span necessary for adaptation to manifest itself in a biophysical system. As a simplistic example, in the short run, fishermen will seek to mitigate revenue declines in one fishery with increased harvests in another. This shift in fishing behavior cannot be easily incorporated into a model without increasing its complexity beyond the scope of the research. Researchers should ponder the implicit tradeoffs between oversimplifying a system and contributing to scientific knowledge in choosing modeling approaches. Similarly, QNMs have limitations that need to be considered including: variables are treated as constant or at equilibrium, relationships between variables are considered linear, and components of the system are weighted equally (Dambacher et al., 2009; Reum et al., 2015).

Despite drawbacks, our co-produced sablefish model helps to capture current GOA sablefish stock and ecosystem dynamics (i.e. including more frequent blooms of gelatinous marine organisms, shifts in zooplankton composition, and the dominance of juveniles/small sablefish) and represents a unique attempt to combine social, environmental, and biological components of the sablefish fishery in Southeast Alaska.

Further, the influence of human dimension components within some of these scenarios (e.g. increased cephalopods/jellies and whale recovery), underscores the need to understand the relative effects of drivers in EBFM to account for holistic impacts of management decisions. Conceptual models are an essential step of any IEA framework as they facilitate the identification of ecosystem objectives, the selection of ecological and socio-economic ecosystem indicators, and are the basis for risk assessments and quantitative ecosystem models (Levin et al., 2009; Harvey et al., 2016). Further, by amalgamating LEK and diverse scientific sources we improved our overall capacity of interpreting local biological, ecological, and social dynamics involving sablefish. An example of the latter was the construction of one press perturbation scenario solely based on LEK, reflecting local and recent observations on the distribution and abundance of gelatinous zooplankton, thus helping scientists to develop new hypotheses and test potential management scenarios. This interdisciplinary approach between scientists and stakeholders improves the accuracy in describing complex socio-ecological systems and helps to develop social learning while enhancing transparency of the assumptions built into the models (Salter et al., 2010).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Judith Rosellon-Druker, Marysia Szymkowiak, Kerim Y. Aydin, Curry J. Cunningham, Emily A. Fergusson, Stephen Kasperski, Gordon H. Kruse, Jamal H. Moss, Melissa Rhodes-Reese, Kalei S. Shotwell, Ellen Spooner, and Ellen M. Yasumiishi.

Acknowledgments

Appendix A. Environmental variables of the sablefish conceptual model

FROM key variable	TO key variable	Link direction	Link description	Citation
Temperature	Sablefish (larvae/ juvenile/adult)	Positive/ Negative	High recruitment is correlated with higher coastal water temperatures and lower offshore temperatures (where older and larger sablefish reside). Positive recruitment events for sablefish are related to intensified Aleutian Low. Otolith-derived growth rate of late larvae and early juveniles is positively correlated with temperature.	Sogard and Olla (1998); Sigler et al. (2001); Stoner and Sturm (2004); Shotwell et al. (2014); Yasumiishi et al. (2015)
Freshwater input	Sablefish (juvenile)	Positive	Age-2 recruitment is correlated with freshwater discharge. Increased freshwater discharge may result in early spring blooms that support larger zooplankton biomass. This zooplankton production is sustained through summer by the onshore transport of nutrient rich water.	Shotwell et al. (2014); Coffin and Mueter (2016)
Winds	Phytoplankton (diatoms)	Positive	There is a positive relationship between age-1 recruitment and upwelling-favorable winds in the Eastern GOA. Upwelling-favorable winds and freshwater discharge may positively affect recruitment through productivity-related mechanisms.	King et al. (2000); Coffin and Mueter (2016)
The Blob	Temperature	Positive	Anomalously warm sea surface temperatures during the blob or blob-like events.	Urawa et al. (2016)
ENSO	Phytoplankton (diatoms/ picoplankton)	Negative/ Positive	During ENSO years (1997–1999), Southeast Alaska experienced nitrate depletion in spring and summer. Low silicate levels were observed in coastal waters, suggesting that diatom growth may have been nutrient limited. The interannual variability in the structure and composition of the picoplankton community may also be related to ENSO. For example, during another ENSO cycle (2001–2002), chlorophyll-a was low and *Prochlorococcus* and bacterial biomass was high.	Whitney and Welch (2002); Liu et al. (2007); DiLorenzo et al. (2008)
ENSO	Temperature	Positive	Heat fluxes diminish in winter and contribute to anomalously warm upper ocean temperatures during an ENSO cycle.	Spies (2007)
Aleutian low	Temperature	Positive	Warmer than average coastal sea surface temperatures during the Aleutian low.	Francis et al. (1998)
Aleutian low	Winds	Positive	Enhanced winds during Aleutian Low.	Francis et al. (1998)
Aleutian low	Freshwater input	Positive	During Aleutian low, the GOA presents heavy precipitation, snow accumulation and intense downwelling, constraining a large coastal freshwater discharge in the nearshore region. The freshwater discharge is also augmented by subsequent glacial meltwater.	Wang et al. (2004); Roger and Grosch (2006); Kohan et al. (2019)
Freshwater input	Phytoplankton (diatoms)	Positive	Micronutrients are supplied from mechanisms such as resuspension of shelf sediments and river discharge. This condition is associated	Stabeno et al. (2004); Etherington et al. (2007); Weingartner et al. (2009); Arimitsu et al. (2016)

(continued)

FROM key variable	TO key variable	Link direction	Link description	Citation
Temperature	Phytoplankton (diatoms/ picoplankton)	Negative/ Positive	with high and sustained chlorophyll-a levels promoting diatom blooms. In the GOA, under cold and well-mixed water conditions, nutrients are high, and phytoplankton is generally dominated by diatoms. In contrast, under warm, stratified, and stable water conditions, nutrients are low, and the phytoplankton community is generally dominated by picoplankton and flagellates.	Strom et al. (2016)

Appendix B. Biological variables of the sablefish conceptual model

FROM key variable	TO key variable	Link direction	Link description	Citation
Euphausiids/Large copepods	Sablefish (juvenile)/Pacific cod/Herring/ Pollock/Capelin/Sand lance/Other sablefish prey	Positive	Predominant prey	McFarlane and Beamish (1992); Sigler et al. (2001); Coutré et al. (2015); Strom et al. (2016); Hanselman et al. (2019)
Small copepods	Sablefish (larvae)/Other sablefish prey	Positive	Prey	McFarlane and Beamish (1992); Sigler et al. (2001); Coutré et al. (2015); Strom et al. (2016); Hanselman et al. (2019)
Shrimp†	Sablefish (adult)	Positive	Prey	Hanselman et al. (2019)
Squids*†	Sablefish (adult/juvenile)	Positive/ Negative	Prey/Competition	Shaul and Geiger (2016); Hanselman et al. (2019)
Herring	Sablefish (juvenile)	Positive	Predominant prey	Coutré (2014); Coutré et al. (2015)
Amphipods†	Sablefish	Positive	Prey	Hanselman et al. (2019)
Polychaetes†	Sablefish	Positive	Prey	Coutré et al. (2015); Hanselman et al. (2019)
Pollock	Sablefish (juvenile)	Positive	Prey	Yang and Nelson (2000)
Capelin	Sablefish (adult/juvenile)	Positive	Prey	Coutré et al. (2015); Hanselman et al. (2019)
Pacific cod	Sablefish (adult)	Positive	Prey	Hanselman et al. (2019)
Sand lance	Sablefish (adult/juvenile)	Positive	Prey	Coutré et al. (2015); Hanselman et al. (2019)
Jellyfish	Sablefish	Positive	Predominant prey	Yang and Nelson (2000)
Salmon (coho, chinook, pink)	Sablefish (juvenile)	Negative	Predation	Wing (1985); Hanselman et al. (2019)
Sperm and killer whales	Sablefish	Negative	Predation	Kawakami (1980); Peterson and Hanselman (2017); Hanselman et al. (2018)
Salmon sharks†	Sablefish	Negative	Predation	Aydin et al. (2007)
Steller sea lions†	Sablefish (juvenile)	Negative	Predation	Aydin et al. (2007); Csepp et al. (2011)
Arrowtooth†	Sablefish	Negative	Predation/ Competition	Aydin et al. (2007); Hanselman et al. (2019)
Puffins	Sablefish	Negative	Predation	Sydeman et al. (2017)
Salmon and salmonoid offal†	Sablefish	Positive	Prey	Yang and Nelson (2000); Sturdevant et al. (2009); Coutré (2014); Coutré et al. (2015); Yasumiishi et al. (2015)
Halibut (adult)*†	Sablefish	Negative	Predation/ Competition	Best and St. Pierre, 1996; Aydin et al. (2007); Hanselman et al. (2019)
Rockfish*†	Sablefish	Positive/ Negative	Prey/Predation/ Competition	Gaichas and Ianelli (2005); Yang et al. (2006); Aydin et al. (2007)
Algae and terrestrial leaf litter*†	Sablefish	Positive	Part of stomach content	Coutré (2014)
Spiny dogfish*†	Sablefish	Negative	Predation	Jones and Geen (1977)
Grenadier*†	Sablefish	Negative	Competition	Yang et al. (2006)
Lanternfish*†	Sablefish	Positive	Prey	Yang et al. (2006)
Skates*†	Sablefish	Negative	Predation	Aydin et al. (2007)
Diatoms	Euphausiids/Large copepods	Positive	Prey	Strom et al. (2016)
Picoplankton	Gelatinous zooplankton/Small copepods	Positive	Prey	Strom et al. (2016)

Note: * reflects LEK components. † reflects that these variables were considered as "other prey" or "other predators" within the conceptual model.

References

Alaska Department of Fish and Game ADFG, 2020. Sperm whale (*Physeter macrocephalus*) species profile. https://www.adfg.alaska.gov/index.cfm?adfg=spermwhale.printe rfriendly. (Accessed 10 October 2020).

Alaska Fisheries Science Center AFSC, 2020. Longline survey data. https://www.afsc. noaa.gov/maps/longline/Map.php. (Accessed 15 January 2020).

Archer, S.K., Kahn, A.S., Leys, S.P., Norgard, T., Girard, F., Du Preez, C., Dunham, A., 2018. Pyrosome consumption by benthic organisms during blooms in the northeast Pacific and Gulf of Mexico. Ecology 99, 981–984. https://doi.org/10.1002/ ecy.2097.

Arimitsu, M.L., Piatt, J.F., Mueter, F., 2016. Influence of glacier runoff on ecosystem structure in Gulf of Alaska fjords. Mar. Ecol. Prog. Ser. 560, 19–40. https://doi.org/ 10.3354/meps11888.

Aydin, K., Gaichas, S., Ortiz, I., Kinzey, D., Friday, N., 2007. A Comparison of the Bering Sea, Gulf of Alaska, and Aleutian Islands Large Marine Ecosystems through Food Web Modeling, 178. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-AFSC., p. 299

Best, E.A., St Pierre, G., 1986. Pacific halibut as predator and prey. International Pacific Halibut Commission 27. Technical Report. 21.

Breslow, S.J., Sojka, B., Barnea, R., Basurto, X., Carothers, C., Charnley, S., Coulthard, S., Dolšak, N., Donatuto, J., García-Quijano, C., Hicks, C.C., 2016. Conceptualizing and operationalizing human wellbeing for ecosystem assessment and management. Environ. Sci. Pol. 66, 250–259. https://doi.org/10.1016/j.envsci.2016.06.023.

Brodeur, R., Perry, I., Boldt, J., Flostrand, L., Galbraith, M., King, J., Murphy, J., Sakuma, K., Thompson, A., 2018. An Unusual Gelatinous Plankton Event in the NE Pacific: the Great Pyrosome Bloom of 2017, 26. PICES Press, pp. 22–27.

Carroll, K., Green, K., 2013. The Southeast Alaska Northern Southeast inside Sablefish Fishery Information Report with Outlook to the 2012 Fishery, 13–08. Alaska Department of Fish and Game, Division of Sport Fish and Commercial Fisheries, p. 48. Fishery Management Report.

Cavole, L.M., Demko, A.M., Diner, R.E., Giddings, A., Koester, I., Pagniello, C.M., Paulsen, M.L., Ramirez-Valdez, A., Schwenck, S.M., Yen, N.K., Zill, M.E., 2016. Biological impacts of the 2013-2015 warm-water anomaly in the Northeast Pacific: winners, losers, and the future. Oceanography 29, 273–285. https://doi.org/ 10.5670/oceanog.2016.32.

Chiba, S., Batten, S.D., Yoshiki, T., Sasaki, Y., Sasaoka, K., Sugisaki, H., Ichikawa, T., 2015. Temperature and zooplankton size structure: climate control and basin-scale

comparison in the North Pacific. Ecol. Evol. 5, 968–978. https://doi.org/10.1002/ece3.1408.

Coffin, B., Mueter, F., 2016. Environmental covariates of sablefish (*Anoplopoma fimbria*) and Pacific ocean perch (*Sebastes alutus*) recruitment in the Gulf of Alaska. Deep Sea Res. Part II Top. Stud. Oceanogr. 132, 194–209. https://doi.org/10.1016/j.dsr2.2015.02.016.

Cohen, J., 1988. Set correlation and contingency tables. Appl. Psychol. Meas. 12, 425–434. https://doi.org/10.1177/014662168801200410.

Coutré, K.M., 2014. Feeding Ecology and Movement Patterns of Juvenile Sablefish in Coastal Southeast Alaska. Master's thesis. University of Alaska, Fairbanks.

Coutré, K.M., Beaudreau, A., Malecha, P., 2015. Temporal variation in diet composition and use of pulsed resource subsidies by juvenile sablefish. Trans. Am. Fish. Soc. 144, 807–819. https://doi.org/10.1080/00028487.2015.1037015.

Csepp, D.J., Vollenweider, J.J., Sigler, M.F., 2011. Seasonal abundance and distribution of pelagic and demersal fishes in southeastern Alaska. Fish. Res. 108, 307–320. https://doi.org/10.1016/j.fishres.2011.01.003.

Dambacher, J.M., Gaughan, D.J., Rochet, M., Rossignol, P.A., Trenkel, V.M., 2009. Qualitative modelling and indicators of exploited ecosystems. Fish Fish. 10, 305–322. https://doi.org/10.1111/j.1467-2979.2008.00323.x.

Dickey-Collas, M., 2014. Why the complex nature of integrated ecosystem assessments requires a flexible and adaptive approach. ICES J. Mar. Sci. 71, 1174–1182. https://doi.org/10.1093/icesjms/fsu027.

Di Lorenzo, E., Schneider, N., Cobb, K.M., Franks, P., Chhak, K., Miller, A.J., McWilliams, J.C., Bograd, S.J., Arango, H., Curchitser, E., 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. Geophys. Res. Lett. 35, 1–6. https://doi.org/10.1029/2007GL032838.

Doyle, M.J., Mier, K.L., 2016. Early life history pelagic exposure profiles of selected commercially important fish species in the Gulf of Alaska. Deep Sea Res. Part II Top. Stud. Oceanogr. 132, 162–193. https://doi.org/10.1016/j.dsr2.2015.06.019.

Etherington, L.L., Hooge, P.N., Hooge, E.R., Hill, D.F., 2007. Oceanography of Glacier Bay, Alaska: implications for biological patterns in a glacial fjord estuary. Estuar. Coast 30, 927–944. https://doi.org/10.1007/BF02841386.

Fergusson, E., Watson, J.T., Gray, A., Murphy, J., 2018. Annual Survey of Juvenile Salmon, Ecologically-Related Species, and Biophysical Factors in the Marine Waters of Southeastern Alaska, 1771. NOAA, NMFS-AFSC Document, p. 65. May-August 2016.

Fey, M., Weidlich, S., Leuthold, N., Ames, R., Downs, M., 2016. Fishing Communities of Alaska Engaged in Federally Managed Fisheries. North Pacific Fishery Management Council Report, p. 32.

Fissel, B., Dalton, M., Garber–Yonts, B., Haynie, A., Kasperski, S., Lee, J., Lew, D., Seung, C., Sparks, K., Szymkowiak, M., Wise, S., 2019. Stock Assessment and Fishery Evaluation Report for the Fisheries of the Gulf of Alaska and Bering Sea/Aleutian Islands Area: Economic Status of the Groundfish Fisheries off Alaska. North Pacific Fishery Management Council Report, p. 297.

Francis, R.C., Hare, S.R., Hollowed, A.B., Wooster, W.S., 1998. Effects of interdecadal climate variability on the oceanic ecosystems of the NE Pacific. Fish. Oceanogr. 7, 1–21. https://doi.org/10.1046/j.1365-2419.1998.00052.x.

Frölicher, T.L., Fischer, E.M., Gruber, N., 2018. Marine heatwaves under global warming. Nature 560, 360–364. https://doi.org/10.1038/s41586-018-0383-9.

Gaichas, S., Ianelli, J., 2005. Gulf of Alaska thornyheads. In: Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of Alaska. North Pacific Fishery Management Council Report, p. 36.

Hall-Arber, M., Pomeroy, C., Conway, F., 2009. Figuring out the human dimensions of fisheries: illuminating models. Mar. Coast. Fish. 1, 300–314. https://doi.org/10.1577/C09-006.1.

Hanselman, D.H., Pyper, B.J., Peterson, M.J., 2018. Sperm whale depredation on longline surveys and implications for the assessment of Alaska sablefish. Fish. Res. 200, 75–83. https://doi.org/10.1016/j.fishres.2017.12.017.

Hanselman, D.H., Rodgveller, C.J., Fenske, K.H., Shotwell, S.K., Echave, K.B., Malecha, P.W., Lunsford, C.R., 2019. Assessment of the sablefish stock in Alaska. In: Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of Alaska. North Pacific Fishery Management Council, p. 216.

Harvey, C.J., Reum, J.C., Poe, M.R., Williams, G.D., Kim, S.J., 2016. Using conceptual models and qualitative network models to advance integrative assessments of marine ecosystems. Coast. Manag. 44, 486–503. https://doi.org/10.1080/08920753.2016.1208881.

Hijmans, R.J., Phillips, S., Leathwick, J., Elith, J., 2017. Dismo: species distribution modeling. R package version 1.1-4. https://cran.r-project.org/web/packages/dismo/index.html. (Accessed 1 January 2020).

Himes-Cornell, A.H., Hoelting, K.R., Maguire, C., Munger–Little, L., Lee, J., Fisk, J., Felthoven, R., Geller, C., Little, P., 2013. Community Profiles for North Pacific Fisheries-Alaska, 259. U.S. Department of Commerce, NOAA, Technical Memorandum NMFS-AFSC, p. 713.

Jones, B.C., Geen, G.H., 1977. Food and feeding of spiny dogfish (*Squalus acanthias*) in British Columbia waters. J. Fish. Res. Board Can. 34, 2056–2066. https://doi.org/10.1139/f77-274.

Jones, T., Parrish, J.K., Peterson, W.T., Bjorkstedt, E.P., Bond, N.A., Ballance, L.T., Bowes, V., Hipfner, J.M., Burgess, H.K., Dolliver, J.E., Lindquist, K., 2018. Massive mortality of a planktivorous seabird in response to a marine heatwave. Geophys. Res. Lett. 45, 3193–3202. https://doi.org/10.1002/2017GL076164.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 77, 437–472. https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Karinen, J.F., Barnett, H.J., Masuda, M., 2010. Soft flesh in sablefish, *Anoplopoma fimbria*, of southeastern Alaska: relationships with depth, season, and biochemistry. US Natl. Mar. Fish. Serv. Mar. Fish. Rev. 72, 26–35.

Kasperski, S., Holland, D.S., 2013. Income diversification and risk for fishermen. Proc. Natl. Acad. Sci. *U.S.A.* 110 https://doi.org/10.1073/pnas.1212278110, 2076–2081.

Kawakami, T., 1980. A review of sperm whale food. Sci. Rep. Whales. Res. Inst. 32, 199–218.

King, J.R., McFarlane, G.A., Beamish, R.J., 2000. Decadal-scale patterns in the relative year class success of sablefish (*Anoplopoma fimbria*). Fish. Oceanogr. 9, 62–70. https://doi.org/10.1046/j.1365-2419.2000.00122.x.

Kohan, M.L., Mueter, F.J., Orsi, J.A., McPhee, M.V., 2019. Variation in size, condition, and abundance of juvenile chum salmon (*Oncorhynchus keta*) in relation to marine factors in Southeast Alaska. Deep Sea Res. Part II Top. Stud. Oceanogr. 165, 340–347. https://doi.org/10.1016/j.dsr2.2017.09.005.

Krieger, J.R., Sreenivasan, A., Heintz, R., 2019. Temperature-dependent growth and consumption of young-of-the-year sablefish *Anoplopoma fimbria*: too hot, too cold or just right? Fish. Res. 209, 32–39. https://doi.org/10.1016/j.fishres.2018.09.005.

Lee, J.S., Cook, M.A., Luckenbach, J.A., Berejikian, B.A., Simchick, C.A., Oden, S.M., Goetz, F.W., 2017. Investigation of long-term effects of larval rearing temperature on growth, deformities, flesh quality, and phenotypic sex of cultured sablefish (*Anoplopoma fimbria*). Aquaculture 479, 91–99. https://doi.org/10.1016/j.aquaculture.2017.05.010.

Levin, P.S., Fogarty, M.J., Murawski, S.A., Fluharty, D., 2009. Integrated ecosystem assessments: developing the scientific basis for ecosystem-based management of the ocean. PLoS Biol. 7, e1000014 https://doi.org/10.1371/journal.pbio.1000014.

Levin, P.S., Breslow, S.J., Harvey, C.J., Norman, K.C., Poe, M.R., Williams, G.D., Plummer, M.L., 2016. Conceptualization of social-ecological systems of the California current: an examination of interdisciplinary science supporting Ecosystem-based Management. Coast. Manag. 44, 397–408. https://doi.org/10.1080/08920753.2016.1208036.

Levins, R., 1974. Discussion paper: the qualitative analysis of partially specified systems. Ann. N. Y. Acad. Sci. 231, 123–138. https://doi.org/10.1111/j.1749-6632.1974.tb20562.x.

Liu, H., Chang, J., Tseng, C.M., Wen, L.S., Liu, K.K., 2007. Seasonal variability of picoplankton in the northern south China sea at the SEATS station. Deep Sea Res. Part II Top. Stud. Oceanogr. 54, 1602–1616. https://doi.org/10.1016/j.dsr2.2007.05.004.

Liu, H., Hopcroft, R.R., 2008. Growth and development of *Pseudocalanus* spp. in the northern Gulf of Alaska. J. Plankton Res. 30, 923–935. https://doi.org/10.1093/plankt/fbn046.

Lord, F., 2011. Understanding social impacts by using new variables and a causal model diagram in New England fisheries. Impact Assess. Proj. Apprais. 29, 59–68. https://doi.org/10.3152/146155111X12913679730476.

Mason, J., Beamish, R., McFarlane, G., 1983. Sexual maturity, fecundity, spawning, and early life history of sablefish (*Anoplopoma fimbria*) off the pacific coast of Canada. Can. J. Fish. Aquat. Sci. 40, 2126–2134. https://doi.org/10.1139/f83-247.

McFarlane, G.A., Beamish, R.J., 1992. Climatic influence linking copepod production with strong year-classes in sablefish, *Anoplopoma fimbria*. Can. J. Fish. Aquat. Sci. 49, 743–753. https://doi.org/10.1139/f92-083.

McKinstry, C.A., Campbell, R.W., 2018. Seasonal variation of zooplankton abundance and community structure in Prince William Sound, Alaska, 2009-2016. Deep Sea Res. Part II Top. Stud. Oceanogr. 147, 69–78. https://doi.org/10.1016/j.dsr2.2017.08.016.

Melbourne-Thomas, J., Wotherspoon, S., Raymond, B., Constable, A., 2012. Comprehensive evaluation of model uncertainty in qualitative network analyses. Ecol. Monogr. 82, 505–519. https://doi.org/10.1890/12-0207.1.

Murray, G., Johnson, T., McCay, B.J., Danko, M., St Martin, K., Takahashi, S., 2010. Cumulative effects, creeping enclosure, and the marine commons of New Jersey. Int. J. Commons 4, 367–389. https://doi.org/10.18352/ijc.148.

National Marine Fisheries Service NMFS, 2007. Magnuson-Stevens Fishery Conservation and Management Act as Amended through January 12, 2007. Public Law 94-265. NOAA, NMSF.

Norris, J., 1997. Adaptive radiation of sablefish, *Anoplopoma fimbria*. In: Wilkins, M.E., Saunders, M.W. (Eds.), Biology and Management of Sablefish, Anoplopoma fimbria, 130. U.S. Department of Commerce, NOAA, Technical Report NMFS., pp. 99–114

North Pacific Fishery Management Council NPFMC, 2018. D2 sablefish discard allowance. Discussion paper. https://meetings.npfmc.org/Meeting/Details/142. (Accessed 18 June 2020).

North Pacific Fishery Management Council NPFMC, 2019. D8 small sablefish discards. Discussion paper. https://meetings.npfmc.org/Meeting/Details/583. (Accessed 18 June 2020).

Palacios-Agundez, I., Casado-Arzuaga, I., Madariaga, I., Onaindia, M., 2013. The relevance of local participatory scenario planning for ecosystem management policies in the Basque Country, northern Spain. Ecol. Soc. 18, 7. https://doi.org/10.5751/ES-05619-180307.

Peterson, M.J., Carothers, C., 2013. Whale interactions with Alaskan sablefish and Pacific halibut fisheries: surveying fishermen perception, changing fishing practices and mitigation. Mar. Pol. 42, 315–324. https://doi.org/10.1016/j.marpol.2013.04.001.

Peterson, M.J., Hanselman, D., 2017. Sablefish mortality associated with whale depredation in Alaska. ICES J. Mar. Sci. 74, 1382–1394. https://doi.org/10.1093/icesjms/fsw239.

Puccia, C.J., Levins, R., 1985. Qualitative Modeling of Complex Systems: an Introduction to Loop Analysis and Time Averaging. Harvard University Press, Cambridge, MA.

Raymond, B., McInnes, J., Dambacher, J.M., Way, S., Bergstrom, D.M., 2011. Qualitative modelling of invasive species eradication on subantarctic Macquarie Island. J. Appl. Ecol. 48, 181–191. https://doi.org/10.1111/j.1365-2664.2010.01916.x.

Raymond-Yakoubian, J., Raymond-Yakoubian, B., Moncrieff, C., 2017. The incorporation of traditional knowledge into Alaska federal fisheries management. Mar. Pol. 78, 132–142. https://doi.org/10.1016/j.marpol.2016.12.024.

Reum, J.C., McDonald, P.S., Ferriss, B.E., Farrell, D.M., Harvey, C.J., Levin, P.S., 2015. Qualitative network models in support of ecosystem approaches to bivalve aquaculture. ICES J. Mar. Sci. 72, 2278–2288. https://doi.org/10.1093/icesjms/fsv119.

Richardson, A.J., 2008. In hot water: zooplankton and climate change. ICES J. Mar. Sci. 65, 279–295. https://doi.org/10.1093/icesjms/fsn028.

Rosellon-Druker, J., Szymkowiak, M., Cunningham, C.J., Kasperski, S., Kruse, G.H., Moss, J.H., Yasumiishi, E.M., 2019. Development of social-ecological conceptual models as the basis for an integrated ecosystem assessment framework in Southeast Alaska. Ecol. Soc. 24, 30. https://doi.org/10.5751/ES-11074-240330.

Royer, T.C., Grosch, C.E., 2006. Ocean warming and freshening in the northern Gulf of Alaska. Geophys. Res. Lett. 33, 1–6. https://doi.org/10.1029/2006GL026767.

Rutecki, T.L., Varosi, E.R., 1997. Distribution, age, and growth of juvenile sablefish, *Anoplopoma fimbria*, in Southeast Alaska. In: Wilkins, M.E., Saunders, M.W. (Eds.), Biology and Management of Sablefish, Anoplopoma fimbria, 130. U.S. Department of Commerce, NOAA, Technical Report NMFS, pp. 45–54.

Salter, J., Robinson, J., Wiek, A., 2010. Participatory methods of integrated assessment—a review. Wiley Interdiscip. Rev. Clim. Change. 1, 697–717. https://doi.org/10.1002/wcc.73.

Sasaki, T., 1985. Studies on the Sablefish Resources of the North Pacific Ocean, 22. Far seas fisheries research laboratory, Bulletin. Shimizu, Japan.

Saunders, M.W., Leaman, B.M., McFarlane, G.A., 1997. Influence of ontogeny and fishing mortality on the interpretation of sablefish, *Anoplopoma fimbria*, life history. In: Wilkins, M.E., Saunders, M.W. (Eds.), Biology and Management of Sablefish, Anoplopoma fimbria, 130. U.S. Department of Commerce, NOAA, Technical Report NMFS., pp. 81–92

Shaul, L.D., Geiger, H.J., 2016. Effects of climate and competition for offshore prey on growth, survival, and reproductive potential of Coho salmon in Southeast Alaska. North Pac. Anadromous Fish. Comm. Bull. 6, 329–347. https://doi.org/10.23849/npafcb6/329.347.

Shenker, J.M., Olla, B.L., 1986. Laboratory feeding and growth of juvenile sablefish, *Anoplopoma fimbria*. Can. J. Fish. Aquat. Sci. 43, 930–937. https://doi.org/10.1139/f86-115.

Shotwell, S.K., Hanselman, D.H., Belkin, I.M., 2014. Toward biophysical synergy: investigating advection along the polar front to identify factors influencing Alaska sablefish recruitment. Deep Sea Res. Part II Top. Stud. Oceanogr. 107, 40–53. https://doi.org/10.1016/j.dsr2.2012.08.024.

Sigler, M.F., Rutecki, T.L., Courtney, D.L., Karinen, J.F., Yang, M.S., 2001. Young of the year sablefish abundance, growth, and diet in the Gulf of Alaska. Alaska Fish. Res. Bull. 8, 57–70.

Sigler, M.F., Lunsford, C.R., 2016. Survey protocol for the Alaska sablefish longline survey. https://www.fisheries.noaa.gov/resource/document/survey-protocol-alaska-sablefish-longline-survey. (Accessed 15 April 2020).

Sill, L.A., Koster, D., 2017. The Harvest and Use of Wild Resources in Sitka, 423. 2013. Alaska Department of Fish and Game, Division of Subsistence, Alaska, p. 178. Technical Paper.

Simonsen, K.A., Ressler, P.H., Rooper, C.N., Zador, S.G., 2016. Spatio-temporal distribution of Euphausiids: an important component to understanding ecosystem processes in the Gulf of Alaska and eastern Bering Sea. ICES J. Mar. Sci. 73, 2020–2036. https://doi.org/10.1093/icesjms/fsv272.

Sitka Economic Development Association SEDA, 2019. Sitka Economic Profile, 2019. McDowell Group, Anchorage, AK.

Sogard, S.M., Berkeley, S.A., 2017. Patterns of movement, growth, and survival of adult sablefish (*Anoplopoma fimbria*) at contrasting depths in slope waters off Oregon. Fish. Bull. 115, 233–252. https://doi.org/10.7755/FB.115.2.10.

Sogard, S.M., Olla, B.L., 1998. Behavior of juvenile sablefish, *Anoplopoma fimbria* (Pallas), in a thermal gradient: balancing food and temperature requirements. J. Exp. Mar. Biol. Ecol. 222, 43–58. https://doi.org/10.1016/S0022-0981(97)00137-8.

Sogard, S.M., Olla, B.L., 2001. Growth and behavioral responses to elevated temperatures by juvenile sablefish *Anoplopoma fimbria* and the interactive role of food availability. Mar. Ecol. Prog. Ser. 217, 121–134. https://doi.org/10.3354/meps217121.

Spies, R.B., 2007. Long-term Ecological Change in the Northern Gulf of Alaska. Elsevier, Oxford, UK.

Stabeno, P.J., Bond, N.A., Hermann, A.J., Kachel, N.B., Mordy, C.W., Overland, J.E., 2004. Meteorology and oceanography of the northern Gulf of Alaska. Continent. Shelf Res. 24, 859–897. https://doi.org/10.1016/j.csr.2004.02.007.

Stoner, A.W., Sturm, E.A., 2004. Temperature and hunger mediate sablefish (*Anoplopoma fimbria*) feeding motivation: implications for stock assessment. Can. J. Fish. Aquat. Sci. 61, 238–246. https://doi.org/10.1139/f03-170.

Strom, S.L., Fredrickson, K.A., Bright, K.J., 2016. Spring phytoplankton in the eastern coastal Gulf of Alaska: photosynthesis and production during high and low bloom years. Deep Sea Res. Part II Top. Stud. Oceanogr. 132, 107–121. https://doi.org/10.1016/j.dsr2.2015.05.003.

Sturdevant, M.V., Sigler, M.F., Orsi, J.A., 2009. Sablefish predation on juvenile Pacific salmon in the coastal marine waters of Southeast Alaska in 1999. Trans. Am. Fish. Soc. 138, 675–691. https://doi.org/10.1577/T08-157.1.

Surry, A., King, J.R., 2015. A New Method for Calculating ALPI: the Aleutian Low Pressure Index. Fisheries and Oceans Canada, Science Branch Pacific Biological Region, 3135. Canadian Technical Report of Fisheries and Aquatic Sciences, p. 31.

Sydeman, W.J., Piatt, J.F., Thompson, S.A., García-Reyes, M., Hatch, S.A., Arimitsu, M.L., Slater, L., Williams, J.C., Rojek, N.A., Zador, S.G., Renner, H.M., 2017. Puffins reveal contrasting relationships between forage fish and ocean climate in the North Pacific. Fish. Oceanogr. 26, 379–395. https://doi.org/10.1111/fog.12204.

Szymkowiak, M., Kasperski, S., 2020. Sustaining an Alaska coastal community: integrating place based well-being indicators and fisheries participation. Coast Manag. 9, 1–25. https://doi.org/10.1080/08920753.2021.1846165.

Tuler, S., Agyeman, J., Agyeman, J., da Silva, P.P., LoRusso, K.R., Kay, R., 2008. Assessing vulnerabilities: integrating information about driving forces that affect risks and resilience in fishing communities. Hum. Ecol. Rev. 15, 171–184.

Urawa, S., Irvine, J.R., Kim, J.K., Volk, E.C., Zavolokin, A.V., Azumaya, T., Beacham, T. D., Bugaev, A.V., Farley Jr., E.V., Guyon, J.R., 2016. Forecasting Pacific salmon production in a changing climate: a review of the 2011-2015 NPAFC Science Plan. North Pac. Anadromous Fish. Comm. Bull. 6, 501–534. https://doi.org/10.23849/npafcb6/501-534.

Wadsworth, R.M., Criddle, K., Kruse, G.H., 2014. Incorporating stakeholder input into marine research priorities for the Aleutian Islands. Ocean Coast Manag. 98, 11–19. https://doi.org/10.1016/j.ocecoaman.2014.06.003.

Wang, J., Jin, M., Musgrave, D.L., Ikeda, M., 2004. A hydrological digital elevation model for freshwater discharge into the Gulf of Alaska. J. Geophys. Res. 109, 1–15. https://doi.org/10.1029/2002JC001430.

Weingartner, T., Eisner, L., Eckert, G.L., Danielson, S., 2009. Southeast Alaska: oceanographic habitats and linkages. J. Biogeogr. 36, 387–400. https://doi.org/10.1111/j.1365-2699.2008.01994.x.

Whitney, F.A., Welch, D.W., 2002. Impact of the 1997-1998 el niño and 1999 La niña on nutrient supply in the Gulf of Alaska. Prog. Oceanogr. 54, 405–421. https://doi.org/10.1016/S0079-6611(02)00061-7.

Wild, L.A., Mueter, F., Witteveen, B., Straley, J.M., 2020. Exploring variability in the diet of depredating sperm whales in the Gulf of Alaska through stable isotope analysis. R. Soc. Open Sci. 7, 191110. https://doi.org/10.1098/rsos.191110.

Wing, B.L., 1985. Salmon Stomach Contents from the Alaska Troll Logbook Program 1977-84, 91. U.S. Department of Commerce, NOAA, Technical Memorandum NMFS-F/NWC., p. 43

Wing, B.L., 1997. Distribution of sablefish, *Anoplopoma fimbria*, larvae in the eastern Gulf of Alaska: neuston-net tows versus oblique tows. In: Wilkins, M.E., Saunders, M.W. (Eds.), Biology and Management of Sablefish, Anoplopoma fimbria, 130. U.S. Department of Commerce, NOAA, Technical Report NMFS, pp. 13–25.

Yang, Q., Cokelet, E.D., Stabeno, P.J., Li, L., Hollowed, A.B., Palsson, W.A., Bond, N.A., Barbeaux, S.J., 2019. How "The Blob" affected groundfish distributions in the Gulf of Alaska. Fish. Oceanogr. 28, 434–453. https://doi.org/10.1111/fog.12422.

Yang, M., Dodd, K., Hibpshman, R., Whitehouse, A., 2006. Food Habits of Groundfishes in the Gulf of Alaska in 1999 and 2001, 164. U.S. Department of Commerce, NOAA, Technical Memorandum NMFS-AFSC, p. 201.

Yang, M., Nelson, M.W., 2000. Food Habits of the Commercially Important Groundfishes in the Gulf of Alaska in 1990, 1993, and 1996, 112. U.S. Department of Commerce, NOAA, Technical Memorandum NMFS-AFSC, p. 187.

Yasumiishi, E.M., Shotwell, S.K., Hanselman, D.H., Orsi, J.A., Fergusson, E.A., 2015. Using salmon survey and commercial fishery data to index nearshore rearing conditions and recruitment of Alaskan sablefish. Mar. Coast. Fish. 7, 316–324. https://doi.org/10.1080/19425120.2015.1047070.

Zador, S.G., Gaichas, S.K., Kasperski, S., Ward, C.L., Blake, R.E., Ban, N.C., Himes-Cornell, A., Koehn, J.Z., 2017. Linking ecosystem processes to communities of practice through commercially fished species in the Gulf of Alaska. ICES J. Mar. Sci. 74, 2024–2033. https://doi.org/10.1093/icesjms/fsx054.

Zador, S., Yasumiishi, E., 2018. Ecosystem Considerations. Stock Assessment and Fishery Evaluation Report for the Gulf of Alaska. North Pacific Fishery Management Council, p. 213.

Zar, J.H., 1999. Biostatistical Analysis. Prentice Hall, Upper Saddle River, NJ.