Journal of Ocean and Coastal Economics

Volume 6 | Issue 1 Article 2

June 2019

Aquatic Invasive Species Change Ecosystem Services from the World's Largest Wild Sockeye Salmon Fisheries in Alaska

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Recommended Citation

Schwoerer, Tobias; Little, Joseph M.; and Adkison, Milo D. (2019) "Aquatic Invasive Species Change Ecosystem Services from the World's Largest Wild Sockeye Salmon Fisheries in Alaska," *Journal of Ocean and Coastal Economics*: Vol. 6: Iss. 1, Article 2.
DOI: https://doi.org/10.15351/2373-8456.1094

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Acknowledgments
We thank the 56 experts participating in this study and experts who contributed their knowledge to the design of the elicitation. The study was approved by the Institutional Review Board of the University of Alaska and has been performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. The Alaska Sustainable Salmon Fund funded T.S. and J.L. The Alaska SeaGrant funded T.S. The analysis was conducted by T.S., and the paper was written by T.S., J.L. and M. A.. The authors have no conflict of interest to disclose.

Abstract
This study combines a multi-method approach to structured expert judgment with market valuation to forecast fisheries damages from introduced invasive species. The method is applied to a case study of Alaska's first submersed aquatic invasive plant, *Elodea spp.*, threatening Alaska's salmon fisheries. Assuming that *Elodea spp.* remains unmanaged, estimated mean damages to commercial sockeye fisheries aggregated across Alaska amount to a potential $159 million annually with a 5% chance of exceeding $577 million annually ($2015 USD). The associated mean loss of natural capital amounts to $5.1 billion cumulatively over the next 100 years reaching $400 million after 10 years. Results from the expert elicitation indicate that there is a 35% chance of positive net benefits associated with the believed positive effects of *Elodea spp.* on sockeye salmon (*Oncorhynchus nerka*). Despite the potential for positive net gains, the magnitude of the most probable damage estimate may justify substantial investment in keeping productive freshwater systems free of aquatic invasive species. The damage estimate for Alaska is significantly larger than similar estimates in the Great Lakes where ecosystems are already impaired by multiple aquatic invasive species, underscoring the value of keeping functioning ecosystems with global market value productive. This study is the first to estimate ecosystem service loss associated with introduction of an aquatic invasive species to freshwater habitat that supports the world's most valuable wild sockeye salmon fisheries. Important policy implications related to natural resource management and efficient allocation of scarce resources are discussed

1. INTRODUCTION

Invasive species pose a threat to the health of aquatic ecosystems worldwide, and affect ecosystem services important to economic sectors such as agriculture, forestry, and fisheries. While most bioeconomic research focuses on current invasions, there has been little research examining the risk of invasion to intact ecosystems that have not yet been affected. The absence of information on potential future damages has resulted in inadequate management response as other threats appear more pressing (Perrings et al. 2002). Reasons for hampered policy progress are related to the challenges of valuing the economic benefits and costs associated with mitigating the risk of invasive species, as well as the fact that people remain unaware of the issue when not directly or immediately affected by environmental harm (Doelle 2003). In this context, aquatic invasive species are especially worrisome because their presence below the surface of a waterbody can limit early detection. Compared to terrestrial invasive plants, aquatic invasive species are more likely to be established before being detected. The lag in detection lowers the chance of successful eradication and, ultimately, the minimization of long-term costs to society (Perrings et al. 2002). To effectively address the problem, interdisciplinary solutions are needed to quantify and reduce the risk of long-term ecological and economic damages (Shogren 2000).

Despite the continued development of economic methods to value nonmarket and public goods, established methods often rely on the collection of new data. Particular challenges arise with complex valuation exercises designed to model the changes to ecosystem services as a function of human-ecological feedbacks (Finnoff et al. 2005). For example, damage assessments in fisheries often take a production function approach, explicitly modeling relationships among fish populations, human harvesting, and invasion dynamics (D. Knowler 2005; Frésard and Boncoeur 2006). Deciding which complexities to address and which to set aside is a common conundrum for researchers. Economic valuation is most straightforward when an invader has a direct effect on a harvestable resource because the link between ecology and economics can be established through reliable market data (Barbier, Acreman, and Knowler 1997). Notably, within a rapid response model in which timely action results in long-term cost savings, such a simplified valuation approach can provide critical information to managers.

In the absence of biophysical research establishing a linkage between the invader and a harvestable resource, structured expert judgment (SEJ) can be used to bridge the knowledge gap (Cooke 1991). While SEJ is an incomplete substitute for biophysical experimentation, it provides important insights into management. SEJ allows for explicit treatment of uncertainty in cost-benefit analysis and, as such, can inform managers about the economic value of physical experimentation aimed at reducing uncertainty (Peterman and Anderson 1999). SEJ has been widely applied for decades to estimate the human health impacts of air pollution (Morgan et al. 1984), climate change drivers (Morgan 2011), invasive species impacts (Rothlisberger et al. 2012), and changes in fisheries and marine ecosystems (Rothlisberger et al. 2012; Teck et al.

2010). A common challenge in SEJ is the proper aggregation of opinions across individuals with different levels of expertise. Some approaches use equal weights among experts while others use a performance-weighted average based on seed (test) questions with known answers, commonly known as Cooke's method (Cooke 1991; Grigore et al. 2016). However, in cases with high uncertainty which require a diverse group of experts, seed questions can be difficult to frame appropriately (Grigore et al. 2016).[1] The usefulness of seed questions has been questioned in instances where experts from various specialized fields were needed to quantify uncertainty in the medical field (Fischer, Lewandowski, and Janssen 2013; Soares et al. 2011). Many recent studies suggest that equal weighting is preferable to performance-based aggregation as it avoids overweighing counterintuitive results that can lead to biased expert combinations (Clemen 2008; Morgan 2014). Yet, despite this recent research into Cooke's performance weighting scheme, the question remains how to vet expert opinion.

This study avoids the use of seed questions and applies equal weighting after a multi-method approach is used to assure data quality and elimination of inconsistent experts. Cooke's performance scoring is replaced by a coherence check eliminating illogic judgments. The study contributes a vetting technique to an ongoing area of research that focuses on multi-method approaches to expert elicitation (O'Hagan et al. 2006).

The first method uses a discrete choice model (DCM) which is widely used to measure and predict human behavior but has found little application in expert elicitation (McFadden 1973). DCM uses scenarios to observe experts' choices and does not require them to translate knowledge into probabilistic judgments as such assessments can be derived indirectly from estimated individual-specific utility functions (Schwoerer, Little, and Hayward 2018). Therefore, DCM broadens the expert pool and thus allows for later elimination of incoherent experts. Recent research into the trade-offs between increasing the expert pool and the level of expertise informants in the pool bring to the elicitation shows that pool expansion combined with screening outperforms Cooke's method of post-elicitation weighting (Maestas, Buttice, and Stone 2014).

The second method is an interval judgment in the tradition of (SEJ) but without seed questions (Cooke 1991). The SEJ elicits the range of parameter values for the uncertain quantity of interest. A coherence check between the two methods eliminates illogical judgments before aggregating remaining expert judgments applying equal weights. The joint probability distribution is then integrated into the risk analysis framework. The approach avoids some of the

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[1] As discussed, bioeconomic analysis of biological invasions often center on measuring existing impacts. In this context, expert elicitation that informs this analysis relies on experts who are knowledgeable or have witnessed existing effects (Rothlisberger et al. 2012). In contrast, expert elicitation studies aimed at predicting what an invader will likely do in an intact ecosystem are more difficult because the uncertainty is higher. This requires the expert pool to be broad because knowledge needs to be attained from different fields of knowledge (Maestas, Buttice, and Stone 2014).

limitations of Cooke's approach, allowing for a more detailed vetting of expert opinion which is useful given the high level uncertainty and varied expertise.

Economic damage assessments in commercial fisheries have gained attention in recent years as marine and coastal ecosystems face increasing human impact through trade, commerce, and development (D. Knowler 2005; Frésard and Boncoeur 2006). In North America, much of the ecological and economic research on invasion impacts to fisheries has focused on the Great Lakes region (Rothlisberger et al. 2012; Wittmann et al. 2014). Bioeconomic research on aquatic invasions in the Great Lakes quantified damages to ongoing invasions yet studies that quantify the value of preventing intact ecosystem services from being invaded are lacking. The risk from invasive species will likely not be eliminated when invasive species populations have established and irreparably impaired ecosystems (Doelle 2003). The opportunity cost of the continued allocation of resources toward already impaired systems results in the forgone prevention of invasions into intact and highly productive ecosystems.

The last wild salmon runs in the world provide a case study for quantifying the potential risk of aquatic invasive species on ecosystems of global economic significance. In Alaska, Pacific salmon (*Oncorhynchus spp.*) are the economic backbone of many coastal communities (Sethi, Reimer, and Knapp 2014; Knapp, Guettabi, and Goldsmith 2013). Wholesale values of Alaska salmon amounted to $1.28 billion in 2016, only $50 million less than Pollock, Alaska's largest first wholesale value fishery (McDowell Group 2017). As human presence and activity in ecosystems in the Arctic and Subarctic increases, the threat of invasive species also increases, particularly for highly productive fisheries in this region (Short, Gross, and Wilkinson 2004). Yet, invasive species protection and prevention have received little attention (Schwörer, Federer, and Ferren 2014).

This study was motivated by the discovery of *Elodea spp.* (*Elodea*), an invasive submersed aquatic plant, in three of Alaska's salmon-producing watersheds. It was also recently found at Anchorage's Lake Hood, the world's largest floatplane base. Floatplanes serve as a pathway to spread the plant to remote freshwater sites, most of which are located in salmon habitats that have not yet been invaded (Carey et al. 2016). Lack of biophysical evidence on the ecological effects of *Elodea* for salmon production in Alaska freshwater habitat is related to an overall gap in research examining how invasive aquatic plants affect food web dynamics and fish as well as macroinvertebrate communities (Schultz and Dibble 2012). While non-native aquatic plants play similar roles compared to native aquatic plants, certain traits are problematic, such as rapid growth, the production of biochemicals that influence the growth and survival of other aquatic plant species in its vicinity, and phenotypic plasticity—the ability of genes to produce more than one trait when interacting with different environments. These are all characteristics found in *Elodea* (Schultz and Dibble 2012; Erhard, Pohnert, and Gross 2007). Information on the potential economic risk presented by the *Elodea* is critical for decision-making; yet, the lack of biophysical evidence relating *Elodea* to salmon abundance and productivity has prevented economic analysis (Carey et al. 2016). Expert elicitation related to *Elodea's* potential effects on salmon found that invasions occurring in salmon habitat are believed to possibly lead to both negative and positive outcomes for sockeye salmon (Schwoerer, Little, and Hayward 2018). These results underline the need for a bioeconomic risk analysis which weighs the various possible outcomes of an invasion.

The research objective is to inform statewide management decisions for the treatment *of Elodea* and provide a first estimate of the range of damages related to potential invasions. The first section of this paper provides background regarding commercial sockeye salmon fisheries in Alaska. Next, a bioeconomic market valuation is developed that integrates SEJ-derived growth rates for sockeye salmon (*Oncorhynchus nerka*) with a market demand model which uses published commercial fisheries data (ADFG 2018, 2016). The SEJ approach is justified due to lack of data specifying the biological relationship between *Elodea* and salmon which prevents analysis of the structural changes to the stock recruitment relationship for salmon. The model's primary purpose is to inform invasive species managers about the future costs and benefits of taking action to prevent further environmental and economic damages from the distribution of *Elodea* across Alaska.[2] The range of outcomes suggests that negative consequences outweigh potential positive net benefits to salmon fisheries over a hundred-year timeframe. The magnitude of the most probable damages indicate that substantial investment is justified to keep productive ecosystems free of aquatic invasive species in Alaska. The paper ends with a discussion of the modeling approach and provides policy implications.

2. BACKGROUND

2.1 Elodea ecology, management, and history in Alaska

There are two species of *Elodea* in Alaska that are also hybridized (Les and Tippery 2013; Thum 2015 personal communication). *Elodea canadensis* (Canadian waterweed) and *E. nuttallii* (Nuttall's waterweed) are both native to North America between California (35°N) and British Columbia (55°N), but is not native to Alaska (Cook and Urmi-König 1985). Since the ecology of these two plant species is very similar, the following analysis refers to either of these two species as *Elodea*. The plant prefers sand and small gravel substrate in cold, static or slow-moving water to 9 m depth (Riis and Biggs 2003; Rørslett, Berge, and Johansen 1986). Elodea is tolerant of a wide range of environmental conditions and has successfully invaded aquatic ecosystems worldwide (Josefsson 2011)[3]. Cyclical population dynamics have been observed for *E. canadensis* for isolated populations peaking between three and ten years after invasion and declining or even disappearing thereafter (Heikkinen et al. 2009; Mjelde et al. 2012). Sudden

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[2] Note, the aim of the model is different from common population models developed for fisheries management, where structural changes to the stock recruitment relationship would be specified (D. Knowler 2005).

[3] Elodea is established in the British Isles and many other parts of Europe (Heikkinen et al. 2009) Elodea is established in the British Isles and many other parts of Europe (Heikkinen et al. 2009)

collapses remain unexplained but have been observed throughout Europe (Simberloff and Gibbons 2004; Mjelde et al. 2012). In regulated rivers in its native range, *Elodea* has been found to encroach on spawning sites of Chinook salmon (*Oncorhynchus tshawytscha*) (Merz et al. 2008).

Common human-related pathways of introduction include the aquarium trade, boats, and floatplanes (Sinnott 2013; Strecker, Campbell, and Olden 2011). Natural dispersal includes flooding and wildlife transport (Spicer and Catling 1988; Champion, Winton, and Clayton 2014). In Alaska, *Elodea* reproduces vegetatively with stem fragments surviving desiccation and freeze (Bowmer, Jacobs, and Sainty 1995). Elodea has some of the highest fragmentation and regeneration rates among aquatic invasive plants causing rapid dispersal which presents severe challenges for mechanical removal (Redekop, Hofstra, and Hussner 2016). Possible management actions include draining and drying, herbicides, the introduction of herbaceous fish, and mechanical removal through suction dredging or hand pulling (Hussner et al. 2017). For the purpose of eradication, Fluridone and Diquat are herbicides that are most effective while mechanical methods cause populations to rapidly spread (Josefsson 2011). In Alaska, Fluridone and Diquat have eradicated *Elodea* in three waterbodies (Morton 2016). At concentrations around 6 ppb, Fluridone selectively removes *Elodea* with few non-target effects (Kamarianos et al. 1989; Schneider 2000).

In Alaska, *Elodea* was discovered in Fairbanks (Interior Alaska) in 2010, drawing attention to an already established, but until then largely ignored, population in Cordova (Figure 1, Gulf). New infestations have been found every year since 2010. Aquarium dumps are the likely vector near urban locations, while floatplanes are the most likely pathway responsible for long-distance dispersal into remote roadless locations (Hollander 2014). It came as no surprise when, in 2015, *Elodea* was detected in Lake Hood (Figure 1, Cook Inlet), the world's largest seaplane base (Hollander 2015). The discovery of *Elodea* 90 river miles downstream from an unmanaged infestation in Fairbanks was likely caused by flooding (Friedman 2015). The increasing frequency of new discoveries associated with previously unknown pathways underscores the importance of the issue for Alaska.

2.2 Commercial sockeye salmon fisheries

Alaska's commercial sockeye salmon fisheries can be regionally divided into five large watersheds (Figure 1) (USGS 2017). The regions include Bristol Bay and Kuskokwim in western Alaska; Cook Inlet in Southcentral Alaska; Kodiak which encompasses the island of Kodiak and the southern coast of the Alaska Peninsula; and the Gulf which includes the Kenai Peninsula's Gulf coast, Prince William Sound, and watersheds supporting the Copper and Bering River fishing districts.[4] These regions have varying seafood processing capacity, run sizes, harvest levels, and prices that depend on global market forces.

Since the 1990s, Alaska salmon prices have experienced downward pressure caused by the rapid and sustained growth of farm raised salmon. Yet over the past decade, prices have recovered due to marketing efforts aimed at wild and sustainably-caught Alaska salmon. Also, disease outbreaks in salmon farms elsewhere have had positive price effects on Alaska salmon (Knapp, Roheim, and Anderson 2007).[5] In 2014, wild salmon comprised about 30% of global salmon production by volume. Alaska sockeye salmon production is associated with the largest share (65%) of wild salmon sold on global markets. Of this share, 37% of wild Alaska sockeye are caught in Bristol Bay (McDowell Group 2015). With the Bristol Bay sockeye salmon fishery, it can be argued that Alaska sockeye production influences global prices (Knapp, Roheim, and Anderson 2007). Table 1 shows historical wholesale prices for the four main product categories for sockeye salmon—frozen, fresh, canned, and other.[6] Given a globally traded product, variations in price exist and are correlated across regions (Table 2).

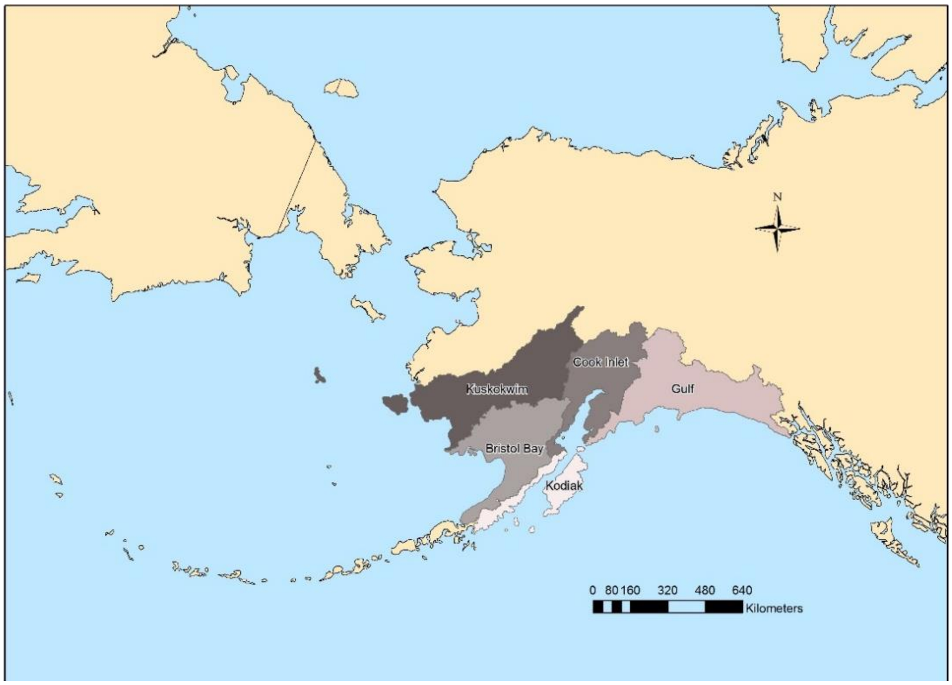

Figure 1. Watersheds supporting commercial sockeye salmon fisheries that were part of this study. This study region was selected because *Elodea* is present in the Cook Inlet and Gulf regions.

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[4] The geographic focus is aimed at currently known *Elodea* infestations, excluding Southeast Alaska's salmon fisheries from the analysis.

[5] Alaska's constitution prohibits salmon farming in state waters within three nautical miles.

[6] While there are additional subcategories, the analysis focuses on these four categories for which wholesale prices are published (ADFG 2016b).

Table 1. Fisheries characteristics by region, 2006-2015

Region	Sockeye harvest ('000 lbs)			Sockeye mean (SD) wholesale prices (real $/lbs) a)			
	mean	**min**	**max**	**canned**	**Frozen**	**fresh**	**other b)**
Bristol Bay	154,193	92,000	184,792	$ 3.66 (2.4)	$ 4.01 (2.3)	$ 2.71 (1.1)	$ 7.54 (2.5)
Cook Inlet	18,920	12,266	36,216	n/a e)	$ 4.19 (3.0)	$ 3.40 (2.5)	$ 8.24 (6.3)
Gulf	16,386	8,004	24,785	$ 5.69 (2.9)	$ 3.79 (2.7)	$ 4.20 (2.4)	$ 6.30 (2.9)
Kodiak	11,980	7,692	17,007	n/a e)	$ 3.22 (2.8)	$ 3.12 (1.3)	n/a
Chignik c)	9,338	4,125	17,889	n/a	$ 3.22 (2.8)	n/a	n/a
Kuskokwim d)	746	329	1,379	n/a	$ 1.11 (1.2)	n/a	n/a

a) Mean (standard deviation) in 2015 USD adjusted for inflation using the U.S. Consumer Price Index. b) Salmon roe products Sujiko in Bristol Bay and mainly Ikura in Gulf. For Cook Inlet: fillets with skin no ribs. c) Assumes Kodiak prices due to lack of data. The analysis treats the Chignik fishing district as a separate region because of available harvest data. However, results are combined with Kodiak. d) Prices reported for the exclusive economic zone (EEZ) were used due to lack of data. e) Region stopped production of this product or production is very inconsistent from year to year due to swings in run size. Source: Alaska Department of Fish and Game Fisheries Management Annual Reports and Commercial Operators Annual Reports.

Table 2. Correlation among regional wholesale prices for sockeye salmon, 2006-2015

	Bristol Bay	**Cook Inlet**	**Kuskokwim**	**Gulf**	**Kodiak**	**Chignik a)**
Bristol Bay	1.00					
Cook Inlet	0.89	1.00				
Kuskokwim	0.06	0.26	1.00			
Gulf	0.78	0.89	0.44	1.00		
Kodiak	0.80	0.90	0.18	0.73	1.00	
Chignik a)	0.80	0.90	0.18	0.73	1.00	1.00

a) Due to lack of data, assumes prices behave similarly to Kodiak. Note, correlations are based on just one product: frozen headed and gutted sockeye salmon. Prices published for the exclusive economic zone (EEZ) are used for the Kuskokwim due to lack of location-specific price data. Note, Spearman's rank-ordered coefficients are more appropriate for modeling correlation among distributions compared to Pearson's correlation coefficients (Palisade Corporation 2016). Source: ADFG (2016b)

There are also regional differences in seafood processors and the sockeye salmon products they produce. Table 3 shows region-specific production shares and overall processing yields. The latter is an average equal to the ratio of output weight sold over input weight bought by processors (Knapp, Roheim, and Anderson 2007).

Table 3. Production shares and processing yield by region, 2006-2015

Product	**Bristol Bay** [a)]	**Cook Inlet** [b)]	**Kuskokwim**	**Gulf** [c)]	**Kodiak** [b)]	**Chignik** [a)]
Canned	0.32			0.34		
Fresh	0.02	0.12		0.08	0.12	
Frozen	0.64	0.86	1.00	0.57	0.88	1.00
Other	0.02	0.02		0.01		
Processing yield [d)]	0.70	0.78	0.75	0.71	0.78	0.75

a) McDowell Group (2015). b) Author estimates based on observed historic prices (ADFG, 2016b; Knapp et al., 2007).c) Knapp et al. (2007). d) Weighted using product-specific yields: canned 0.59, fresh 0.97, frozen (headed & gutted) 0.75, other 0.75 (Knapp et al., 2007; author assumptions for other).

3. METHODS

The damage assessment approach consists of two components. The first describes the elicitation, evaluation, and aggregation of expert opinion on the impacts of *Elodea* on sockeye salmon productivity in Alaska. Two methods were used to accomplish this, a Discrete Choice Model (DCM) (Schwoerer, Little, and Hayward 2018) and Structured Expert Judgment (SEJ) (Cooke 1991). The second component is the bioeconomic model used to estimate changes in consumer surplus (Freeman 2003). This approach follows the methodology of previous assessments of economic impacts from invasive species in the Great Lakes (Rothlisberger et al. 2012). The section ends with an outline of the biological and economic parameter values used in estimating potential damages to sockeye salmon fisheries.

3.1 Expert judgment

In order to quantify uncertainty about *Elodea's* effects on salmon habitat and population the approach drew on broad expertise from three areas of knowledge: (1) Pacific salmonids in freshwater habitats, (2) the ecological role of submersed aquatic vegetation, and (3) freshwater aquatic invasive plants. An extensive literature review of nearly 300 sources identified an expert pool of 111 individuals with combined knowledge in all of these areas. Expert selection was based on the number of citations in peer-reviewed publications using Google Scholar. Due to the localized issue of *Elodea* in Alaska and the small number of potential experts, the expert pool was expanded to include fishery biologists, fishery scientists, fish habitat biologists, and invasive species specialists from state and federal resource management agencies. These individuals brought knowledge on localized variability and local observations to the expert pool as all of them had or continue to work with Alaska salmon, aquatic systems, or invasive species.

For a pretest, we initially followed Cooke's method which asks experts questions with known answers, also called seed or calibration questions (Cooke, 1991). Based on experts' performance in these seed questions, their judgment is later weighted giving more weight to well performing experts. Several attempts to employ Cooke's (1991) method failed because of the difficulty finding questions appropriate to all diverse areas of expertise. Therefore, instead of relying on inappropriate seed questions the DCM and SEJ were used to evaluate experts and test for coherence of opinion.

The DCM asked experts to choose from hypothetical salmon habitat scenarios that they believed would result in the long-term persistence of salmon. The scenarios varied in their description of habitat and invasion characteristics (Schwoerer, Little, and Hayward 2018).[7] Based on the DCM data, each expert's probability of choosing invaded over uninvaded habitat for persistent salmon populations was estimated (Schwoerer, Little, and Hayward 2018). In a second follow-up exercise, a SEJ was used to ask experts to state intervals for the annual average sockeye growth rates to be expected in *Elodea*-invaded habitat. Both the DCM and SEJ included an extensive background document informing experts about *Elodea*'s known ecological effects and were aimed at bridging knowledge gaps and reducing overconfidence in the interval judgment (Speirs-Bridge et al. 2010).[8] In the SEJ the annual average sockeye growth rate was referred to as "salmon production over many life cycles, manifesting itself as a long-term trend in abundance" (McElhany et al. 2000). The elicited growth rates apply to the whole population of sockeye salmon and do not specify *Elodea*'s effects on specific age structures. As such, the first question in the elicitation specified the 25th and 75th percentile of the probability distribution related to the annual average sockeye growth rate in *Elodea*-invaded habitat, the second question established the tails of the distribution, and the third question showed the median. The fourth question tested expert's comprehension of the task (Speirs-Bridge et al., 2010) and was also used to further eliminate experts from the pool (see below).

Q1. Imagine Alaska's sockeye salmon systems would be invaded with *Elodea* and you had long-term population records with estimated sockeye growth rates for a random sample of 100 of these sockeye systems. What range of typical sockeye growth rates would you expect to see, that is, rates you would see about half of the time?

Q2. What is the very lowest and very highest sockeye growth rate you would expect to see, if Alaska's sockeye salmon systems would be invaded with *Elodea*? Think about the extreme cases, in other words the tails of the distribution.

Q3. What is your best guess for the sockeye growth rate you would expect to see most often, if Alaska's sockeye salmon systems would be invaded with *Elodea*?

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[7] Environmental characteristics included location of *Elodea* within the salmon system, description of the salmon system, dissolved oxygen levels, predation, prey abundance, and other factors.

[8] Even though the existing literature describes the reductions in overconfidence relating specifically to the 4-step interval elicitation procedure, the more elaborate nature of the scenario-based approach prior to the interval judgment is believed to have similar overconfidence-reducing effects. While a test of this assumption could be subject to future research, it is outside the scope of this study.

Q4. For sockeye salmon, what sockeye growth rate would cause you to be concerned about extirpation of the population? Please specify in % and use a "-" (minus sign) for decline rates.

Based on the probability of salmon persistence in *Elodea*-invaded habitat estimated through the DCM and the stated sockeye growth rates in the SEJ a coherence check was applied. The purpose of the coherence check was to identify experts whose probability of sockeye salmon persistence in *Elodea*-invaded salmon habitat from the DCM was consistent with the annual average sockeye growth rates they believed would be possible in *Elodea*-invaded salmon habitat stated in the SEJ. A logical and consistent expert either indicated a lower than 50:50 chance of persistence in *Elodea*-invaded habitat in the DCM exercise and stated a negative median growth rate in the SEJ or a higher than 50:50 chance of persistence in the DCM and a positive median growth rate in the SEJ. Inconsistent experts (persistence/negative or extirpation/positive) were excluded from further analysis.

Assuming a standard normal distribution, individual expert's interval judgments from Q1 to Q3 were combined applying equal weights to each expert (Cooke 1991). Figure 2 presents the expert vetting and aggregation process in more detail.

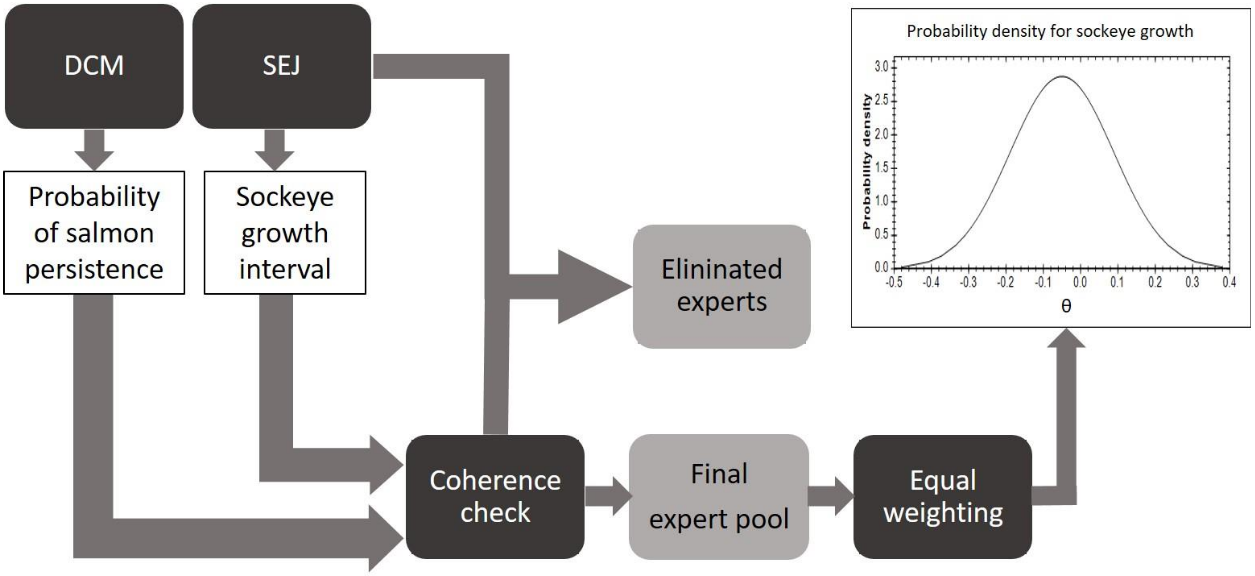

Figure 2. Expert vetting process used for aggregating expert opinion on annual average sockeye growth rates in habitat invaded by *Elodea*.

3.2 Bioeconomic model

Many commercial salmon fisheries in Alaska create significant economic rent indicated by the high permit prices in for example the Bristol Bay salmon fisheries (Knapp, Guettabi, and Goldsmith 2013). Biological invasions in this context could be seen as dissipating rent, therefore, we follow a benefit approach to the economic valuation of ecosystem services impaired by a biological invasion (Freeman 2003).

If *Elodea* changes the provisioning of ecosystem services—the amount of harvestable sockeye salmon—the introduction of *Elodea* changes the benefits consumers derive from the resource. Consumer surplus provides an economic measure of ecosystem benefits and is calculated by taking the difference between the maximum amount consumers are willing to pay for the resource and what they are actually paying. For example, if the consumer only pays $6 per pound for sockeye salmon, but would be willing to pay up to $10 per pound, the difference of $4 is the benefit to that consumer, which aggregated across society is equal to consumer surplus.

The model calculated the change in consumer surplus that resulted from a change in annual harvest and a consequential change in the real price per pound ($/lbs), assuming a linear demand function (Freeman 2003). Since the SEJ-derived intervals entailed positive and negative sockeye growth rates, this approach allowed for potential positive and negative net changes in consumer surplus. These net changes imposed by quantity changes in annual harvest were equal to the change in the area under the ordinary (Marshallian) demand curve and equal to the consumer surplus in year *t* minus the consumer surplus in year *t+1*. In mathematical terms, annual damages per region were expressed as follows:

$$\begin{aligned}\Delta CS_{t+1} &= CS_t - CS_{t+1} \\ &= \frac{\gamma}{2}\left(h_t(p' - p_t) - h_{t+1}(p' - p_{t+1})\right)\end{aligned} \tag{1}$$

where γ was processing yield, h was sockeye harvest in lbs, p was the real (inflation-adjusted) per lbs wholesale price for sockeye salmon in 2015 USD received by Alaska primary processors. Prices were weighted by sockeye product ratios commonly observed in the Alaska processing sector (Table 3). The choke price at which demand ceases is equal to p. Using the own-price elasticity of demand, ε, the choke price equals $p' = h_t/\varepsilon + p_t$. Further, harvest in period $t+1$ is expressed as a function of SEJ-derived sockeye growth rates θ, thus $h_{t+1} = f(h_t,\theta)$. After substituting and rearranging, Equation 1 becomes

$$\Delta CS_{t+1} = \frac{\gamma}{2}\left[\left(h_t - f(h_t,\theta)\right)\left(\left(\frac{h_t}{\varepsilon} + p_t\right) + \frac{f(h_t,\theta)p_t}{h_t\varepsilon}\right) - p_t h_t\right]. \tag{2}$$

The functional response of harvest to an *Elodea* invasion was represented by $h_{t+1} = f(h_t,\theta)$. Consistent with common practice in fisheries modeling, catch was assumed to be proportional to stock size and fishing effort (Haddon 2011).[9] Year-by-year changes in harvest were modeled using density-dependent population dynamics in logistic form such that harvest levels at $t+1$ equaled $h_{t+1}=h_t(1+\theta(1-h_t/K))$, where K is the ecologically limited harvest. Due to the seasonal reproduction of salmon, the discrete time model with an annual time-step is well suited for modeling the growth changes in salmon (Haddon 2011).

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[9] Under this assumption the catchability of the fishing fleet does not change over time or stock size.

The logistic growth model describes the population dynamics for an entire population of salmon irrespective of age-class, making it consistent with the SEJ-derived population growth rates. Due to a number of limitations the logistic growth model is not often used to describe population dynamics in fisheries (Larkin 1977), but it does have the advantage of being useful in situations where data is limited (Beverton and Holt 1957; Haddon 2011). The logistic growth model differs from commonly used population models like the Ricker model in how it describes population change at very high population densities (Ricker 1975). In the logistic growth model, growth at very high densities declines more rapidly, an assumption supported by the encroachment effects of *Elodea* observed on spawning adult salmon (Merz et al. 2008). In addition, the limiting environmental conditions of *Elodea*'s encroachment into salmon spawning beds is captured by the harvest limitation (K) in the logistic model but is lacking in an exponential growth model.

Under exponential growth, the expert-elicited positive effects of *Elodea* for salmon would result in runaway growth, or the believed negative effects would cause short-term extirpation—both biologically unrealistic outcomes. While long-term persistence is not guaranteed under the logistic growth model, the model indicates that, despite environmental perturbation, salmon populations can persist long-term. The invasion of *Elodea* in the British Isles recently reached its ecological limit, after 65 years since introduction (NBN 2015). The NBN data showed that landscape-wide spread of an *Elodea* invasion over a much longer timeframe compared to the 20-year time horizon considered for persistent salmon populations in invaded habitat (Peterson et al. 2008). Research on salmon habitat and *Elodea* occurring in its native range suggests that the effects of *Elodea* encroaching on spawning adults has had incremental rather than catastrophic consequences (Merz et al. 2008). The effects of *Elodea* on salmon in the invasive range may manifest themselves over a longer timeframe without immediate catastrophic outcomes. Moreover, the boom and bust cycle of *Elodea* populations can lead to temporarily more or less pronounced biological effects for different life stages over time (Simberloff and Gibbons 2004). For these reasons, the logistic growth model was chosen to describe the biological relationship between *Elodea* and salmon.

The model was initialized in year zero by the pre-invasion historical sockeye harvest, h_0, and the pre-invasion historical wholesale prices per region, p_0. Potential economic damages to commercial sockeye salmon fisheries were expressed over a 100-year time horizon in the following two ways. First, the annual changes in consumer surplus estimated by Equation 2 are converted into net present value terms (NPV)

$$NPV = \sum_{t=0}^{100} \Delta CS_t \left(1+d\right)^{-t} \tag{3}$$

where d is the real social discount rate and takes into account the public's time preference related to natural capital. NPV is a measure for natural capital, from which a constant flow of ecosystem services can be calculated such that

$$NPV_{annual} = NPV \frac{d}{1-\left(1+d\right)^{-100}}. \tag{4}$$

NPV measures the value of the stock of natural capital (Equation 3) at time *t*, annualized NPV is the constant flow of ecosystem services associated with natural capital (Equation 4). Put simply, natural capital is wealth, ecosystem services are income. The regional estimates were summed to show combined statewide damages.

Several simplifying assumptions were made relating to the economic and environmental conditions of the commercial salmon fisheries and the invasion by *Elodea*. First, the analysis estimated potential damages to fisheries should the regions become invaded by *Elodea* in the first year of a 100-year time horizon and remain unmanaged. Therefore, the estimated damages were hypothetical for regions that have not yet been colonized by *Elodea*. Second, the predicted changes caused by *Elodea* only change the weight of fish landed and do not alter the consumer demand function. Third, market conditions were assumed to be in equilibrium so that there were no incentives for harvesters and processors to enter or exit the market. Similarly, participation by fishing permit holders did not change over time. Fourth, wholesale prices were assumed to proxy prices for end consumers. Analysis based on retail prices would have been more difficult, complicated by exchange rates and a number or other issues. Retail prices exhibit variations which reflect factors, such store location, parking, and the availability of other products, which can’t be attributed to salmon (Knapp et al., 2007). Lastly, from an economic perspective, the fishery was assumed to be optimally managed, meaning the ecological and economic systems were in equilibrium throughout the 100-year time horizon. This assumption ignores various management inefficiencies such as over-capitalization which remains an issue for Alaska salmon fisheries due to regulations resulting in a derby-style “race for fish” (Knapp and Murphy 2010). Alaska commercial salmon fisheries, however, are sustainably managed as certified by the Marine Stewardship Council (MSC) (MSC 2017; Clark et al. 2006).

3.3 Model simulation and parameter assumptions

The deterministic nature of the economic valuation did not require a simulation approach. However, Monte Carlo simulation was used to estimate NPV for a range of parameter inputs. Historical data was used to determine the range of salmon harvests and prices. Due to the deterministic nature of the model and contrary to common stochastic modeling approaches, the simulation held these uncertain parameters fixed over the model’s time horizon. The simulation tested up to 10,000 possible input assumptions for each uncertain parameter, generating a distribution for Equations 3 and 4. The simulation stopped when there was a 95% chance that the mean NPV was within ±3% tolerance of its true value (Palisade Corporation, 2016b).[10]

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[10] Sampling type: Latin Hypercube, random number generator: Mersenne Twister.

Uncertain parameters include the expert-elicited annual average growth rate for sockeye salmon, θ, the pre-invasion sockeye harvest in year zero, h_0, pre-invasion wholesale prices, p_0, own-price elasticity of sockeye demand, ε, and the social discount rate, d. For the annual average growth rate for sockeye salmon, θ, the equally-weighted percentiles were used to fit a normal distribution describing the joint probability density function for θ. A normal distribution is suitable for this purpose because many unknown ecological processes are likely at play in *Elodea*-invaded habitat and average out over a large sample (Hilborn and Mangel 1997). For example, long-term variation of salmon returns is also driven by Pacific climate variability and other factors (Hare, Mantua, and Francis 1999). Since the return of salmon from different populations can vary within the same year, each harvest distribution is assumed to be independent of all others (Schindler et al. 2010).

To describe the variation of historical harvest, region-specific commercial sockeye harvest records in pounds landed from 2006 to 2015 were used to fit a uniform distribution (Table 4). For the purpose of testing different model assumptions surrounding historical harvest, this non-informative distribution was found to best accommodate this purpose across regions. The lognormal distribution is commonly used in economics to describe the distribution of income, wealth, and prices and was used to specify the pre-invasion wholesale price in each region (Table 1 and Table 4) (Aitchison and Brown 1976). The correlation of prices among regions was modeled based on estimated Spearman's rank-order correlation coefficients observed between 2000 and 2015 (Table 1). To derive this correlation, the model generated rank-correlated pairs of prices for two regions at a time following a distribution-free approach to induced rank correlation (Iman and Conover, 1982; Palisade Corporation, 2016a).

Reliable market data on prices and quantities was then used to derive estimates of economic benefit. In order to measure changes in consumer surplus, the approach requires an estimate of the own-price elasticity of demand. The elasticity describes how responsive consumer demand for salmon is to changes in the price of salmon (Freeman 2003). With this information, associated changes in consumer surplus can be estimated. Unfortunately, there are no specific estimates of own-price elasticities for Alaska sockeye salmon. Estimates from elsewhere in North America serve as a proxy. A variety of sources were consulted that estimated the elasticity of demand for fresh and frozen wild sockeye salmon in the Pacific Northwest, Oregon, or Canada (DeVoretz 1982; Wang 1976; Johnston and Wood 1974; Swartz 1978). Due to farmed salmon dominating world markets, more recent demand investigations have focused on farmed instead of wild salmon demand (Asche, Bard, and Atle 2019; Andersen, Roll, and Tveteras 2008). All estimates indicated elastic demand, $|\varepsilon| > 1$, and ranged between a minimum of -12.78 and a maximum of -1.472 (DeVoretz 1982; Wang 1976). A uniform distribution was applied using maximum and minimum values related to elasticity estimates as bounds to reflect the uncertainty in these historical estimates (Table 4). There are several arguments that would support higher elasticities $|\varepsilon| > 1$; the most important of which is the availability of very close substitutes to wild sockeye salmon, such as coho, pink, or chum salmon. Wild sockeye is also considered a normal good where demand increases with rising income and vice versa. To the contrary, brand loyalty to a wild and sustainably harvested product is an argument for more inelastic demand if current marketing efforts and consumer awareness continue (McDowell Group 2015).

Since our analysis is focused on changes to consumer welfare and the benefits to society from public investments in cleanup that are more or less uncertain for current and future generations, a triangular distribution of discount rates was used to account for such uncertainty. Much uncertainty does not surround the cost of capital due to Alaska's Aa2 credit rating, but rather relates to whether successful statewide eradication of elodea can be achieved. Therefore, the distribution of the marginal opportunity cost of capital chosen for the analysis included the risk free rate as well as a rate much higher than the risk free rate, comparable to the 6% used by Rothlisberger et al. (2012) for their analysis of economic damages caused by the invasion of *Dreissena* mussles in the Great Lakes. Also, the real 30-year social discount rate recommended by OMB ranges between 1% and 6% (OMB 2016). The triangular distribution with a most likely rate of 3% is consistent with best practices in financial valuation (Winston and Albright 2016). A distribution also reflects varying time preference rates observed across society. This approach is suitable for intergenerational time horizons and in cases where damages accrue in the private as well as public sectors as in the *Elodea* case suggests the use of multiple discount rates (Arrow et al. 2013; Baumgärtner et al. 2015).[11] Table 4 summarizes the model parameter assumptions used in the analysis.

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[11] The upper bound of 6% reflect real annual rates of return for Alaska's commercial salmon fisheries (Huppert, Ellis, and Noble 1996). The lower bound is consistent with recent research which suggests that impacts to ecosystem services should be discounted at much lower rates compared to impacts related to manufactured capital (Baumgärtner et al. 2015). A reduction in harvest due to an *Elodea* invasion could result in fishing vessels being on dry dock rather than fishing with private opportunity costs to capital.

Table 4. Bioeconomic model parameters

Parameter	**Units**	**Region-specific**	**Specification**	**Source**
Annual average sockeye growth rate of salmon occupying *Elodea*-invaded salmon habitat, θ	decimal	no	Normal (–0.0522, SD: 0.1388)	This study
Pre-invasion harvest, h_0	lbs	yes	Normal (see Table 1)	ADFG 2016a
Pre-invasion wholesale price[a)], p_0	2015 USD	yes	Lognormal (see Table 1)	ADFG 2016b
Own-price elasticity of demand, ε	decimal	no	Uniform (–12.78, –1.472)	Wang 1976; DeVoretz 1982
Ecological limit of sockeye harvest, K	lbs	yes	Max. hist. harvest (see Table 1)	ADFG 2016a
Processing yield, γ	decimal	yes	See Table 3	Knapp et al. 2007
Real social discount rate, d	decimal	no	Tri (0.01, 0.03, 0.06)	Rothlisberger et al. 2012, OMB 2016

a) Weighted by the region-specific sockeye product amounts for frozen, canned, fresh, and other product categories (see Table 3).

2.4 Sensitivity analysis

A sensitivity analysis was used to test the robustness of the estimate and contained two parts. First, Latin Hypercube sampling was used to randomly draw input parameter values from the distributions outlined in Table 4 (Palisade Corporation 2016). Second, the combined uncertainty of all the input parameters was then measured by assessing the variance of the loss distribution using 100,000 iterations.

4. RESULTS

4.1 Coherence check of expert judgment

A total of 56 experts participated in the DCM and 44 experts took part in the SEJ focused on the judgment of annual average sockeye growth in *Elodea*-invaded habitat. Five of the remaining experts were unreachable or had retired by the time of the follow-up interval judgment. Six of the remaining experts were unwilling to provide interval judgments and stated lack of knowledge or unfamiliarity with sockeye growth rates as reasons for not responding. One of the remaining experts did not complete the full interval judgment. Of the 44 participating experts in the interval judgment, five experts stated positive sockeye growth rates when asked about growth rates of populations that would cause them to be concerned about extirpation. Consequently, these experts were eliminated. The scatterplot in Figure 3 A shows how the 39 remaining experts varied in their opinion between the DCM and the SEJ. The vertical axis indicates each expert's probability of sockeye persistence as estimated by the DCM and the horizontal axis represents the expert's best estimate for the annual average sockeye growth rate elicited in the SEJ. A total of eight experts provided illogical estimates in the SEJ and are illustrated by triangular markers (Figure 3 A). The eight experts were eliminated before aggregating their interval judgments to form a joint and normal probability distribution (Figure 3 B). This normal probability distribution depicted a 37% chance of observing positive annual average sockeye growth rates in *Elodea*-invaded habitat (Mean: –0.0522, SD: 0.1388). This distribution of the combined expert opinion incorporated both *Elodea's* negative and positive potential growth effects on sockeye salmon.

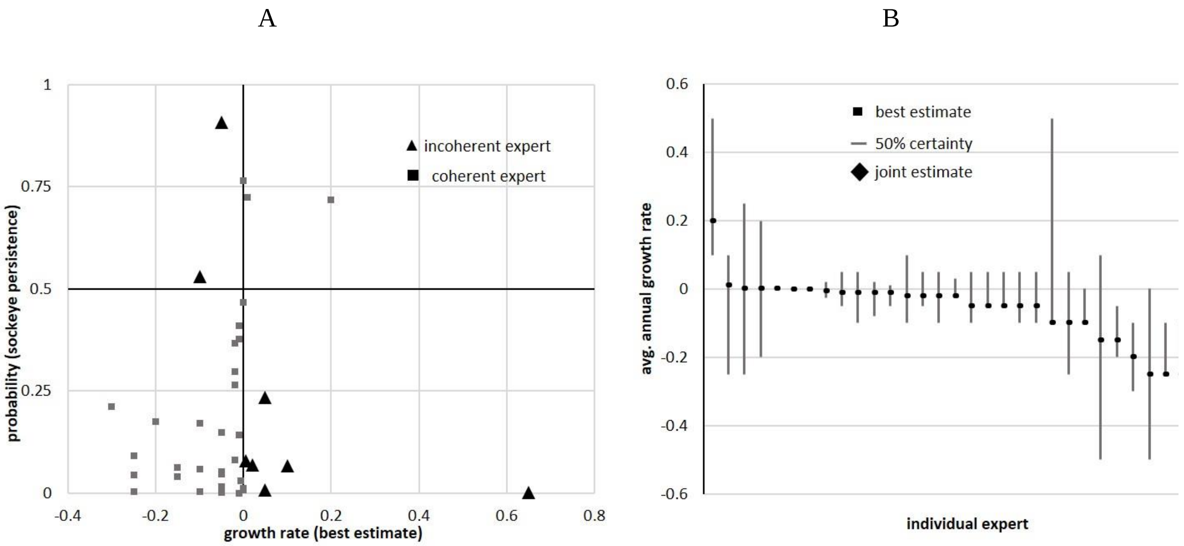

Figure 3. Exhibit A) presents the coherence check comparing expert's probability of sockeye persistence as calculated by the DCM with annual average growth rates for sockeye populations in *Elodea*-invaded salmon habitat from as stated in the SEJ. Exhibit B) shows each coherent expert's believed distribution of average annual sockeye growth rates in *Elodea*-invaded salmon habitat (25th, mean, and 75th percentile).

4.2 Potential economic loss

Figure 4 illustrates the non-discounted annual loss in consumer surplus (in 2015 US dollars) over the 100-year time period for Bristol Bay. Annual loss is not only increasing, it becomes increasingly more uncertain in future years. Consistent with expert opinion identifying some potential for positive sockeye growth and positive net benefits in *Elodea*-invaded salmon habitat, the 90% uncertainty bars extend below the zero-damage line.

Equation 3 was used to calculate the net present value of potentially lost natural capital which amounted to a mean of $5.1 billion for all five regions combined (90% CI: –$4.6 billion in net benefits, $20.0 billion in damages) (Table 6). A more detailed look at the NPV distribution and 90% uncertainty range show that despite the 35% probability of positive ecosystem services (negative damages), the upper bounds of damages were much larger than the potential benefits. The associated constant annual loss in ecosystem services for all five regions combined amount to a mean loss of $159 million annually (90% CI: –$144.4 million in net benefits, $577.3 million in damages) (Table 6). Across the five regions, this estimate ranged between a mean of $0.2 million in annual damages in the Kuskokwim to $111.9 million in annual damages in Bristol Bay (Table 6). Considering that the annual real (inflation-adjusted) wholesale value of Bristol Bay sockeye ranged between $221 and $458 million in the past ten years, the estimated annual damages from *Elodea* would be equivalent to a third to two thirds reduction in wholesale value (McDowell Group 2015).

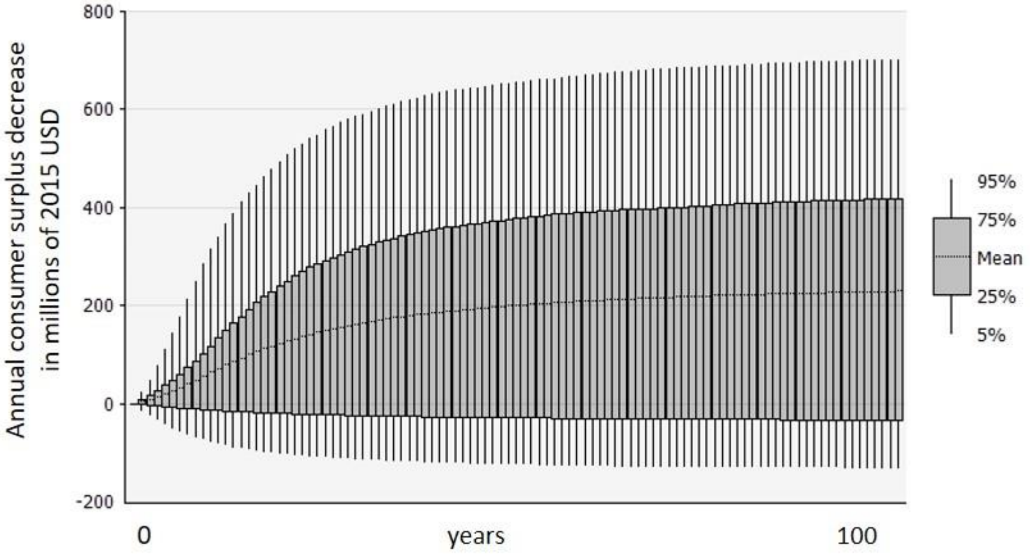

Figure 4. Annual non-discounted consumer surplus loss over the next 100 years assuming Bristol Bay's sockeye salmon habitat is invaded by *Elodea* and remains unmanaged.

Table 1. Potential damages to commercial sockeye fisheries by region ($ million)

Region	**Change in ecosystem services (NPV_{annual})**			**Change in natural capital (NPV)**		
	Mean	**5%**	**95%**	**Mean**	**5%**	**95%**
Bristol Bay	111.9	–101.0	401.6	3,558.6	–3,175.8	13,957.5
Cook Inlet	23.3	–26.1	95.0	739.4	–834.4	3,196.9
Gulf	15.0	–17.3	56.3	474.8	–547.8	1,920.7
Kodiak	9.0	–8.5	38.8	287.5	–267.7	1,283.5
Kuskokwim[d)]	0.2	–0.3	1.0	6.8	–7.8	34.3
Total	159.4	–144.4	577.3	5,067.1	–4,589.5	20,029.7

Reasons for the differences are linked to the varying regional characteristics discussed above. Bristol Bay shows the largest economic impact followed by Cook Inlet, Gulf, Kodiak, and

Kuskokwim regions (Table 6). Important to note is that across all regions, the most probable outcomes are showing loss.

5. SENSITIVITY ANALYSIS

The SEJ-derived annual average sockeye growth rates in *Elodea*-invaded salmon habitat contributed to more than half of the variance observed in the simulated NPV distribution. This result is not surprising considering the large uncertainty in this parameter. Some of the lowest growth rate assumptions increased the mean loss by over $8 billion, while some of the largest growth rates decreased the mean loss by $8 billion, resulting in a mean of $3.4 billion in net benefits. The discount rate and Bristol Bay wholesale price for frozen sockeye product contributed much less to the variance than the growth rate (Table 7). A Bristol Bay price assumption of $18.59/lbs increased losses by $4.4 billion, whereas $0.82/lbs reduced losses by $2.2 billion (Table 2.7). Sensitivity of model outcomes to assumptions surrounding the own-price elasticity of demand were insignificant and contributed less than 1% to variance in NPV, less than wholesale prices in other regions (not shown).[12] As expected, the sockeye growth rate and discount rate both were negatively correlated with damages whereas wholesale prices were positively correlated (Figure 5). The effect of positive sockeye growth rates in Elodea-invaded salmon habitat (θ) on the mean NPV was reduced by the harvest constraint, creating a convexity of the solid line in Figure 5 above the 70th input percentile. Initial harvest assumptions did not significantly contribute to variance in NPV.

Table 2. Sensitivity of annualized damage estimates to parameter assumptions with the largest influence on simulation outcomes

		Change in mean NPV (billions 2015 USD) a)	
	% Contribution to variance	**Lowest input assumption**	**Highest input assumption**
Annual average sockeye growth rate, θ	52.8%	8.8	-8.7
Discount rate, d	5.6%	5.0	-2.9
Price for frozen product in Bristol Bay, p_0 b)	6.6%	-2.2	4.4
Own-price elasticity, ε	0.22%	-0.7	0.9

a) Mean NPV equal to $5.188 billion. Changes are calculated holding all other parameters constant at their mean levels. b) Similar changes relate to other frozen product prices in the Gulf, Chignik, Cook Inlet, and Kodiak regions.

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[12] A test using a triangular distribution with a peak of -4.82 lead to mean damages within 0.1% of the shown result.an

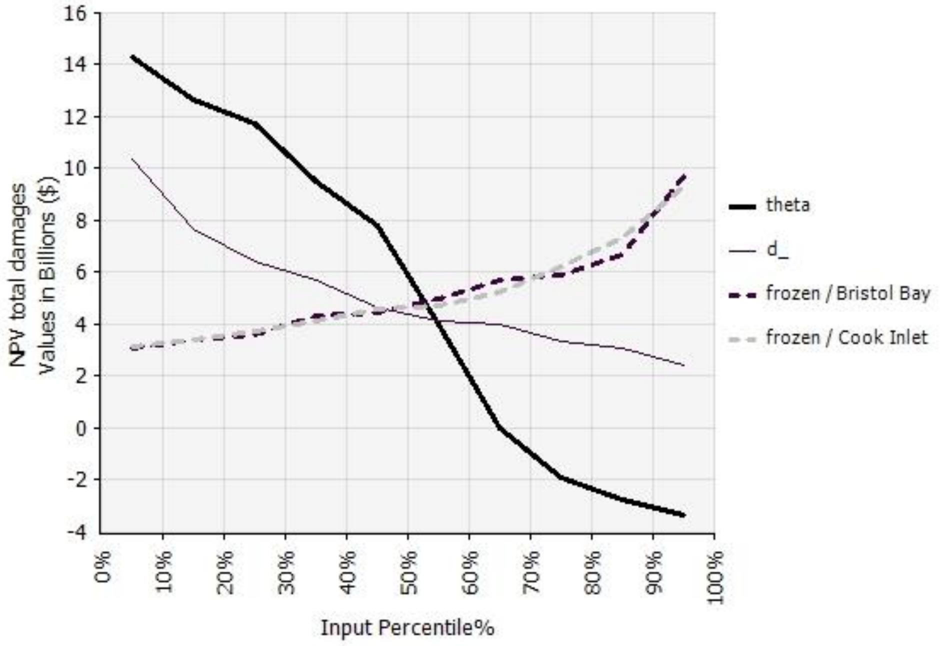

Figure 5. Change in mean NPV for all regions combined dependent on percentile changes related to the three parameters contributing the most to variance in the NPV distribution.

6. DISCUSSION

This study offers a damage forecast related to *Elodea*'s effect on sockeye salmon fisheries that stands in stark contrast to comparable bioeconomic damage assessments of aquatic invasive species elsewhere. This study followed methodology used in estimating fisheries damages of aquatic invasive species in the Great Lakes and as such offers a direct comparison of damages (Rothlisberger et al. 2012; Rosaen, Grover, and Spencer 2012). In their highest of four scenarios, Rothlisberger et al. (2012) estimated the cumulative damages related to *Dreissena* mussles invading the Great Lakes through marine shipping at $2.16 billion over the next fifty years. Weighing the damages from biological invasions in the Great Lakes to the transportation savings associated with shipping, the primary pathway for invasions, the damages outweigh the transportation cost savings by $750 million. In contrast, this study estimates the cumulative mean damages to commercial salmon fisheries in Alaska at $5.1 billion over the next 100 years.[13]

There are a number of contributions made by this examination. First, the analysis explicitly addresses uncertainty in the predicted damage distributions by applying a unique coherence check for vetting expert opinion. The approach taken is more conducive to a larger expert pool because it does not require probabilistic statements and avoids the use of seed questions, which

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[13] Rothlisberger et al. (2012) presented cumulative damages, thus, the annual damages were recalculated to provide comparison. Also note, the economic benefits of *Elodea*, in specific the non-market values related to use of *Elodea* in aquariums is insignificant. In addition, the positive effects of *Elodea* for salmon fisheries were accounted for by this study.

are often difficult or impossible to frame for experts from different fields. Thus, the multi-method approach to expert elicitation offers wider application across specialized fields. Additional options for combining expert opinion include Bayesian approaches or the use of geometric means which are limited to positive values (logarithmic opinion pool) (O'Hagan et al. 2006). While these methods vary in ease of application, there is disagreement on how well each one performs in specific situations (Hammitt and Zhang 2013; O'Hagan et al. 2006; Morgan 2014; Clemen 2008). Besides the simple application of the equal weights method for post-elicitation, the multi-method approach performed well but will require further performance testing in a broader range of applications (Morgan 2014).

Second, the study informs invasive species management not only about the potential negative economic consequences of an invader but also accounts for the invader's ability to aid in the growth of a harvestable resource. Few studies assessing the economic impacts of biological invasions account for multi-directional effects of an invasion (Gleditsch and Carlo 2011). The observed range of expert opinion on *Elodea*'s growth effects on sockeye salmon is consistent with research pointing towards various positive and negative effects of aquatic invasive plants on fish species and supports the expert elicitation approach taken (Schultz and Dibble 2012). Third, the benefit approach to valuation used publicly available data on fish harvest and wholesale prices, providing a more reliable method when compared to economic valuation techniques based on stated preference approaches (e.g., contingent valuation) (Freeman 2003). Fourth, the study is in contrast to most economic invasive species assessments that estimate damages only after substantial and often irreversible injury has occurred to native ecosystems (Rothlisberger et al. 2012; Lodge et al. 2016).

The sensitivity analysis showed that results are robust considering the assumptions. The mean damages could be underestimated for the following reasons. First, the study only included sockeye salmon, which since 1984 amounted to half of the wholesale value of Alaska salmon (ADFG 2016)[14]. Second, the analysis leaves out potential effects on other sectors such as recreational or subsistence fisheries. For example, in Bristol Bay other research found that recreational and subsistence fisheries can amount to more than twice the net economic value attributable to the commercial salmon fishery (Duffield et al. 2013). Third, the study does not quantify the effects of *Elodea* on other ecosystem services. For example, there is evidence that *Elodea* affects nutrient cycling (Ozimek, Donk, and Gulati 1993), reduces lakefront property values by up to 16% (Zhang and Boyle 2010), and has severe impacts on biodiversity (Mjelde et al. 2012). In addition, *Elodea* invasions of remote waterbodies can also affect floatplane access and lead to recreation losses. Some of these limitations also underline that the true value of ecosystem services that are affected by *Elodea* are likely higher and cannot solely be expressed in monetary units. However, damages would likely be smaller if the model would account for the varying spatial dispersal across Alaska by for example the floatplane pathway. Additionally, a

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[14] Sockeye salmon amount to 26% of Alaska's commercial salmon catch in volume.

more detailed model would also account for the probability that isolated elodea populations collapse naturally.

Fourth, potential damages to salmon harvesters as expressed by changes to the producer surplus are not accounted for in the framework. A production function approach, where habitat quality is a direct input into salmon production, could measure such welfare changes (D. J. Knowler et al. 2003). Fifth, the assumption of ordinary Marshallian demand prevents a more detailed analysis of how the underlying individual consumer preferences could change given that the invasion of *Elodea* changes the quality of fish or consumers' perceived changes to environmental quality. For example, consumers may be hesitant to buy wild Alaska salmon knowing that the species' existence is threatened by aquatic invasive species. In instances where the quality of the ecosystem service is of concern, measures of compensating or equivalent surplus would be more appropriate. Last, the estimated damages do not include the potential cost of managing *Elodea* and, thus, do not provide a full accounting of the social costs of a potential invasion.

Damage assessments are usually based on empirical evidence of economic and ecological changes after invasions while controlling for different drivers of ecosystem and human system conditions. Our early-stage assessment of potential damage lacks empirical data on changes resulting from the invasion. Obtaining expert knowledge provided a feasible solution to data limitation, while being able to explicitly quantify uncertainty in the estimates. Some simplifications were needed. The use of the logistic growth model ignores specific age-structure effects of *Elodea* on salmon and also ignores correlation between growth rates and carrying capacity. Low levels of dissolved oxygen associated with crashing *Elodea* populations are a concern for freshwater life stages (Schwoerer, Little, and Hayward 2018) and encroachment of *Elodea* in salmon spawning beds is a concern for spawning adults in other locations outside Alaska where *Elodea* occurs in its natural range (Merz et al. 2008). These density-dependent effects would likely have higher impacts on sockeye populations spawning in slow moving streams and shallow water depth that is more suitable to *Elodea* compared to lake spawners in deeper waters (Braun and Reynolds 2014; Dodds and Biggs 2002).

Detailed age-structure data would allow analysis of fisheries management actions under an invasion scenario. The application of the logistic growth model instead focused on explaining the effects of *Elodea* on an entire population of salmon irrespective of age classes and is not suitable to provide fisheries management advice (Larkin 1977). Recognizing that expert elicitation is no panacea for biophysical research that establishes the ecological relationship between the invader and the harvestable resource, expert elicitation does however, enable researchers to quantify a first damage estimate from which further research can be expanded.

Not surprisingly, the expert-derived growth rates for sockeye salmon contribute the most to variance in the damage estimate. This result suggests that investments into biophysical research on the effects of *Elodea* on salmon are warranted to improve the precision of damage estimates.

7. CONCLUSION

Even though the range of potential damages estimated are large, the mean annual damage of $159 million suggests that investment in preventing aquatic invasive species from gaining a foothold in Alaska is justified. Considering the attention and investment the invasive species threat in the Great Lakes has received in the past decade, the much larger damage estimate presented here raises the question as to whether these investments are optimally allocated. The results presented here suggest that future invasive species investments are better directed towards preventing damage to some of the most productive and intact ecosystems of national and global significance, especially as still in their pristine state are rare (Pinsky et al. 2009). With the invasive species problem still in its infancy in Alaska, society still has the opportunity to take prevention seriously

Directions for future research should be aimed at first reducing uncertainty associated with damage estimate by conducting biophysical research into *Elodea*'s growth effects on sockeye and possible other salmonids and second accounting for *Elodea*'s landscape-wide distribution pathways. The sensitivity analysis of this study clearly showed that the believed distribution of annual average growth rates for sockeye salmon in *Elodea*-infested salmon habitat is the primary driver of uncertainty in the damage estimate. Since the study does not account for the landscape-wide distribution of *Elodea* into salmon-bearing watersheds, accounting for the primary human pathways of long-distance dispersal through floatplane and boat traffic could further refine and potentially reduce damage estimates. Similarly, accounting for the natural rate of *Elodea* collapse would have the similar effects.

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