INVASIVE ELODEA THREATENS REMOTE ECOSYSTEM SERVICES IN ALASKA:

A SPATIALLY-EXPLICIT BIOECONOMIC RISK ANALYSIS

By

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Abstract

This dissertation links human and ecological systems research to analyze resource management decisions for elodea, Alaska's first submerged aquatic invasive plant. The plant likely made it to Alaska through the aquarium trade. It was first discovered in urban parts of the state but is being introduced to remote water bodies by floatplanes and other pathways. Once introduced, elodea changes freshwater systems in ways that can threaten salmon and make floatplane destinations inaccessible. The analysis integrates multiple social and ecological data to estimate the potential future economic loss associated with its introduction to salmon fisheries and floatplane pilots. For estimating the effects on commercial sockeye fisheries, multiple methods of expert elicitation are used to quantify and validate expert opinion about elodea's ecological effects on salmon. These effects are believed to most likely be negative, but can in some instances be positive. Combined with market-based economic valuation, the approach accounts for the full range of potential ecological and economic effects. For analyzing the lost trip values to floatplane pilots, the analysis uses contingent valuation to estimate recreation demand for landing spots. A spatially-explicit model consisting of seven regions simulates elodea's spread across Alaska and its erratic population dynamics. This simulation model accounts for the change in region-specific colonization rates as elodea populations are eradicated. The most probable economic loss to commercial fisheries and recreational floatplane pilots is $97 million per year, with a 5% chance that combined losses exceed $456 million annually. The analysis describes how loss varies among stakeholders and regions, with more than half of statewide loss accruing to commercial sockeye salmon fisheries in Bristol Bay. Upfront management of all existing invasions is found to be the optimal management strategy for minimizing long-term loss. Even though the range of future economic loss is large, the certainty of long-term damage favors investments to eradicate current invasions and prevent new arrivals. The study serves as a step toward risk management aimed at protecting productive ecosystems of national and global significance.

Dedication

To Suvan and Kai—may they long fish for salmon and enjoy the natural wonders for which they will be stewards.

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General Introduction

Overview

Invasive species are an increasing threat to the health of aquatic ecosystems worldwide. Biological invasions are changing the benefits humans derive from the natural environment. For sectors of the economy directly dependent on healthy and productive ecosystems such as fisheries and recreation, biological invasions can affect livelihoods (Nunes and van den Bergh, 2004; Rothlisberger et al., 2012). While most research focuses on estimating damages of existing invasions, little research has taken a forward looking approach by predicting future impacts (Jeschke et al., 2014; Lodge et al., 2016). While estimating financial damages of existing invasions can lead to more public awareness, these studies are less relevant for management because they don't take a forward looking perspective. Most importantly, they are unable to inform decision-makers about the value of prevention. Lack of damage forecasting can result in inadequate human response to protecting the most valuable ecosystems (Doelle, 2003). For example, investments to reduce damages in already impaired ecosystems likely have lower social returns compared to investments preventing the spread of invasions into pristine ecosystems (Finnoff et al., 2007).

Comprehensive bioeconomic risk analysis can inform investment decisions by evaluating the net social returns associated with management options including the option to delay or not take action (Lodge et al., 2016). Critical components of such analyses include forecasting costs and benefits over an ecologically relevant time period that captures the potential population dynamics of the invader and related changes to market and non-market values (Shogren et al., 2006). Furthermore, in cases where the invader is dispersed by humans, bioeconomic models can better predict risk if they account for landscape-wide spread (Epanchin-Niell and Hastings, 2010). Since intervention can alter the spread of the invader, linked social-ecological models account for these important feedback mechanisms and enable the evaluation of management decisions on a landscape-scale (Finnoff et al., 2010; Holmes et al., 2010). Few studies have integrated all of the above to guide management decisions (Lodge et al., 2016; Maguire, 2004). Often, the availability of local data is a barrier to such comprehensive analysis. For example, data about the pathway related to a biological invader are costly and difficult to acquire. Moreover, non-market values are very specific to local environmental and economic conditions and require sophisticated methods (Spash and Vatn, 2006). As a consequence, researchers are inclined to use methods that are

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less reliable and borrow economic values from elsewhere applying them to local conditions (Holmes et al., 2010).

The recent discovery of Alaska's first documented submerged freshwater aquatic invasive plant, *Elodea spp.* (elodea) motivated this study. The plant was found in more than twenty locations across Alaska. Concerns about elodea spreading to remote freshwater locations increased drastically when it was found in Anchorage's Lake Hood, the world's busiest floatplane base (Hollander, 2015). Since Alaska has vast freshwater resources supporting the world's largest wild salmon fisheries, the spread of elodea raises concern about impacts to local salmon fisheries (Carey et al., 2016). Also, the explosive and dense invasive plant growth creates safety hazards for pilots and can prevent pilots from accessing places pilots want to land for recreational and other purposes (CH2MHILL, 2005). Given the urgency of statewide management action, quantitative information on the risk of elodea to the state's economy is critical for decision-making. Additionally, the study is inspired by the demand for more sophisticated tools informing active risk management in Alaska. The study serves as a stepping stone towards a more proactive risk management approach for elodea and other invasive species yet to arrive in Alaska.

The following background describes elodea's ecology and management history in Alaska and includes the specific problem statement and research objectives of this dissertation. Also, a brief outline provides an outlook for consecutive chapters. This introduction ends by defining and explaining the measure of economic value used to estimate the market and non-market consequences related to elodea's believed ecological effects in Alaska.

Elodea ecology, management, and history in Alaska

Elodea is Alaska's first known submerged freshwater invasive plant and is considered a threat to the state's freshwater resources with wide ranging ecological and economic consequences (Morton et al., 2014). Elodea reduces biodiversity, compromises water quality, affects dissolved oxygen levels, and changes the structure of aquatic vegetation affecting the trophic interactions between fish and macroinvertebrates (Schultz and Dibble, 2012). The presence of elodea in salmon bearing streams and lakes can reduce the quality of spawning and rearing habitat (Groves and Chandler, 2005; Merz et al., 2008). While the threats imposed by elodea on Alaska's salmon resources seem obvious, there is little known about how far and how fast elodea can spread into local salmon streams and waterbodies and what effect it will have on salmon reproduction. The plant can also form dense mats clogging waterways and interfere with water-based recreation and transportation (Halstead et al., 2003; Johnstone et al., 1985). In Alaska, it has impeded boat navigation and recreation (Friedman, 2015) and is a concern for floatplane operation safety (CH2MHILL, 2005; Hollander, 2015). Similar invasive aquatic plants have reduced lake front property values in other U.S. states between 16% and 19% (Horsch and Lewis, 2008; Olden and Tamayo, 2014; Zhang and Boyle, 2010).

There are five species of elodea. *Elodea canadensis* (Canadian waterweed) is native to North America between Santa Monica in California (35°N) and Haida Gwaii in British Columbia (55°N). *Elodea nuttallii* (Nuttall's waterweed) roughly overlaps this range. *Elodea bifoliata* occurs in western North America and *Elodea potamogeton* and *E. callitrichoides* are native to South America (Cook and Urmi-König, 1985). The plant prefers sand and small gravel substrate with large amounts of available iron; cold, static, or slow-moving water; depth of up to nine meters; and water with low turbidity (Riis and Biggs, 2003; Rørslett et al., 1986). Since elodea is known to be a nutrient scavenger, eutrophic waters are more supportive of heavy long-term infestations (Mjelde et al., 2012; Rørslett et al., 1986). Elodea reproduction is primarily vegetative with stem fragments and vegetative buds rooting in new locations. Vegetative buds can survive desiccation, low temperatures, and being frozen in ice (Bowmer et al., 1995). Elodea has some of the highest fragmentation and regeneration rates among aquatic invasive plants causing rapid dispersal and severe challenges for mechanical removal (Redekop et al., 2016).

Figure 1 *Elodea spp.* in Alexander Lake, Alaska, June 2016.
Source: Heather Stewart, DNR

Elodea can tolerate a wide range of environmental conditions and has successfully invaded aquatic ecosystems worldwide. *Elodea canadensis* and *E. nuttallii* aggressively invaded the British Isles in the 19th and early 20th century (Simpson, 1984). Elodea is established in much of Europe with populations generally on the decline but high rates of invasion remain in northern Europe, Asia, Africa, Australia, and New Zealand (Josefsson, 2011). Cyclical population dynamics have been observed for *E. canadensis* peaking between three and ten years after invasion and declining or even disappearing thereafter (Heikkinen et al., 2009; Mjelde et al., 2012; Simpson, 1984). These sudden collapses remain unexplained but have been observed throughout Europe (Mjelde et al., 2012; Simberloff and Gibbons, 2004). Common human-related pathways of introduction include the aquarium trade, boats, and floatplanes (Johnstone et al., 1985; Sinnott, 2013; Strecker et al., 2011). Natural long-distance dispersal pathways include flooding as well as waterfowl and wildlife transport (Champion et al., 2014; Spicer and Catling, 1988).

Possible management actions include draining and drying, herbicides, the introduction of herbaceous fish, and mechanical removal through suction dredging or hand pulling (Beattie et al., 2011; Josefsson, 2011). Fluridone and Diquat are herbicides known to be the most effective management options, while mechanical methods such as cutting or suction dredging result in plant fragments population spread to new areas (Josefsson, 2011). Fluridone is a systemic

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herbicide that the plant absorbed through its chutes disrupting photosynthesis. It has successfully been used to manage elodea in Alaska and other locations in the U.S. (Madsen et al., 2002; Morton, 2016). At very low concentrations Fluridone selectively removes elodea with few non-target effects (Hamelink et al., 1986; Kamarianos et al., 1989; Schneider, 2000). Diquat is a contact herbicide that is absorbed by the plant's leaves where it interferes with respiration. It is slightly toxic to fish with no shown bioconcentration (Cochran, 1994; Davies and Seaman, 1968; Harper et al., 2007). Diquat is commonly used in combination with Fluridone as a cost-effective method of preventing the spread from partial-lake to full-lake infestations.

Figure 2 Elodea in Lake Hood, Anchorage, 2015. The orange colored aquatic weed harvester can be seen in the top right. In the past, this floating machine has been used to harvest dense aquatic vegetation to improve the safety of floatplane operations. Source: Heather Stewart, DNR

In Alaska, elodea was discovered in Chena Slough near Fairbanks in Interior Alaska in 2010. This discovery also drew attention to an already established population in Cordova which had been discovered in 1982 but largely ignored population detected in Cordova, Southcentral Alaska, in 1982. New, previously unknown infestations were found in every year since 2010, including locations in Interior Alaska and Southcentral Alaska (Figure 3). In 2011, elodea was discovered in Sand Lake, Anchorage, where introduction likely occurred through an aquarium dump. Detection surveys conducted in 2012 found elodea in six remote waterbodies in the Cordova area, in two additional urban lakes in Anchorage, and three lakes on the Kenai

Peninsula. In 2016, elodea has been discovered in Potter Marsh, Anchorage, and in 2017 in Sports Lake, Kenai. The likely pathways in these locations are believed to be human-caused through aquarium dumps, boat, and floatplane traffic. Other natural distribution mechanisms include flooding as well as waterfowl and wildlife (Sytsma and Pennington, 2015).

Realizing the continued spread across the state, stakeholders and land management agencies started to take action. In 2012 and 2013, a bill to establish a rapid response fund was introduced in the 27th and 28th Alaska but in both instances was not passed. In 2013, three years after its first discovery, elodea was manually removed in Chena Slough during a control trial using a suction dredge on 0.59 acres of the 55 acres infested at the time (Lane, 2014). In the same year, a memorandum of understanding (MOU) was created between the Alaska Department of Natural Resources (DNR), designated to be the lead agency for managing freshwater aquatic plants, Alaska Department of Fish and Game (ADFG), and Alaska Department of Environmental Conservation (DEC). The MOU was aimed at more efficient permitting and the development of a statewide plan to eradicate elodea and coordinate interagency response. As a first step, elodea and four other invasive aquatic plants were added to a list of quarantined invasive plants (State of Alaska, 2016). In Anchorage, many stakeholder meetings were held to deal with controversy over appropriate management action and lead agency responsibilities (Sinnott, 2014).

In 2014, more evidence accumulated that floatplanes are distributing elodea from urban source locations to remote waterbodies with the discovery of elodea in Alexander Lake, Matanuska-Susitna Borough. Elodea was mainly growing in the approach path to a cabin owned by a floatplane pilot residing on Sand Lake in Anchorage (Hollander, 2014). One year later, elodea was also found in Lake Hood, Anchorage, one of the world's largest seaplane bases (Figure 2). In the same year, elodea was also discovered in Totchaket Slough along the Tanana River, at least 90 river miles downriver from the largely unmanaged infestation in Chena Slough which was found in 2010 (Friedman, 2015).
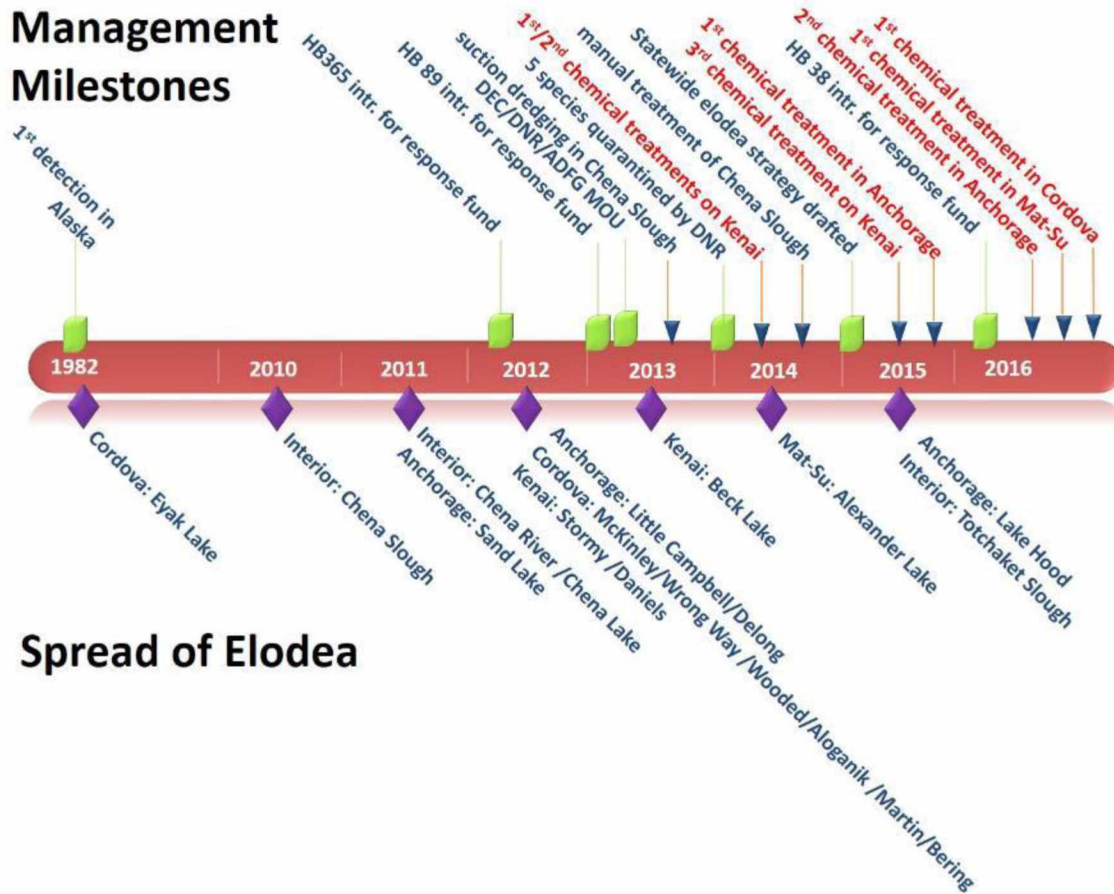
Figure 3 Timeline of discovery and management actions for elodea-infested waterbodies in Alaska. Note, elodea was also found in 2016 and 2017 in Potter Marsh and Sports Lake not stated above. Source: John Morton, FWS

Among the alarming trends of long-distance dispersal of elodea across the state, 2015 also had its success stories with the completion of chemical treatment of three lakes on the Kenai Peninsula (Morton, 2016). With budget remaining, the Kenai Peninsula Borough government decided to invest remaining funds for immediate chemical treatment of Lake Hood to reduce the risk of re-infestation of the Kenai lakes. Also, the recently created MOU allowed for quick implementation of an emergency response. But the first success was also followed by further setbacks in 2016. In just two years, the infestation in Alexander Lake grew from ten acres observed in 2014 to 500 acres in 2016 (Figure 4).[1] The initially planned partial lake treatment

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[1] The explosive growth pattern has been documented elsewhere and underlines the need for timely and cost-effective action (Jones et al., 1993; Leung et al. 2002).

based on 2014 data was estimated to cost $96,000 for herbicide but due to the explosive growth observed in 2016 required a budget of $500,000 for a full lake treatment (Stewart, 2016). 2016 also saw trial chemical treatment in one of the infested waterbodies in the Cordova area and eDNA sampling as well as large scale monitoring efforts being conducted by the National Park Service and U.S. Fish and Wildlife Service. After two failed attempts, a bill establishing a response fund was once again introduced to the 29th Alaska Legislature without becoming law.

Figure 4 Rake samples (top) from elodea beds (bottom) in Alexander Lake, June 2014 (left) and June 2016 (right). Source: Heather Stewart, DNR

Different management agencies and implementing organizations are working on elodea infestations across the state. Successful eradication on the Kenai was made possible through effective leadership and public private partnership within the Kenai Peninsula Cooperative Weed Management Area.[2] Among the partners with major involvement were the U.S. Fish and Wildlife

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[2] Cooperative Weed Management Areas are voluntary public private partnerships between resource management agencies, tribes, private land owners, conservation organizations, and other interested stakeholders. Their goals are to prevent the introduction and spread of invasive plants, implement effective and economically feasible management action, facilitate cooperation among managing and implementing stakeholders, and educate the public about invasive plants. There are five cooperative weed management areas in Alaska: Fairbanks, Anchorage, Kodiak Archipelago, Kenai Peninsula, and Juneau.

Service, Homer Soil and Water Conservation District[3] and Kenai Peninsula Borough government. In Anchorage, mainly DNR and the U.S. Fish and Wildlife Service have taken a leadership role and started chemical treatment of all infested waterbodies. Alexander Lake which is located on state land is chemically treated by DNR. The infestations in the Cordova area are managed by the U.S. Department of Agriculture's Forest Service, and the infestations in Fairbanks are lead by the Fairbanks Cooperative Weed Management Area and Fairbanks Soil and Water Conservation District.

Problem statement

Evidence-based decision making in natural resource management is frequently hampered by a lack of relevant quantitative information, particularly when timely action is necessary to avoid damage to native ecosystems and local economies. For the invasive species issue quick decisions can minimize long-term costs but concrete evidence about the invader's impacts on the ecology and economy is often limited or non-existent. In such instances, resource managers tend to address risk qualitatively or even haphazardly mixing facts with values instead of being able to follow a data-driven approach that separates evidence from the perceived values at stake (Maguire, 2004). In the presence of significant uncertainty, formally quantifying expert opinion can give structure to a more substantiated decision process and is particularly useful when a broader knowledge base is needed, for example in predicting extreme events in invasion ecology (Franklin et al., 2008; Willis et al., 2004).

Currently, resource management agencies in Alaska remain reliant on an invasiveness ranking system providing little information on immediate decision making (Carlson et al., 2008). In this system, four experts (assessors) provide numeric scores and supporting documentation for different risk categories including qualitative ratings for establishment, ecological impact, dispersal ability, and management options (Carlson et al., 2008). After four additional peer reviewers vet the initial assessment, a score between 0 and 100 is calculated. Elodea's current score of 79 is in the top 10% of all listed terrestrial and aquatic plant species in Alaska (Nawrocki et al., 2011). Similar ordinal scoring systems are used elsewhere (Hiebert and Stubbendieck, 1993; Pheloung et al., 1999; Warner et al., 2003).

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[3] Soil and Water Conservation Districts are government entities established under state law to provide technical assistance for the protection of land and water resources in their designated local areas. In Alaska there are twelve conservation districts.

The discrete score stops short of informing managers about the quality of the assessment, particularly problematic with very small assessor groups (Maestas et al., 2014). While such scoring systems inform resource managers about the relative risk for numerous species, it does not provide information on the absolute risk, in specific, on how catastrophic the invasion of a certain species can be. By ignoring the potential consequences, the ranking fails to inform decisions on whether to take or not to take action. More specifically, a single index number prevents further integration into decision analysis or damage assessments as would be achieved by a probabilistic measure and economic valuation of ecosystem services that are at risk. These components can then be integrated into a bioeconomic risk analysis informing decision makers about the return on investment for actual conservation investments that reduce the estimated risk from biological invasions (Maguire, 2004).

Research objectives and tasks

The first research objective is pragmatic and is aimed at improving information critical to decision-making. In specific, the study is for resource managers to gain immediate guidance on when and where to intervene given the potential range of future economic damages to fisheries and recreationists from elodea invasions. The second objective is focused on the contributions to the literature showing that rigorous social science techniques can improve the practice of ecological expert elicitation. Further, such techniques can also be used for collecting and analysing human-related pathway data and for quantifying non-market values that are at stake. Below are the research tasks organized in chronological order of the forthcoming chapters:

1. Account for uncertainty in elodea's potential effects on salmon persistence and productivity in Alaska by applying different methods to elicit, quantify, screen, and combine expert opinion.
2. Estimate region-specific market and non-market economic consequences of elodea invasion to multiple beneficiaries of freshwater ecosystem services that are at risk, particularly to stakeholders responsible for the pathway.
3. Model the floatplane pathway of distributing elodea from urban source locations to remote waterbodies across Alaska.
4. Provide recommendations for optimal management based on cost benefit calculations related to a set of management actions.

The above research tasks lead into the following chapters. Chapter 1 borrows techniques from marketing research to quantify expert's knowledge about elodea's potential effects on

Alaska's salmon resources. This chapter contributes a social science technique to ecological expert elicitation that offers more detailed perspectives on expert opinion than commonly used techniques. It allows for rigorous multi-method expert screening when combined with other techniques described in Chapter 2. There results from Chapter 1 are used to vet the performance of experts within a commonly used interval judgment related to salmon growth rates expected in elodea-invaded habitat. A market valuation then estimates the range of expected future loss to commercial fisheries. Chapter 3 presents a survey with floatplane pilots that is primarily geared towards pathway analysis but is further extended to estimate a recreation demand model. This approach demonstrates that web-based surveys can meet multiple objectives contributing several pieces of information to bioeconomic risk analysis. This chapter estimates the average trip value pilots would lose contingent on elodea invading their floatplane destinations. Chapter 4 integrates the previous three chapters for a spatially-explicit bioeconomic risk analysis. The net benefits associated with a set of possible management options are evaluated and provide recommendations for optimal management of elodea across seven regions of Alaska. The analysis accounts for uncertainty related to elodea's erratic population dynamics observed in its non-native range.

Definition of key economic measures

The study estimates the potential annual damages to commercial fisheries using a benefit approach to economic valuation of ecosystem services (Freeman, 2003). If elodea changes the provisioning of ecosystem services—that is, the amount of harvestable sockeye salmon—it also changes the benefits consumers derive from the resource. Similarly, if floatplanes carry invasive elodea into remote water bodies, these destinations can become inaccessible, forcing pilots to change destinations or stop flying. These changes can in turn reduce recreation benefits people receive from visiting the remote sites (Hausman et al., 1995). Consumer surplus is a measure of these benefits—it is the difference between the maximum amount people are willing to pay for consuming 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; aggregated across society, that is the consumer surplus. If elodea reduces the harvest of sockeye, prices will increase and consequently diminish the consumer surplus. Similarly, if the invasion of elodea in floatplane destinations leads to fewer visits because planes can no longer land safely, the difference between how many visits to a site

there are before and after elodea is introduced, explains the loss in consumer surplus (Freeman, 2003).

The study provides two different measures related to the economic loss in consumer surplus. Economic values are often expressed as either stocks or flows. For example, a person's wealth is a stock, while that person's income is a flow. Similarly, the economic valuation of natural resources that are impaired by biological invasions, measures the loss in natural capital as the cumulative loss related to an impaired ecosystem (stock). This study presents the cumulative loss over a 100-year time period consistent with ecologically relevant time scales. In contrast to the cumulative loss stands the constant annual loss in ecosystem services. This measure of economic value is often easier to comprehend. In the case of impaired ecosystems, it is a measure of the constant annual change in the flow of ecosystem services and as such equals the constant annual loss to society from an invasion.

Chapter 1.   Quantifying Expert Knowledge Using a Discrete Choice Model: Persistence of Salmonids in Habitat Invaded by Elodea[1]

1.1   Abstract

Resource management decisions often lack quantitative information specific to the resource issue leaving managers reliant on intuition and experience. Probabilistic expert knowledge can improve understanding compared to traditional, less rigorous approaches. This study applies a discrete choice model to elicit probabilities indirectly for quantifying believed salmonid persistence in habitat invaded by *Elodea spp.*, Alaska's first submersed aquatic invasive plant. The approach systematically organizes expert perspectives in a real-world environment to evaluate outcomes across alternative habitat scenarios. This data-driven approach estimates marginal components of risk and provides statistical aggregation techniques across the expert pool. Results show that experts believe high dissolved oxygen levels are twice as important for sustaining salmonids in elodea-invaded habitat as they are for salmonids occupying uninvaded habitat. The median probability of experts choosing invaded over uninvaded habitat for persistent salmonids is 0.041 (mean 0.21). This article contrasts the advantages and limitations of the approach, presents expansions for future research, and suggests integrating choice probabilities into structured decision-making. Advantages include self-administered expert questionnaires and the broadening of the expert pool to include experts without the skills to express knowledge in probabilistic terms.

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[1] Schwoerer.T. 2017. Quantifying Expert Knowledge Using a Discrete Choice Model: Persistence of Salmonids in Habitat Invaded by Elodea. Prepared for submission to Ecological Economics.

1.2 Introduction

Resource managers frequently face a lack of quantitative information when they make management decisions, particularly in cases where they need to act quickly to avoid damage to native ecosystems and local economies. The management of invasive species provides just one example where quick decisions can minimize long-term costs, but where concrete evidence about how these species are affecting an ecosystem or an economy is often limited or non-existent. In such instances, resource managers tend to address risk qualitatively—or even haphazardly— mixing facts with values when they do not have the data they need to separate evidence from the perceived values at stake (Maguire, 2004). Such an ad-hoc approach can lead to poor decisions and wasted resources, as well as conflicts among stakeholders with different objectives and mandates (Humair et al., 2014; Rotherham and Lambert, 2011). When there is so much uncertainty, resource managers can benefit from having the opinions of experts formally quantified, particularly when they need a broader knowledge base—for example, in predicting extreme events in invasion ecology (Franklin et al., 2008; Willis et al., 2004).

The use of expert knowledge in ecological management has increased over the past three decades, but such knowledge is often collected in ways that aren't transparent and can't be repeated (Drescher et al., 2013; Humair et al., 2014; Huntington, 2000). In the natural sciences, eliciting expert opinion still largely depends on traditional techniques such as risk scoring or ranking, or direct encoding of probabilities, with experts asked to convey their knowledge in probabilistic or quantitative terms (Suner et al., 2012; Walshe and Burgman, 2010). A common issue in eliciting expert opinion is how to aggregate opinions across people with varied expertise. Various approaches use a weighted average to adjust expert knowledge based on the outcome of calibration questions (Drew and Perera, 2011); apply equal weights; or eliminate outlier experts (Drescher et al., 2013). By contrast, Bayesian hierarchical methods use all expert information to estimate individual-level parameter distributions and evaluate uncertainty (Gelman et al., 2013).[2]

The challenges of eliciting expert judgment about potential risks from extreme ecological events can be compounded, if experts overweight small risks and underweight risks that could

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[2] Two other methods are generally used to estimate individual and group level utilities from choice data: aggregate logit and latent class. Aggregate logit describes preferences for the entire sample presenting utilities in form of sample averages, not considering heterogeneity in the sample. Latent class analysis in contrast was developed to account for more heterogeneity in the sample across groups of the sample, where each individual respondent is assumed to have the same preferences within the respondent's group.

potentially create serious consequences (Kahneman and Tversky, 1984). Several approaches are used to remedy this problem, including extreme value theory, which bounds probability distributions using deliberative methods. Other participatory techniques hold experts accountable for their judgments (Burgman et al., 2012). But these expert group settings are subject to considerable bias when individuals dominate or polarize the group, or if harmony becomes more important than assessment (Martin et al., 2012). Then, proper aggregation across experts becomes a common problem.

This study is motivated by the recent discovery of Alaska's first known invasive submersed aquatic plant, elodea (*Elodea spp.*), in productive Salmonid habitats of Alaska (Carey et al., 2016; Knapp et al., 2007). Lack of evidence about the ecological effects of elodea on salmonids in non-regulated freshwater habitat has hampered data-driven approaches to management (Carey et al., 2016; Merz et al., 2008).

1.2.1 Approach

Here a discrete choice model (DCM) for analyzing expert knowledge is applied—an approach intended to avoid many of the problems just discussed, by broadening the expert pool and formalizing elicitation design, process, and analysis. Even though DCMs are now widely used in many different fields, they have not been effectively used for eliciting expert opinion in ecological research but similar scenario-based approaches are being used (Low-Choy et al., 2012).

The study estimates probabilities for extreme ecological events indirectly, using a case study of the invasion of salmonid habitat by elodea. Specifically, the study applies a discrete choice experiment to determine whether experts believe that five species of salmonid—sockeye (*Oncorhynchus nerka*), coho (*O. kisutch*), chinook (*O. tshawytscha*), Dolly Varden (*Salvelinus mulmu*), and humpback whitefish (*Coregonus pidschian*)—can persist in freshwater habitat invaded by elodea. The examination also takes into consideration how important factors such as dissolved oxygen, native and non-native aquatic vegetative cover, and predator and prey populations are to that persistence.

To develop the probabilistic model the study draws on experts with substantive knowledge of Pacific salmonids in freshwater habitat, the ecological role of submerged aquatic vegetation, or invasive freshwater aquatic plants. Persistence is defined as salmonid populations surviving at

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least 20 years after elodea invades their habitat. The experiment found that most experts in the sample believe, with varying levels of uncertainty, that elodea will harm salmonids. The analysis quantifies the relative importance of habitat attributes to salmon fitness and the estimated probability of salmon persistence following elodea invasion of that habitat. Below, the methods and results are described, before discussing recommendations for future research and explaining why the discrete-choice method can be a valuable part of structured expert elicitation in ecological research.

1.3   Expert opinion informing elodea management

Currently, the only tool for assessing the risks posed by invasive species in Alaska is the Invasiveness Ranking System for Non-Native Plants of Alaska (Carlson et al., 2008). Under that system, four experts (assessors) provide numeric scores and supporting documentation for different risk categories, including qualitative ratings for establishment, ecological impact, dispersal ability, and management options (Carlson et al., 2008). After peer review of the expert assessments, the ranking system is used to calculate a score between 0 and 100, with higher numbers indicating a higher level of risk, compared with other listed species. That system currently scores elodea at 79, which is in the top 10% of all listed invasive terrestrial and aquatic plant species in Alaska (Nawrocki et al., 2011). Similar ordinal scoring systems are used elsewhere (Hiebert and Stubbendieck, 1993; Pheloung et al., 1999; Warner et al., 2003).

While such scoring systems inform resource managers about the *relative* risks from numerous species, they do not provide information on the *absolute* risk of a specific invasive species having catastrophic effects—so the ranking cannot help managers decide whether or not to take action. More specifically, a single index number cannot be integrated into decision analysis or damage assessments, the way a probabilistic measure can. Absolute risk requires two components, a measure of the consequences of an ecological outcome and the probability of that outcome (Mäler, 1989). Therefore, a high ranking, in contrast to an estimate of risk, does not suggest action, because the consequences of inaction cannot be determined. In addition, the single score doesn't inform managers about the quality of the assessment, which is particularly problematic with very small groups of experts.

Recent improvements in probabilistic elicitation in the natural sciences focus on complementing probabilistic expert knowledge with artificial intelligence, to detect and correct bias

(Regan et al., 2005; Sikder et al., 2006). While these improvements have enhanced elicitation of expert opinion, they have not addressed a more structured need to quantify expert opinion and minimize bias that usually may unintentionally be incorporated in the study design. In the social sciences, the validity of direct probabilistic reasoning has long been debated (Morgan and Henrion, 1990; Tversky and Kahneman, 1974). Opponents believe that knowledge about a subject area does not readily translate to an ability to convey knowledge in probabilistic terms, particularly for highly uncertain events. Experts often express their knowledge in words rather than numbers, and their attempts to assign numerical values result in heuristics and biases (Saaty, 1990; Tversky and Kahneman, 1974).[3] Such limitations can lead to more costly and lengthy elicitation procedures and extensive training. As a result, the expert pool remains limited by experts familiar with probability encoding, or experts who have the time and willingness to receive training. Small expert samples are more likely to create doubt about whether the results are reliable for interpretation and decision-making (Yamada et al., 2003).

The application of DCM for eliciting expert opinion avoids many of these issues and provides additional ways to analyse and apply expert opinion, beyond what traditional methods can achieve. This modeling approach is grounded in the theory of human behavior and offers a structured and rigorous elicitation format (Boxall and Adamowicz, 2002). Respondents choose among discrete alternatives (environmental scenarios), with a yes-or-no question format that asks them about a potential outcome (e.g., state of nature) based on a set of attributes (e.g., habitat characteristics). Attributes vary across two or more alternatives and together form a choice set. With this approach, experts focus on the ecological relationships among attributes—without having to translate their knowledge into probabilistic terms. The resulting choice data allow researchers to estimate probabilities indirectly, providing quantitative information decision-makers can use.

A key distinction between traditionally collected judgment from scoring or rating systems and DCM choice data is that judgment data do not capture the breadth of information available when experts are asked to make choices under different conditions (Louviere, 1988). DCM can

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[3] In real life, humans subconsciously weigh attributes in their decisions. As the number of rank order tasks increases, respondents apply simplification and elimination strategies that lead to bias and validity concerns (Louviere 1988). Similar issues arise with ratings data that require strong assumptions on the order of preferences to measure them (Louviere 1988). Despite improvements to the ranking exercise through, for example, the Analytic Hierarchy Process (AHP) or Maximum Difference Scaling (MaxDiff), serious theoretical issues remain—such as rank reversal and limitations on the number of rank items (Ishizaka and Labib, 2009).

incorporate site-specific environmental conditions for predicting ecological outcomes under varying assumptions. The DCM approach also bypasses the need for respondents to be formally trained, as rating systems often do. More experts may be willing to take part in DCM, with no need to spend time training and the use of self-administered questionnaires. Choice data from the DCM also expands the analytical options available to better understand expert belief. For example, Bayesian approaches for analyzing individual level expert data and aggregating across experts are readily available (Orme, 2009a).

1.3.1 Discrete choice model of expert opinion

DCMs have often been applied to understand public preferences, values, decision making, and trade-offs (Hoyos, 2010; Knowler et al., 2009; Louviere et al., 2007). Less frequently, DCMs have been used to analyze how resource managers make decisions about wildfires, which—like invasive species—can have catastrophic consequences if managed poorly (Wibbenmeyer et al., 2013). DCM assumes people are rational decision-makers—although we know they are not perfectly rational (Lichtenstein and Slovic, 1971). Still, we also know that people do try to be rational (Dixon, 2012; Simon, 1972)—and this study is less about rational decision-making than it is about reflecting consistent knowledge, among experts with significant knowledge about ecological processes.

The goal of DCM is to measure the influence of attributes on choices among alternatives, accounting for as much heterogeneity as possible between individuals and groups of experts (Ben-Akiva and Lerman, 1985; McFadden, 1973). To achieve that goal, the random utility model (RUM) defines overall utility of an alternative j to individual n as U_{nj}, comprised of observable utility V_{nj} and the unobservable utility, ε_{nj} thus $U_{nj} = V_{nj} + \varepsilon_{nj}$ (McFadden 1973). The measured component of utility in linear form for individual n is $V_j = \beta_{0j} + \beta_{1j} f(X_{1j}) + \beta_{2j} f(X_{2j}) + ... + \beta_{kj} f(X_{kj})$, where β_0 represents the average of all the unobserved sources of utility, $\beta_{1,...,k}$ is the coefficient or part-worth that estimates the contribution

of attribute $X_{1,...,k}$ to the observed sources of relative utility (Hensher et al., 2005).[4] X_1 is the first attribute in k number of attributes.

The choice rule states that each respondent evaluates all alternatives presented, U_j for $j = 1,...,J$ alternatives in the choice set, then compares $U_1, U_2,...,U_J$ and finally chooses the alternative with maximum utility $\max(U_j)$. The probability of an individual respondent choosing alternative i is equal to the probability that the utility associated with alternative i is equal to or greater than the utility of any other alternative, U_j, in the choice set, so that $p_i = p(U_i \geq U_j)$, where $i \neq j$ and $j \in j = 1,...,J$. Since utility is comprised of an observable and unobservable component, the choice rule becomes a random utility maximization rule. The probability of i being chosen is equal to the probability that the difference in unobservable sources of utility is less than or equal to the difference in observable utility for alternative i after the respondent evaluates all the other alternatives, so that $p_i = p(\varepsilon_j - \varepsilon_i) \leq (V_i - V_j)$ where $i \neq j$ and $j \in j = 1,...,J$.[5] Within the choice model, the unobserved components of utility related to an individual selecting an alternative are treated as random pieces of information, uncorrelated with all other alternatives but having the same variance across alternatives (Louviere et al., 2000). The probability that expert n chooses alternative, i, from a set of J alternatives presented in a choice set equals the multinomial logit (MNL) specification:

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[4] Note, the utility level measured is "relative" to the utility levels associated with all other alternatives shown in the choice set. Thus, there exists a base reference utility within the choice set but not across choice sets, preventing comparison of absolute utility for an alternative calculated in one choice set with another choice set (Hensher et al., 2005). The base reference utility is also called "scale of utility."

[5] One could incorporate information on the second, third, etc. most preferred alternative, recognizing that there is useful information in having respondents rate the alternatives. This analysis will focus only on one preferred choice.

$$p_{ni} = \frac{e^{\beta_n X_{ni}}}{\sum_{j=1}^{J} e^{\beta_n X_{nj}}} \; , \tag{1.1}$$

where $i \neq j$ and $j \in j = 1,...,J$ (McFadden, 1973).[6]

1.4   Methods

1.4.1   Hierarchical Bayesian estimation

A hierarchical Bayesian (HB) approach is used to estimate individual-level coefficients, by drawing from a multivariate normal distribution described by a vector of means for the part-worth utilities, α , and a covariance matrix equal to $\frac{D}{N}$, with N being given by the sample size (Orme, 2009a). Estimates of D are drawn from an inverse Wishart distribution.[7] Monte Carlo integration, applying the Metropolis Hastings algorithm and Gibbs sampling, draw conditionally from the joint posterior distribution and simultaneously estimate the parameters α, β, and D. With these estimates in hand, the study derives individual utility distributions (Gelman et al., 2013; Orme, 2009a).[8] The estimated part-worth utilities are a compromise between the aggregate distribution of beliefs across the sample and the individual's belief, and result in a conditional estimate of the respondent's parameters. The posterior distribution of individual parameter estimates allows for an assessment of uncertainty in expert belief.

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[6] In the MNL, the random component of utility is assumed to be IID, independent (uncorrelated alternatives) and identically distributed (across all j the distribution explaining   has constant variance). It assumes that the ratio of probabilities of any two alternatives cannot change if any other alternative is added or taken away from the set of alternatives in a choice set, meaning all pairs of alternatives are equally similar or different. However, if there is sufficient data quality that minimizes the amount of unobserved heterogeneity, the IIA assumption has small consequences (Hensher et al., 2005).

[7] Note, the Wishart distribution is the conjugate prior of the covariance matrix of the multivariate normal distribution and is commonly used to deal with large dimensionality.

[8] The draws from the joint posterior distribution after convergence, quantify uncertainty in the each respondent's utility estimate. The same can be shown using the historic draws for α for the entire sample.

Through Equation 1.1, the individual expert's choice probabilities for given alternatives describing invaded salmon habitat are calculated. The sum of individual choice probabilities for a given alternative are equal to the proportion of times that alternative was chosen over all other alternatives. This proportion is calculated for individual experts, groups of experts, or the entire sample, and can be interpreted as the subjective probability related to the state of nature described by the alternative.[9]

Simulation allows for a detailed look at the sensitivities of choice probabilities in relation to the attribute levels that form alternative habitat hypothesis revealing the relative importance of attribute levels, interactions between attributes, and the degree of disagreement between individuals and groups of experts.[10] Two choice simulation approaches are most commonly used, "randomized first choice" and "share of preference." The latter assumes respondents carefully evaluate each alternative, which is most appropriate for this analysis, and the former assumes less observant choice behavior (Train, 2003).[11]

1.4.2 Study design

The iterative design process started with an extensive literature review and key informant interviews to refine the problem, identify attributes and levels, establish alternatives, and finally, consider and generate the design (Hensher et al., 2005). Software for discrete choice experiments facilitated the final experimental design and data collection (Sawtooth, 2016a). Particular design criteria included maximum variation in attribute levels within choice sets (minimal overlap), equal

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[9] The economics literature refers to this proportion commonly as market share (Hensher et al., 2005; Train 2003).

[10] The scale factor can be used in simulation to adjust the choice shares to the true shares if they are known (Hensher et al., 2005). The exponent of the scale factor by default is set equal to 1 and usually is adjusted downward (B. Orme 2009a).

[11] It assumes that the utility maximizing alternative, i, is equal to $U_i = X_i(\beta + \varepsilon_A) + \varepsilon_p$, where ε_A adds attribute variability accounting for similarity relationships and ε_p adds alternative variability which dims the latter effect. The probability of choosing alternative i in choice set S is equal to the probability that the randomized utility draw is largest compared to the utility draws for all the other alternatives, or mathematically $p(i \mid S) = p(U_i \geq U_j)$ for all j in S. The simulation draws random U_i's and sums the probabilities for a specified alternative, i by individual expert, a group of experts, or for the entire sample.

representation of attribute levels (level balance), and approximately equal choice probability of alternatives (utility balance) (Johnson et al., 2003).

In this study, the "choice" task of the experts was to select, when compared against alternative habitats in the same choice set, the alternative salmon habitat they believe results in long-term persistence of salmon populations. Persistence is defined as the presence of a viable local salmonid population for at least 20 years after elodea is introduced (Peterson et al., 2008). Attribute levels cover extreme values (end-points) that are potentially outside the range with which experts are familiar. Therefore, the design is more likely to cover the actual values of changing environmental attributes, given a perturbation by invasive species.[12]

The study selected attributes and attribute levels based on the literature review, aimed at a broad overview of ecological effects that key informants said were important to the viability of salmonid populations in invaded habitat. Given the relative lack of research examining the effects of aquatic invasive species on salmonid habitat, the study used both local and non-local sources of literature.

The mean vegetation cover observed in Alaska is around 27% in lakes that haven't been invaded and reaching 100% in invaded water bodies (Lane, 2014; Rinella et al., 2008). Elodea can increase dissolved oxygen (DO) in the upper parts of the plants to 9 mg/l, but DO concentrations within 5 cm of the substrate can reach as low as 0.4 mg/l (Spicer and Catling, 1988). Additionally, frequent die-back events can lead to perturbation of the entire lake ecosystem, with very low DO concentrations during such die-backs (Barko and James, 1998; Burks et al., 2001; Diehl et al., 1998; Jeppesen et al., 1998).

Invasive aquatic plants can also indirectly affect fish by affecting food webs, with complex and uncertain outcomes (Erhard et al., 2007; Schultz and Dibble, 2012). Mean macroinvertebrate abundance counts in Alaska lakes range between $374/m^2$ and $1125/m^2$. Zooplankton biomass in Alaska sockeye nursery lakes ranges between 22 mg/m^2 and 2223 mg/m^2 (Edmundson and Mazumder, 2001). The wide range in food availability related to invaded habitat was selected to reflect the uncertain effects of this attribute for salmonids. Lastly, elodea beds provide habitat for predatory northern pike (*Esox lucius*), and have the potential to cause synergistic interactions

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[12] The linearity assumption between the end-points limits valid extrapolation to within the range of attribute levels. The benefit of a simpler and more efficient design however outweighs this limitation.

leading to accelerated impacts on native ecosystems (Casselman and Lewis, 1996; Simberloff and Holle, 1999). Invasive pike in Southcentral Alaska can reach densities of up to 36 pike per surface acre (Sepulveda et al., 2014, 2013).

Two critical design criteria are important to the invasive species case. First, alternative-specific attribute levels reflect the ecological distinction between habitat with and without elodea. Second, unambiguous a-priori preference order in the attribute levels constrains the order and sign of estimated coefficients to be consistent with ecological expectations. For example, by design, more dissolved oxygen, more prey, and less predation is better for salmon. This approach is also known as cardinal utility, a framework applied to decision-making under uncertainty; it allows the assumption of rational choice to be upheld (Table 1.1).[13]

Table 1.1 Attributes and levels

Attribute	Uninvaded habitat		Invaded habitat	
	Level 1	Level 2	Level 1	Level 2
Vegetation type and cover (%)[c]	Indigenous 0%	Indigenous 50%	Elodea 50%	Elodea 100%
Dissolved oxygen (mg/l) [a, c]	5.5	10.5	0.5	5.5
Prey abundance (mg/m^2)[a, c, d]	400	600	30	3000
Piscivorous fish (#/acre) [a, c]	5	20	20	35
Location of aquatic vegetation [b]	backwater, lake, entire habitat range			
Salmon species [b]	sockeye, coho, chinook, dolly varden, humpback whitefish			

a) Attributes that have unambiguous a-priori preference order. b) Non-alternative specific attributes.
c) Alternative-specific attributes dependent on the State of habitat variable (uninvaded or invaded). d) For sockeye mg/m^2 zoopkankton, all other macroinvertebrates /m^2.

The design minimizes ambiguity by using a background document that clearly defines each attribute. The background document further described the elicitation task and was accessible to respondents on all pages of the online elicitation questionnaire (Supplemental file). This approach maximizes interpretation, usefulness, and accuracy of the expert elicitation. The

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[13] Hierarchical Bayes estimation applies constraints for all respondents that are applied on orders of part-worths within attributes, and enforce signs for linear coefficients. They are useful if the goal of the estimation is individual level coefficients; however, this technique is less applicable to situations where researchers are interested in predicting choice shares for the population (B. Orme 2009a). An estimation process called 'simultaneous tying' is geared towards achieving both of these goals (Johnson et al., 2003). The current results presented below estimate utilities without constraints as these can reduce variance but will also increase bias.

careful selection of attributes also minimizes hypothetical bias arising from lack of context, when the hypothetical situation differs from real-world situations (von Gaudecker et al., 2012).

Identifying which alternatives should be included in the choice sets was one of the design challenges[14] the study overcame by conducting preliminary exercises, asking respondents to identify what they felt was important ("adaptive choice-based conjoint" ACBC)[15] (Johnson et al., 2003; Orme, 2009b). This customized design results in smaller required sample sizes and better estimator performance (Cunningham et al., 2010). Before the customized choice sets were presented (Figure 1.1), the questionnaire asked respondents to complete design tasks that informed individual-level prior information used for constructing an efficient design "on the fly" (Figure 1.2 and Appendix 1.A).[16,17] ACBC designs result in choice sets that are more relevant to respondents, resulting in better final choice data. ACBC is particularly useful for predictive purposes under small sample sizes and as such is applicable to expert elicitation (Low-Choy et al., 2009). The design is simulated using robotic respondents resulting in D-efficiency of 75%. Figure 1.2 shows the structure of the questionnaire.[18,19]

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[14] In the worst case, the presented choice sets are not part of the respondent's beliefs or preferences, resulting in additional unexplained utility.

[15] Note, the term "conjoint" is officially being used by Sawtooth Software but is not context-specific as the ACBC software refers to discrete choice experiments (Louviere et al., 2010).

[16] The "Build Your Own" (BYO) task asks experts to select habitat characteristics they believe most likely to support the persistence of salmonids. In a subsequent screener section, attribute combinations are clustered around the BYO and respondents are asked to select which habitat alternatives are a possibility for salmonid persistence. Further probing questions identify attribute levels that are either 'unacceptable' or a 'must have' and inform the design about respondent-specific cut-off rules (Appendix 1.A). Alternatives selected as possibilities in the screener section are carried forward into the final choice sets used for estimation.

[17] When estimating part-worth utilities collected through an adaptive choice model, the assumption of generic HB is that the three sections do not vary in scale even though in reality the BYO has larger scale than the other two. The "Otter's Method" is used to account for the difference in scale during HB estimation (Howell 2007).

[18] The number of screener tasks, unacceptable, and must haves was determined following software suggestions (Sawtooth, 2016a).

[19] Subsequent application of the choice experiment approach to expert elicitation could use hold-out tasks to improve and validate expert opinion. A hold-out task is a fixed choice set given to each respondent but that is not part of the estimated model; instead it is used to test the estimated model against choices in the hold-out task (Howell, 2007).
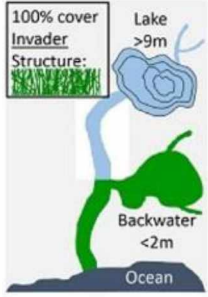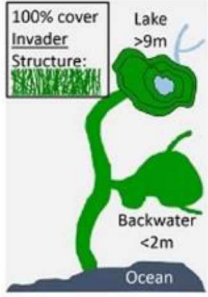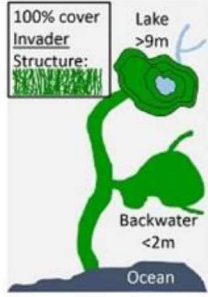
Species using habitat	Humpback Whitefish	Dolly Varden	Sockeye
Habitat map			
State of habitat	invaded by *Elodea*	invaded by *Elodea*	invaded by *Elodea*
Dissolved oxygen (mg/l at 10°C)	10.5	0.5	10.5
Prey abundance	30 indiv./m² macroinvertebrates	3000 indiv./m² macroinvertebrates	3000 mg dry/m² zooplankton
Piscivorous fish/acre	35	35	35
	○	○	○

Figure 1.1 Example of a choice set presented to an expert in the final choice tournament containing ten choice sets.

The purpose of the design tasks in ACBC is to minimize bias and heuristics by design. For example, this design minimizes any tendency of respondents to simply choose answers that may reflect preferences of the broad society—because it presents them with a number of scenarios, with different ecological characteristics, that prompt them to think carefully about their choices (Ding and Huber, 2009). The alternative habitat scenarios also minimize availability bias, because they inhibit respondents from easily retrieving judgments from memory. The design also diminishes representativeness, because it requires experts to consider the functional relationships between attributes rather than similarities. The issue of anchoring is irrelevant, because experts are not required to translate their knowledge into probabilistic terms (Tversky and Kahneman, 1974). The screener tasks act as probing questions that keep experts accountable for their choices, reducing overconfidence. Finally, we paid particular attention to the visual and tabular format of the discrete choice tasks, to minimize filtering heuristics (Hoehn et al., 2010). The questionnaire presents alternatives through hypothetical habitat maps, specifying stream depth and gradient, to further limit ambiguity (Appendix 1.A).
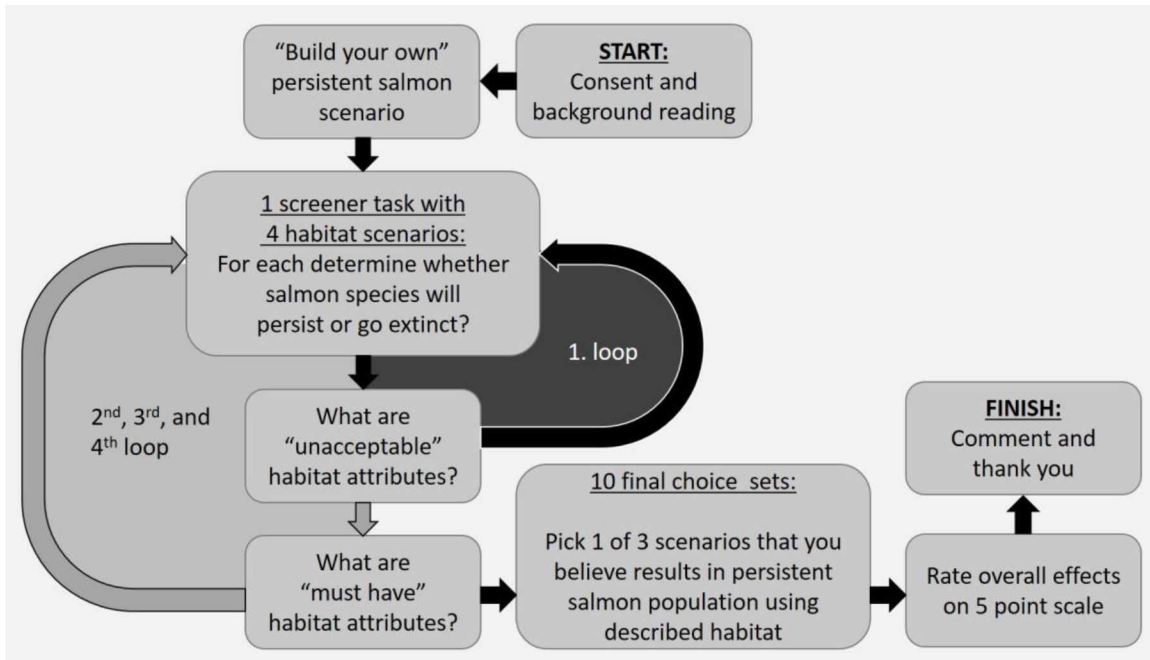
Figure 1.2 Structure of discrete choice questionnaire (using ACBC)

The end of the questionnaire also included a ratings exercise where experts were asked to rate the overall effect of elodea on salmon persistence using a five point semantic differential scale ranging from significantly negative to significantly positive effect (Figure 1.2). The intention of this ratings exercise was to evaluate potential inconsistencies in expert opinion. For example, ratings results can be used to group experts into segments enabling analysis of their choices within each segment to see whether their rating was consistent with their choices in the discrete choice exercise.

A pre-test with 20 arbitrarily selected experts received 12 responses that were used in subsequent rounds of revisions to eliminate ambiguities. As just one example, an earlier version of the elicitation instrument included a calibration, which most experts suggested eliminating because they felt the task called their credibility into question. That change reduced the time respondents had to spend on the questionnaire to about 45 minutes. Final data were collected in March and April of 2015.

1.4.3 Expert pool and response rate

The study identified the expert pool using an extensive literature review of 296 peer reviewed articles. The pool included people with substantive knowledge about Pacific salmonids

in freshwater habitat, the ecological role of submerged aquatic vegetation, and invasive freshwater aquatic plants. Expert selection followed common guidelines for expert elicitation (ACERA, 2010; Drescher et al., 2013; Martin et al., 2012) and was based on the at least 50 citations in peer-reviewed publications (identified with Google Scholar). Due to the localized issue of elodea in Alaska, the expert pool was expanded to include state and federal resource managers with job titles that included fishery biologist, fisheries scientist, fish habitat biologist, and invasive species specialist. They brought knowledge on localized variability and local observations to the expert pool of 111 contacts.[20] Recent research has found that expanding the expert pool improves expert elicitation outcomes (Maestas et al., 2014).

Table 1.2 Sample representativeness

Expertise	Initial expert pool		Respondents	
Salmon	82	74%	45	80%
Aquatic vegetation	38	34%	18	32%
Salmon and other fishes	9	8%	7	13%
Invasive species	24	21%	12	21%
Alaska-based	80	72%	46	82%
Total	111		56	

A total of 56 experts responded, for a response rate of 50%.[21] The sample is representative of the total initial expert pool (Table 1.2). Alaska residents and experts with expertise in both salmon and invasive species were more likely to respond. Concentrated local knowledge and oversampling of salmon expertise can be viewed as desirable rather than a source of selection bias (Drescher et al., 2013). Including non-local experts was aimed at minimizing the motivational bias that can occur when experts have personal stakes in the ecological issue (Drescher et al., 2013; Martin et al., 2012).

1.5   Results

Before discussing the finding in detail, it's useful to look at the big picture: what did the sample of experts tell us about the risk of extinction elodea poses to the group of salmonids

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[20] Research on identifying experts for ecological and resource management issues is an ongoing field of study with no clear guidance and available definitions (Drescher et al. 2013; Martin et al. 2012).

[21] Despite the very good response rate there is a possibility that the responses are not representative of all the available expertise. The study did not include non-respondents, and so did not explore non-response bias.

(chinook, coho, and sockeye salmon, dolly varden trout, and humpback whitefish) included in this study?

• Most respondents agreed, with varying levels of uncertainty, that elodea will harm salmonids to the point that salmonids couldn't survive for 20 years in elodea-invaded habitat. Half the expert sample believes that the probability that salmon can persist in elodea-invaded habitat is less than 0.04, whereas on average the experts believe that the probability is 0.21 (Figure 1.3).

• There was broad agreement among the respondents that the most important ecological factor in habitat invaded by elodea—twice as important as any other habitat characteristic —is the level of dissolved oxygen (Table 1.7).

• Other ecological factors—extent of vegetative cover and local predator and prey populations— had some influence but were much less important with prey abundance being about twice as important than low densities of piscivorous fish (Table 1.7).

• Dividing the respondents into groups, based on how they qualitatively rated elodea's impact on salmon, the study found some disagreement. Consistent with other research that suggests large scale shifts in ocean conditions having varying effects across salmonids, almost all (n=53) believe elodea is more harmful to chinook, humpback whitefish, and Dolly Varden than to coho and sockeye (Table 1.6).

• A sensitivity analysis illustrates how the probability of salmonid persistence can most steeply increase by increasing DO, moderately increase with increases in prey abundance, moderately decrease with increasing elodea cover and increasing density of piscivorous fishes (Figure 1.6).

1.5.1 Base case

The study estimated the MNL model for both the entire sample and for groups of experts separately, which allows for a more detailed examination of choice consistency and how belief varied among experts. Expert opinion is presented using three different measures: part-worth utilities, individual expert choice probabilities, and choice probabilities related to either the sub groups or the entire sample. Part-worth utilities for each individual expert were estimated using HB with a burn-in of 10000 iterations before 1000 random draws were saved. These were then used in the Sawtooth Choice Simulator to derive choice probabilities (Sawtooth, 2016b). Since utilities are relative measures of preference, a base case needs to be defined in order to estimate choice probabilities and allow comparison across groups (Table 1.3).

Table 1.3 Base-case habitat alternative

| Attribute | Invaded | | Uninvaded |
	Base level	Sensitivity range	Base level
Vegetation cover (proportion)	0.5	0.5, 1.0	0.5
Dissolved oxygen (mg/l)	5.5	0.5, 10.5	5.5
Prey abundance (mg/m^2) [a]	400	30, 3000	400
Piscivorous fish (#/acre)	20	20, 35	20

a) For salmonids other than sockeye, the unit is abundance of prey/m^2.

Table 1.4 presents the estimated MNL model and mean part-worth utilities for explanatory variables affecting the choice response variable—the believed persistence of salmonids. Shown by the root likelihood (RLH) of 0.717 (Table 1.4) the model outperforms a similar model of chance in predicting expert choices. To ensure that alternative specifications are not affecting part-worth utilities, the results have been rescaled to zero-centered utility differences. Thus, attributes can be compared so the average value for utilities in each attribute is zero, and the total sum of utility differences between the best and worst attribute level across attributes is equal to 100 times the number of attributes. The estimated mean part-worths change with the number of respondents and weights in the simulation. Signs show directional effects, with positive signs indicating a positive contribution to salmonid persistence, and the mean part-worth value indicates the magnitude of the effect. The coefficient of variation (CV) provides a measure of variability surrounding the mean equal to the standard deviation (SD) divided by the mean. The CV illustrates the level of agreement among experts across attributes. The higher the CV, the more expert's disagree on the attribute's effect on salmonid persistence.

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The state-of-habitat attribute is the most important, because it specifies expert belief in persistent salmonid populations in either invaded or uninvaded habitat. There is wide agreement among experts that habitat not invaded by elodea results in persistent salmon populations, and that invaded habitat threatens persistence (Table 1.4). This result is consistent with the literature and results for the attribute *vegetation cover* (Table 1.4) (Carey et al., 2016; Merz et al., 2008; Sanderson et al., 2009). Low extent of vegetation cover is particularly important in invaded habitat and less so when no invasion is present (Table 1.4). Interesting to note, expert opinion varies a lot more about the effects of vegetation cover in uninvaded versus invaded habitat as the much larger CV for uninvaded habitat shows. For DO and prey abundance, the directional effects are as expected, with higher DO and prey levels showing positive effects on persistence. Experts agree more on these positive effects in in invaded habitat than in uninvaded habitat (Table 1.4). Interesting to note, higher predation levels in elodea-invaded habitat were believed to be less influential on salmon persistence compared to lower predation levels in uninvaded habitat. This result may suggest that experts took into account the refugia effect of higher vegetation cover for elodea-invaded habitat partially offsetting higher predation. However, experts agreed less on this matter as shown by the higher CV for predation in invaded habitat (Table 1.4).

Through simulation, the probability of an expert selecting an invaded habitat believed to result in persistence was analyzed using the base-case assumptions outlined in Table 1.3. Figure 1.3 illustrates the distribution of individual choice probabilities related to invaded habitat with a median choice probability of 0.04 indicated by the dashed line and a mean of 0.21 (dotted line). In other words, half the expert sample believes that the probability that salmon can persist in elodea-invaded habitat is less than 0.04, whereas on average the experts believe that the probability is 0.21.

Table 1.4 Part-worth utility distributions for believed salmon persistence

Attribute	Level	Mean	SD	CV
State of habitat	Elodea-invaded	-129.95	40.49	31%
	Uninvaded	129.95	40.49	
Species	Sockeye	8.85	21.99	248%
	Coho	10.89	32.01	294%
	Chinook	-12.28	36.52	297%
	Dolly Varden	1.42	28.94	2038%
	Whitefish	-8.88	30.73	346%
Location of vegetation	Backwater	16.07	31.40	195%
	Entire system	-14.20	22.94	162%
	Lake	-1.87	24.97	1335%
Vegetation cover [a]	50% invaded	39.67	35.90	90%
	100% invaded	-39.67	35.90	
	0% uninvaded	0.35	38.44	10983%
	50% uninvaded	-0.35	38.44	
Dissolved oxygen (mg/l) [a]	0.5 invaded	-98.90	74.80	76%
	10.5 invaded	98.90	74.80	
	5.5 uninvaded	-52.67	53.77	102%
	10.5 uninvaded	52.67	53.77	
Prey abundance (mg/m^2) [a]	30 invaded	-35.05	29.08	83%
	3000 invaded	35.05	29.08	
	400 uninvaded	-10.59	19.01	180%
	600 uninvaded	10.59	19.01	
Piscivorous fish (#/acre) [a]	20 invaded	15.98	20.45	128%
	35 invaded	-15.98	20.45	
	5 uninvaded	48.06	46.39	97%
	20 uninvaded	-48.06	46.39	
No. of observations		560		
No. of respondents		56		
No. of parameters		26		
Pseudo R^2		0.576		
Root Likelihood (RLH)		0.717		
Average Variance		1.387		
Parameter root mean square		1.630		

a) Alternative-specific attribute levels dependent on state of habitat. b) The RLH of 0.717 is compared to the the RLH of the three alternatives shown in the final choice tournament which equals 0.33, the geometric mean of the predicted probabilities. Other indicators for goodness of fit include the average variance of part-worths and the root mean square (RMS) of all part-worths for the sample.
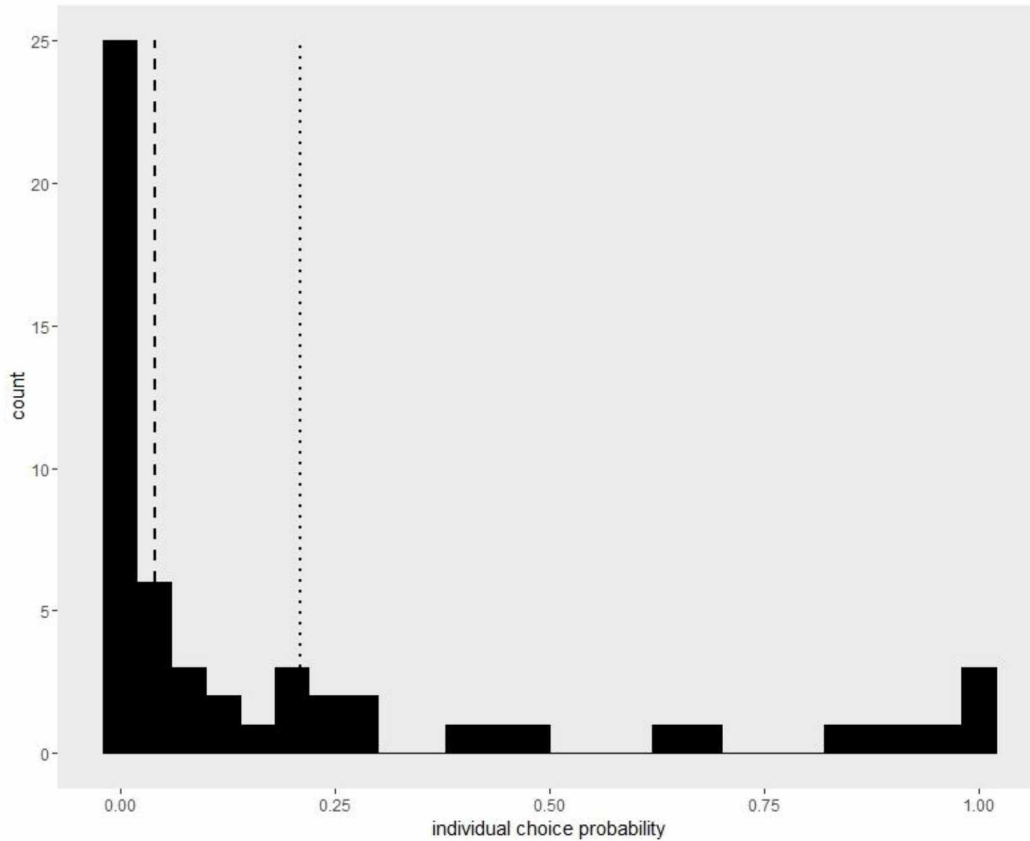
Figure 1.3 Histogram of individual choice probabilities of salmonid persistence in invaded habitat. Sample median (dashed) and mean (dotted line).

For the species attribute, the relatively low magnitudes for mean part-worths show that experts generally think that all species are equally vulnerable to elodea (Table 1.4). However, a closer look at how the estimated choice probabilities for persistence vary among experts reveals insights on experts' outlook for specific salmonid species. Figure 1.4 illustrates that experts were proportionally less likely to select alternative habitat occupied by Chinook salmon (*Oncorhynchus tshawytscha*), humpback whitefish (*Coregonus pidschian*), and Dolly Varden (*Salvelinus malma*) compared to sockeye (*Oncorhynchus nerka*) and particularly coho (*Oncorhynchus kisutch*).
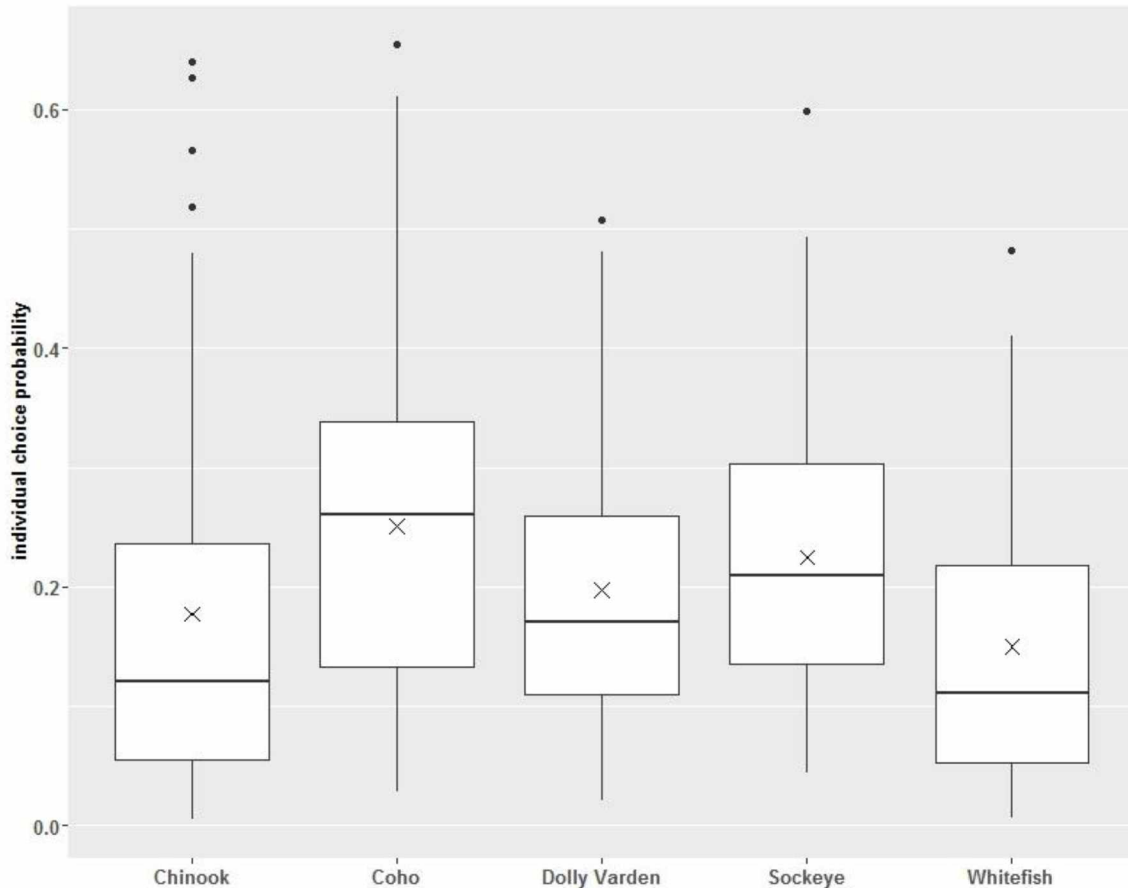
Figure 1.4 Distribution of expert choice probabilities for salmon persistence by species. Lower and upper quartile (box), median (bold line), mean (x).

Similarly, the *location of aquatic vegetation* attribute does not receive much weight in experts' choices among alternative habitats. The presence of aquatic vegetation in the backwater location, regardless of invasion status, is considered a positive contribution to persistence, whereas alternatives showing aquatic vegetation in all parts of salmon habitat or in the lake are believed to be negative. Experts disagree more about the negative effects of aquatic vegetation in the lake location compared to the positive effects of the backwater location as suggested by the CV which differs by a magnitude (Table 1.4 and Figure 1.5).
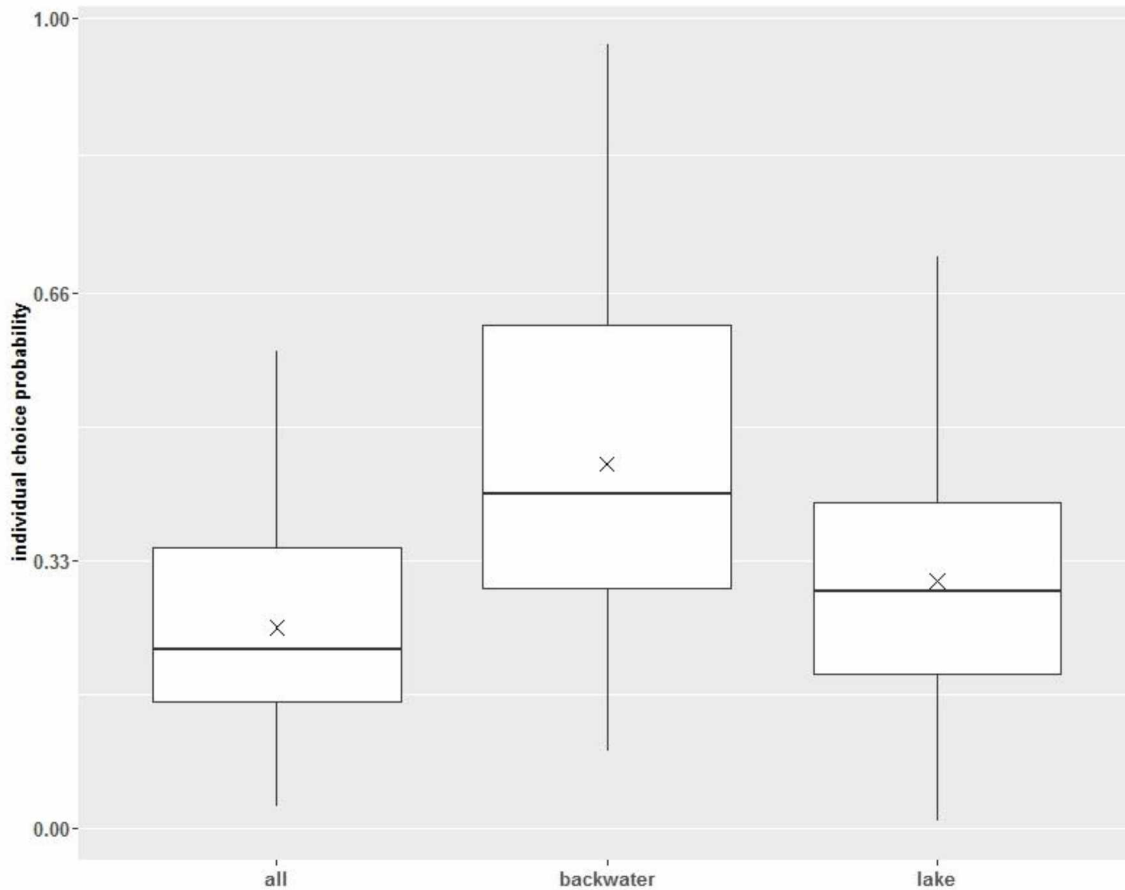
Figure 1.5 Distribution of expert choice probabilities by vegetation location regardless of elodea presence. Lower and upper quartile (box), median (bold line), mean (x).

1.5.2   Sensitivity analysis

A simulation of invaded habitat under varying environmental conditions shows the sensitivity of choice probabilities across the expert sample (Figure 1.6). For each alternative-specific attribute related to invaded habitat, choice probabilities are estimated across the sensitivity range of part-worths presented in Table 1.4. DO levels have the largest marginal effect on choice probability, indicating that at 0.5 mg/l, the mean choice probabilities of salmonid persistence in invaded habitat can reach below 0.1 and at 10.5 mg/l can reach up to 0.5 (Figure 1.6). The steepness of the DO curve illustrates that any directional change in DO can have large consequences on the believed persistence of salmon in invaded habitat, more so than any other attribute included in the design. In contrast to DO stand the marginally smaller effects of prey, elodea cover, and predation upon persistence. Increasing prey abundance has a positive impact on persistence while increasing elodea cover and predation have negative consequences for salmon with elodea cover having a larger effect. In specific, full elodea cover reduces mean

probability of persistence to 0.12, whereas the maximum predator density of 35 fish per acre reduces this mean probability to 0.18 (Figure 1.6).
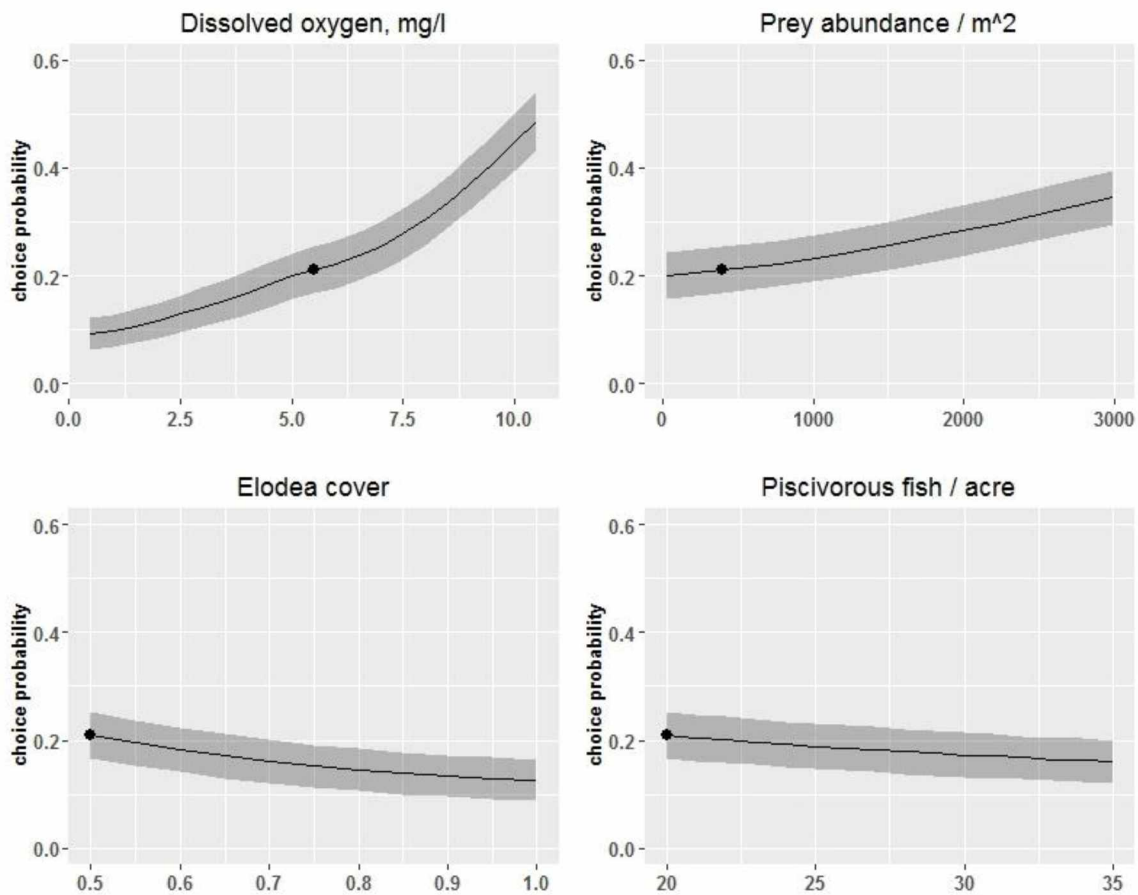
Figure 1.6 Sensitivity of choice probability of salmonid persistence in elodea-invaded habitat given changes in habitat-specific attribute levels. Sample mean (black line), 95% CI (shade), base case (dot).

Uncertainty among experts around the estimated mean choice probabilities for salmon persistence in invaded habitat varies as measured by the standard error. There is less diversity of opinion in regards to lower levels of DO (SE = 0.03) when compared to higher levels of DO (SE = 0.05), lower abundance of prey (SE = 0.04) than higher (SE = 0.05), and less elodea cover (SE = 0.043) versus more (SE = 0.038). Predation also shows a similar pattern across the attribute level range (SE = 0.043, 0.04).

The sample was divided into five expert groups to further explore the level of agreement among experts. Groupings were established using the results of the rating exercise placed at the end of the final choice tournament (Table 1.5).

Table 1.5 Experts' rating of elodea's overall effect on salmonid persistence (n=56)

Group	Overall effect on salmonids	Frequency
1	Significantly negative	10 (18%)
2	Moderately negative	35 (62%)
3	No effect	3 (5%)
4	Moderately positive	1 (2%)
5	Don't know	7 (13%)

Note, none rated elodea to have significantly positive effects.

Table 1.6 presents the mean part-worths for each group. Regardless of whether elodea is present in a salmonid system, experts across groups believe sockeye salmon to be more persistent than chinook, consistent with studies that suggest large scale shifts in ocean conditions favor sockeye and other salmon species, expert outlook for chinook is negative (Adkison and Finney, 2003; Hare et al., 1999). All expert groups, except group 3, believe that coho have a generally better outlook than whitefish. Group 3 favors whitefish over coho for a positive long-term outlook. The effect on persistence related to where aquatic vegetation is located within a salmon system, regardless of an invasion, is consistent with previous results.

Table 1.6 Mean part-worths by expert group based on ratings

Attribute level		Expert rating of elodea's overall effect on salmonids				
		Sign. neg.	Mod. neg.	None	Mod. pos.	Don't know
Respondent count (n=56)		10	35	3	1	7
Habitat state	Elodea-invaded	-156.85	-128.90	-90.22	-89.31	-119.62
	Indigenous	156.85	128.90	90.22	89.31	119.62
Species	Sockeye	7.73	8.90	2.60	35.16	9.13
	Coho	12.85	9.87	-15.36	14.64	23.90
	Chinook	-5.37	-12.80	-10.88	-19.77	-19.13
	Dolly Varden	2.42	3.59	3.67	-5.21	-10.90
	Whitefish	-17.63	-9.57	19.98	-24.82	-2.99
Veg. location	Backwater	26.60	9.69	15.23	15.63	33.36
	Entire system	-20.88	-9.61	-7.11	-51.42	-25.36
	Lake	-5.72	-0.08	-8.12	35.78	-8.00
Veg. cover	50% invaded	47.04	34.99	72.39	22.34	40.98
	100% invaded	-47.04	-34.99	-72.39	-22.34	-40.98
	0% indigenous	6.41	-1.25	-16.10	-7.84	7.93
	50% indigenous	-6.41	1.25	16.10	7.84	-7.93
DO (mg/l) [a]	0.5 invaded	-49.27	-110.33	-152.82	-138.84	-83.85
	10.5 invaded	49.27	110.33	152.82	138.84	83.85
	5.5 indigenous	-56.37	-53.62	-74.34	-90.47	-27.90
	10.5 indigenous	56.37	53.62	74.34	90.47	27.90
Prey (mg/m^2)	30 invaded	-35.47	-36.83	-1.67	-101.46	-30.40
	3000 invaded	35.47	36.83	1.67	101.46	30.40
	400 indigenous	-13.58	-13.67	3.24	9.30	0.32
	600 indigenous	13.58	13.67	-3.24	-9.30	-0.32
Pis. fish (#/acre) [a]	20 invaded	17.68	16.65	13.62	9.81	12.12
	35 invaded	-17.68	-16.65	-13.62	-9.81	-12.12
	5 indigenous	52.94	50.25	-7.02	7.03	59.65
	20 indigenous	-52.94	-50.25	7.02	-7.03	-59.65

a) Alternative-specific attribute level.

Most important, all groups show a preference for habitat without elodea, although the magnitude of the effect differs. For experts whose ratings indicate that they do not believe elodea has an effect on salmonid persistence (group 3 in Table 1.5), habitat status (invaded/uninvaded) is given the least weight among the attributes. This result validates the DCM. However, experts in group 3 more heavily weigh the extent of invasive elodea cover compared to other groups, which suggests that experts with no opinion about the overall impact of elodea on persistence

considered habitat status and elodea vegetation cover among the alternatives presented in the discrete choice task. All groups agree about the directional effect of the extent of elodea vegetation cover, where 100% coverage with invasive elodea is viewed as negative for salmonid persistence. There is more disagreement over the effects of vegetation cover in uninvaded habitat, where those in groups 1 and 5 have stronger preferences for 0% cover whereas the remaining groups believe 50% cover to be more beneficial habitat for persistent salmonids (Erhard et al., 2007; Schultz and Dibble, 2012). As supported by experts' comments (Appendix 1.B) this result indicates that different stages of the life cycle of salmon species were considered when evaluating the aquatic coverage attribute. In addition, varying levels of knowledge regarding the complex role aquatic vegetation plays for fish could also play a role.

The highest level of agreement among groups occurred for the DO variable for both invaded and uninvaded habitat, with group 3 weighing DO most heavily. Additional agreement among groups are the observed directional effects of the prey abundance and predation variables in invaded habitat with one expert (group 4) heavily weighing this attribute more so than almost any other attribute except DO. This expert believes that high prey abundance in elodea beds is a strong driver of persistence, and most likely the reason why the expert rated elodea as having a moderately positive effect on salmonids. The prey and predator abundance attributes in uninvaded habitat showed various levels of disagreement between group 1 and 2. Group 3 had opposing preferences compared to all other groups on the level of preferred predation, showing a preference for higher predation levels.

Table 1.7 provides a comparison of attribute importance within and across groups. Relative importance scores are calculated as $score_k = \dfrac{\max \beta_k - \min \beta_k}{\sum\limits_{k=1}^{k} \left(\max \beta_k - \min \beta_k \right)} 100\%$, where

$\max \beta_k - \min \beta_k$ is the range of part-worth utilities observed across all levels of attribute k ,[22] and are calculated using HB estimated utilities, averaged across the sample, and standardized to sum to 100. If an attribute has twice the score of another attribute, it is twice as important in explaining expert belief (Orme, 2010). For experts in Group 1, state of habitat is the main driver of persistence and three times as important as DO and predation in uninvaded systems. Like their counterparts in group 1, experts in group 2 focused their attention on the state of habitat variable

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[22] Importance scores are directly affected by the range of attribute levels.

but with more weight given to DO levels in invaded systems. Groups 3 and 4 show the most balanced attention across habitat attributes.

Table 1.7 Relative importance of attributes by group

		Expert rating of elodea's overall effect on salmonids				
		Sign. neg.	Mod. neg.	None	Mod. pos.	Don't know
Group ID		1	2	3	4	5
Respondent count		10 (18%)	35 (62%)	3 (5%)	1 (2%)	7 (13%)
Attribute						
Salmonid species		7.51	7.26	8.82	5.45	8.37
Location of vegetation		5.29	3.96	3.73	7.93	8.38
State of habitat		*28.52	*23.44	16.40	16.24	*21.75
Vegetation cover	(invaded)	8.55	7.17	13.16	4.06	7.91
	(uninvaded)	7.97	4.36	3.03	1.43	5.01
Dissolved oxygen	(invaded)	8.96	20.33	*27.79	*25.24	16.20
	(uninvaded)	10.25	10.16	13.52	16.45	7.26
Prey abundance/m²	(invaded)	6.45	7.27	8.10	18.45	5.53
	(uninvaded)	3.14	3.02	1.26	1.69	5.06
Piscivorous fish/acre	(invaded)	3.75	3.84	2.91	1.78	3.71
	(uninvaded)	9.62	9.21	1.28	1.28	10.84

Note, in bold are the two most important attributes, with * indicating the most important attribute. The importance scores sum to 100.

Interestingly, experts in group 5, who in the rating exercise said they did not know the overall effect of elodea on salmon, show preferences similar to experts in group 2. This result illustrates that these respondents were not necessarily outliers but that they may have been uncomfortable providing a rating, even though their preferences show that they have substantial ecological knowledge consistent with that of other experts. Most important, the result highlights the power and advantage of discrete choice methods over rating schemes, in providing a more user-friendly and accurate instrument for eliciting knowledge from a broader spectrum of experts, many of whom would be uncomfortable providing a rating. In the absence of the DCM approach, several of these experts might have opted out of the survey, despite having expertise in the topic.

Most experts do not believe salmonids can persist in invaded habitat, with a smaller proportion disagreeing. A closer look at how individual choice probabilities vary within and across groups reveals some inconsistencies between experts' choices and their ratings of the overall effect of elodea on salmon (Figure 1.7). Seven experts, who rated elodea as either significantly

negative or moderately negative for salmonid persistence, show estimated choice probabilities that are much higher, considering their rating (outliers in upper left of Figure 1.7). Additionally, the single expert in group 4 who rated elodea as moderately positive shows estimated choice probability for salmonid persistence in elodea-invaded habitat much lower than the sample overall. This result is contrary to what the expert stated in the rating task. The group that collectively rated elodea as having no effect on salmonids shows choice behavior that is consistent with their rating. Somewhat surprising, experts who did not know how to rate elodea's overall effect have choice probabilities most representative of the sample overall, again supporting the advantages of choice methods in expanding the expert pool.
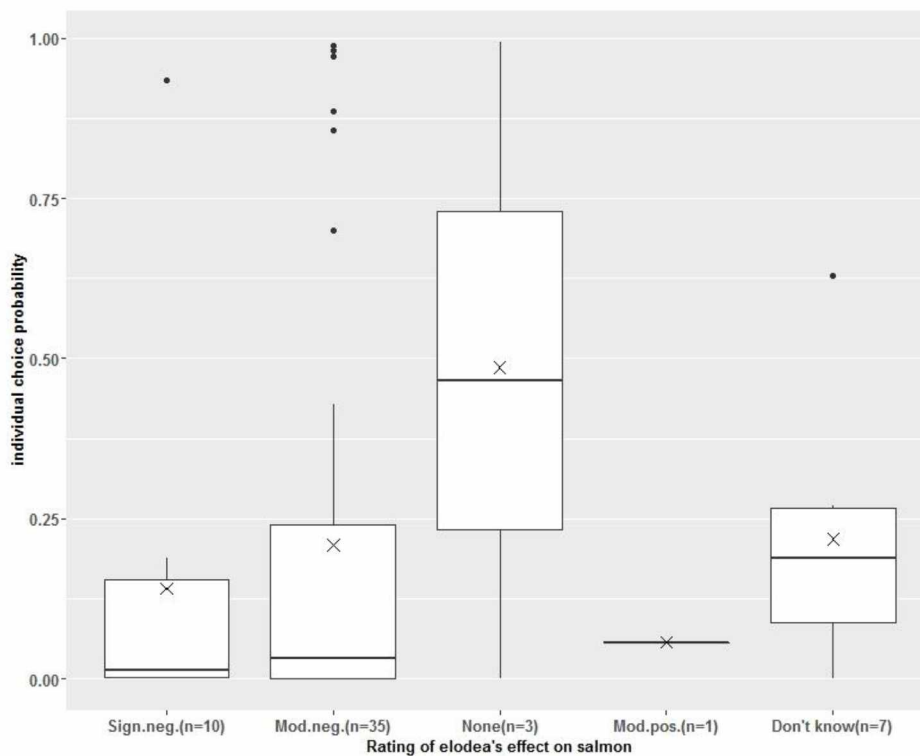
Figure 1.7 Distribution of expert choice probabilities by expert group. Lower and upper quartile (box), group median (bold line), group mean (x).

Lastly, the analysis found that the predicted choice probabilities are robust to the simulation method used for deriving the choice probabilities. Figure 1.8 uses the kernel density, which is similar to a histogram but smoother, to illustrate this point.
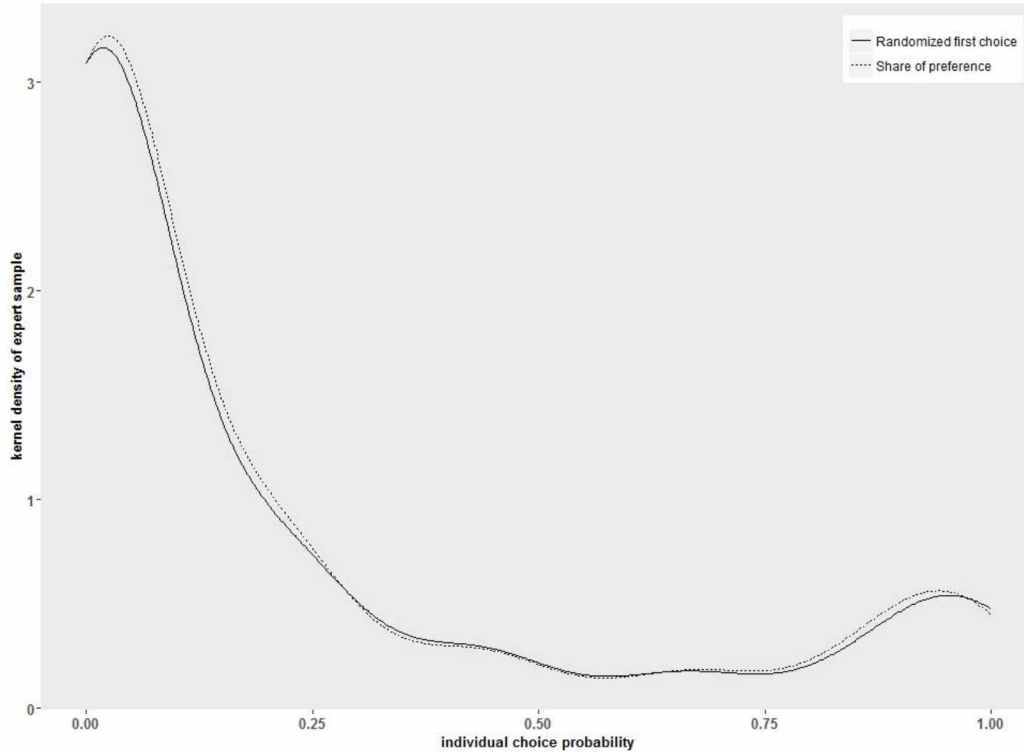
Figure 1.8 Probabilities of salmonid persistence in invaded habitat by simulation.

1.6   Discussion

Existing risk-assessment protocols rely on expert judgment, which often fails to separate "current knowledge" from "personal values" (Maguire, 2004). For example, Alaska's invasiveness ranking system asks experts whether a species' potential to be spread by human activity is low (human dispersal is infrequent or inefficient), moderate (human dispersal occurs regularly), or high (there are numerous opportunities for dispersal to new areas) (Carlson et al., 2008). There are no clear quantitative definitions of what "infrequent," "inefficient," "regularly," or "numerous" mean in practice. Thus, the rating becomes a mix of judgments and personal definitions of the stated terms. As long as personal decisions depend on personal judgments, there is no problem. However, when experts provide judgment on behalf of the public, the resulting ratings become prone to error, as others may have different definitions of the qualitative terms used in the assessment (Maguire, 2004). Additionally, risk assessments tend to separate the connected social values that are at stake, which could further inform the efficient allocation of resources to manage a list of "prioritized species," under limited budget. For example, Alaska's invasiveness ranking system solely asks experts to rate ecological characteristics on a relative scale, failing to

quantify and distinguish risk for invaders with potential catastrophic consequences versus invaders with just potentially "bad" consequences.

Unless resource managers are able to quantify risk in probabilistic terms (and quantify the quality of the assessment), large-scale management actions that require substantial public investments may increasingly face public scrutiny. This study shows that DCM can quantify probabilities related to potential outcomes, but also the social values at stake—and as such it serves two important functions for communicating risk to the public. DCM provides expert information to managers on whether resources should be deployed for taking action, providing information beyond what is available from current ranking systems. In addition, DCM can provide critical information on the quality of an assessment and expand the set of available tools for resource managers making decisions about conservation investments (Maguire, 2004; Turner and Daily, 2007).

The study results have direct practical implications not only for statewide management of elodea in Alaska, but also for improved, evidence-based invasive species management in general. The establishment of elodea in the Arctic and Subarctic illustrates the vulnerability of these regions to invasive species as new transportation corridors open (CAFF, 2013; Heikkinen et al., 2009). DCM provides refined expert input on increasingly complex management challenges requiring action. In order to efficiently allocate society's resources, refining our understanding of trade-offs beyond relative risk assessment is critical for socially optimal decisions (Shogren, 2000). On an agency level, investments to manage invasive species compete with an array of other management goals, such as agricultural and wildlife management allocations. As a society, our investments in managing invasive species compete with investments for broad social goals— such as funding for children's health and education.

While this study should be considered a proof of concept with various advantages, it is still subject to several limitations, some that could be addressed by changing the design and others that should spur future research. This study examined persistence as the system outcome used to develop a set of discrete choice sets for experts to consider as they examined the influence of multiple ecological factors (e.g., presence of elodea, DO, vegetation cover) on salmonid. That specific discrete outcome represents a very clear but rather extreme ecological outcome. Managers have significant interest in less extreme outcomes associated with the potential effects of elodea on salmon. Even though the design of the DCM prevented the collection of information indicating true belief, the open ended comments provide some insights (Appendix 1.B).

Of the 56 respondents, 25 experts used the open ended comment field to provide additional information about the reasoning related to their DCM choices. Of these, only four experts commented about the extreme outcome variable. For example, Expert 22: "I suspect the true response will be more a matter of moderate changes in fish production and survival that will result in either more or fewer fish, but not so extreme as they will cause population extirpation or prevent population viability." Expert 50: "Under only the absolute worst conditions did I think persistence was in doubt." Expert 57: "I found the response variable not sensitive." Expert 79: "Long-term population persistence is often related to the approximate starting abundance of each of the salmonid populations." Expert 111: "It is very difficult to extirpate most fish populations if the water carries sufficient oxygen and there is even minimal food." The fact that few experts commented on the extreme outcome variable is not to say that other experts did not have concerns about choosing an extreme outcome. This result just shows that most experts did not mention the extreme outcome to be problematic for stating their beliefs. This finding is also supported by the findings of experts' rating of elodea's overall effect on salmonid persistence with two thirds of experts stating a moderately negative effect (Table 1.5).

Depending on specifics of the scenario, particularly when less dramatic outcomes are not presented, experts may differ in how critically they consider the idea that the change in the ecosystem described in the scenario would result in complete loss of salmon. This issue could be addressed by altering the design to include an outcome variable in the form of an attribute, or by combining the discrete choice task with a rating exercise, selecting from a scale or a best-worst scaling task (Hensher et al., 2005). While the advantages of such extensions are apparent, they come at the cost of putting an additional burden on respondents, and they may require respondents to have additional skills, again limiting the expert pool. An alternative experiment could also examine expert perspectives on changes in the abundance of salmon rather than the persistence/extirpation dichotomy. That problem may motivate more research into the best designs, resulting in optimal applicability of DCM for eliciting indirect probabilistic knowledge and its use within decision analysis.

Finally, an additional extension of the study could scale and then match the derived choice probabilities to probabilities assessed through biophysical experiments focused on estimating the effects of elodea on salmonids (Hensher et al., 2005). The original expert model could then be validated and updated (Drew and Perera, 2011). An example, where the presented approach could serve as an alternative to directly encoding probabilities, is the probability assessment of

extreme events, particularly for population viability analysis (Burgman et al., 2012). Last, although the DCM method requires more time to collect and analyze data, the resulting data is rich in information and adds to the toolbox for sound expert elicitation in resource management aiding more informed decision-making.

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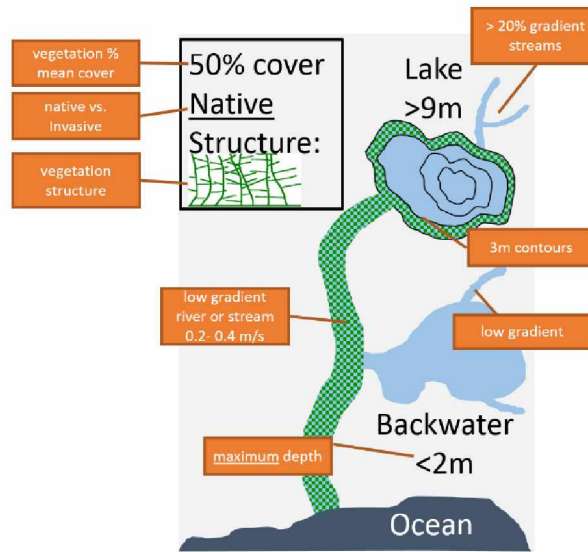
Figure 1.9 Map illustrating hypothetical salmon habitat characteristics, location of aquatic vegetation and % vegetation cover.

Figure 1.10 Example of one of six screener tasks

We've noticed that you've avoided scenarios with certain habitat characteristics shown below. Would any of these characteristics be totally unacceptable for long-term persistence of an Alaska salmon population? If so, mark the _one_ characteristic that is most _un_acceptable.

(Note, habitat characteristics are defined in the background starting on p.3.)

◯ Vegetation cover (invaded habitat) - 50%
◯ Prey abundance/m² (_un_-invaded habitat) - 400
◯ Dissolved oxygen (_un_-invaded habitat) - 5.5
◯ Piscivorous fish/acre (invaded habitat) - 35
◯ Piscivorous fish/acre (_un_-invaded habitat) - 20
◯ Dissolved oxygen (invaded habitat) - 0.5
◯ Prey abundance/m² (invaded habitat) - 30
◯ Vegetation cover (_un_-invaded habitat) - 0%
◯ State of habitat - invaded by _Elodea_

◯ None of these are totally _un_acceptable.
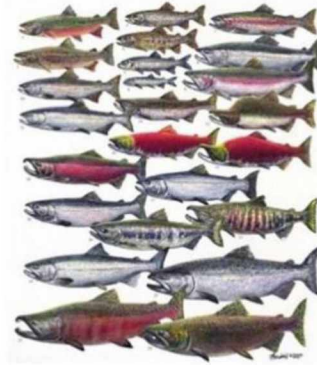
Figure 1.11 Example of an unacceptables task

Table 1.8 Design settings of the ACBC experiment

Design field	Setting
Prohibitions	None
Screening tasks 8	8
Concepts per screening task	4
Min. attributes to vary from BYO selections	2
Max. attributes to vary from BYO selections	4
BYO product modification strategy	Mixed approach
Number of unacceptables	5
Number of must-haves	4
Max number of product concepts in tournament	20
number of concepts per choice task	3
number of calibration concepts	0
Dominated concepts	Avoided
BYO in final tournament	Included

1.9   Appendix 1.B

Table 1.9 Open-ended comments from respondents

Expert	Open ended response
Expert15	The oxygen factor complicates the scenarios. I don't think you will find natural systems with flowing water and no vegetation at 5.5, unless there is some weird chemistry occurring. Also, having pike as predators in all scenarios is equally confounding and unrealistic. I wouldn't think that you would have high levels of pike in systems with no vegetation. The Cordova area and most of the other coastal areas do not have pike. Since we don't have pike here, I don't have a good idea of when pike levels become a factor. I also had to assume that pike were using the lake shorelines and backwaters, but maybe not the river channel and middle of the lake. I guess we could use some information on the velocity of the river to try to determine whether we would expect pike to be there. A swifter river would improve the odds for Chinook. So ... the elodea question becomes muddled with the pike and oxygen factors thrown in. Looking back, I spent more time thinking about them, rather than elodea or natural vegetation. One other thought - the relationship between vegetation as prey cover and the use by pike for concealment may take additional study. I would venture to say that it provides more benefit for pike, which are ambush predators, than for salmonids. The juvenile salmonids would most likely be cruising the edges of the weed beds, not feeding within the thick beds, and would be subject to ambush. I'll have to confess, I didn't really try to weigh these factors against each other in the scenarios. I did feel that it was a negative factor to have shoreline vegetation and high levels of predators.
Expert19	I appreciate the effort and time that has gone into this project and I think it is a worthwhile goal. However, I am concerned about my answers or the expertise need for the answers. I provided an answer to all of the questions, but mostly so that I could see the entire survey, not because I am confident in my ability to provide useful responses. In short, I do not think I have the expertise to answer the questions. For example, in the scenarios that compare species, I cannot answer whether a certain amount of macroinvertebrates has a stronger effect on one species than the amount of zooplankton on another species. When the comparison is for the same species, it is possible to speculate whether predation is more important than dissolved oxygen, but evaluating multiple factors simultaneously is beyond my expertise. Overall, I think the scenarios are active areas of research, not known affects. I think the objective of the survey will make a contribution to the Elodea management and inform invasion ecology and I hope you find my comments useful.
Expert22	Tough problem to get a handle on this because of so much uncertainty in how salmonids will respond to Elodea in Alaska. I assume this led to the sort of either-or structure of the questions "persist vs extirpated" or "viable vs non-viable". However, I suspect the true response will be more a matter of moderate changes in fish production and survival that will result in either more or fewer fish, but not so extreme as they will cause population extirpation or prevent population viability.

Expert23	There are a lot of unknowns in the survey: run timing, climate, nutrient levels, behavior, the presence of species such as stickleback. I certainly made a lot of assumptions.
Expert29	Although a greatly appreciated effort, somewhat difficult to sort through all the scenarios. I'm anxious to see your results. Thanks.
Expert33	Suggest defining type of predators (fish/pike, avian, etc.)in the scenarios. Rearing and spawning habitat of a species is often very different so assessing species persistence based on habitat/predator factors may have differing effects depending on life stage present.
Expert44	I ranked my persistence scores largely based on the species' demography (age and size at reproduction, fecundity, longevity, potential for resilience) and life history (migratory more persistence than resident or partial resident). Here in Oregon the most productive populations of coho salmon, perhaps in the world, reside in shallow, eutrophic coastal dune lakes that have been long-invaded by Elodea and a host of nonnative fishes that would make most in Alaska extremely concerned. There is probably no simple connection to draw here and no reason to believe Elodea or other invasives have a positive effect on coho salmon. I suspect the main factor in play is rapid rate of growth of juveniles using these lakes and their larger size and emigration, and consequent higher probability of returning as an adult.
Expert50	While this exercise is well put together, the scenarios led largely to persistence, in my opinion. Why? Well, each stage of life-history of each species has specific habitat needs which may differ seasonally. Vegetation changes seasonally as well. Predator populations vary over time and they have habitat requirements as well. So when I look at these scenarios, I see many ways in which the problems don't overlap and persistence is the result. I was able my experiences in Bristol Bay, Seward Peninsula, Upper Copper and Susitna river drainages, North Slope, and the Interior (Kuskokwim and Yukon drainages)to the scenarios presented in the questionnaire. Without a doubt, the future influence of elodea is the most unknown, and although it may end being negative, there are areas where elodea will not persist. There are many areas where pike are native and salmonids persist. The life history of the fishes in this questionnaire vary by age, season, and are plastic (to lesser and greater degrees). Finally, I made the assumption the scenarios were not static (12 months of a year), because that would be ridiculous. I applied them to summer (mind you these variables actually will vary over summer as well). Under only the absolute worst conditions did I think persistence was in doubt.
Expert51	I found this survey to be awkward- I felt like the scenarios were too simplistic, and I didn't [k]now enough about the situation-for example, oxygen demand is related to temperature, and species. Also, some species, dollies and cohos for example, are just more resilient than other salmonids, and so in my opinion, would be more likely to persist under a broader range of scenarios than chinook or sockeye. I am not sure how useful this survey results will be to you. Personally, I think you would do better to schedule interviews with experts, and that way you could explore answers in more detail, and get the rationale for why people are responding the way that they are. Good luck with your project!

Expert57	"I found the response variable (likely persist vs. possibly extirpated) not sensitive. I also note that comparisons across species are challenging, because of inherent differences in the sensitivities and life-histories of the different species. For example, coho stray a lot so they will likely persist no matter. "
Expert72	"Was not sure of the gradient of the river for the entire river length. Not sure of the spawning habitat available in the > 20 gradient streams which made some decisions difficult. Experience with Whitefish led to some of the choices. Most of my experience does not include any rivers with the entire length with 50% vegetative structure. With Dolly Varden would they be considered in the pool of piscivorous fish or was it just Pike."
Expert78	The premise is good but I could check likely persistent for almost everything (except maybe whitefish) if conditions during other times during their life-his[t]ory (marine) are consistently good, or vice versa, if its good early on they still might be extirpated if its consistently bad later in life stage.
Expert79	Long-term population persistence is often related to the approximate starting abundance of each of the salmonid population, so the starting population or density would have been useful.
Expert90	"5.5 ppm O2 at 10C is marginal - fish can live here but they would not thrive or be happy. Dolly Varden are also piscivorous, more than rainbow trout."
Expert93	Interesting survey and would be like to see the results once completed. Thanks.
Expert94	"I am not aware of specific experts re: aquatic plant influence on salmonids; more work is required in this area. I also am more familiar with other freshwater fishes, primary centrarchids so not sure how valid and/or relevant my responses ar. Interesting survey! Good luck with you[r] work."
Expert99	"One issue that was really not clear to me was the distinction between % coverage and density. A site can have 50% coverage but widely differing densities. I assumed that the native vegetation coverage at 50% had lower density as indicated in the 'picture'. But I wasn't sure this assumption was valid. Good luck!"
Expert100	Lowland habitats on the Kenai Forelands are significantly at risk due to the[ir] low gradient, shallow nature. Combined with invasion with pike, could threaten production of coho salmon, though all other salmonids could also be significantly at risk. If elodea was established in several lakes, would be hard to prevent further spread. If it does spread then pike eradication efforts would be much more difficult, and might not be feasible in the long term. So it is essential to keep Elodea from being established, as once established eradication would be most difficult. Would also obfuscate effort on pike eradication.
Expert106	"I was extremely un-impressed with the lack of clarity of what this survey is looking for. I've set aside daily duties numerous times in the past to take surveys and have never been more confused from start to finish. The big question is what will this information possibly be used for? Suggestions for the future: Clearly lay out the survey and it's intentions, the information in the beginning alone took an extensive time to read. Choose only the very big questions and focus the questions on those issues. This took way too long to fill out. I work for the people and fish of the State of Alaska, taking personal time away from my assigned duties won't happen for me again unless my supervisor approves and directs me to. "

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Expert111	I don't feel like I was much help. It is very difficult to extirpate most fish populations if the water carries sufficient Oxygen and there is even minimal food. Some species (eg lake trout) really are susceptible to habitat changes but even species like this are rarely driven to extinction.
Expert112	"I do not think the scenarios were very realistic. For example a steady state of 5 mg/L, nor was there a seasonal or life-stage component. Clearly, Elodea could prove beneficial for certain life stages at certain time of year and this was not captured. Moreover, questions about elodea and pike predation should be treated separately. I believe more Elodea doesn't mean more pike. I appreciate the complexity of the issue, and there is no easy answer. Best of luck!"
Expert122	I did not use the background information to aid in answering questions.
Expert127	I am fairly familiar with salmonid habitat, but unfamiliar with whitefish, so this may have biased my answers as I was hesitant to select whitefish regarding likelihood of persistence.
Expert128	This survey does not take into account the actual life-history strategies of juvenile and adult salmon and whitefish species. Chinook salmon, for instance, do not reside in lakes, unless a stocked fish raised in a hatchery. They spawn in relatively fast-flowing, oxygen-rich water with larger cobble and pebble substrates. Whitefish spawn in substrates with differentially-sized gravels and flow and larger oxygen levels. Most of the habitat these species spawn and rear in are not going to get invaded with elodea anyway! A poorly-designed study!!
Expert146	I think Elodea alone is at least minimally negative. I chose significantly negative because in the presence of other invasive species such as northern pike, it would be significant (e.g., Alexander Lake). Not being able to select or know the life stage made the selections more difficult at times, so I typically selected my answers using post-emergent to early juvenile life stages for salmon, which I think are most vulnerable life stages in general.

Chapter 2. Aquatic Invasive Species Change Ecosystem Services from the World's Largest Sockeye Salmon Fisheries in Alaska[1]

2.1 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 each region is invaded and remains unmanaged, the potential median damages to ecosystem services from commercial sockeye fisheries is aggregated across five regions and amounts to $141 million annually in 2015 USD. The associated median loss of natural capital would amount to almost $4 billion. There is a 35% chance of positive net benefits associated with the believed positive effects of elodea on sockeye salmon (*Oncorhynchus nerka*). Despite the potential for positive net gains, the magnitude of the most probable damage estimates 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.

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[1] Schwoerer, T. 2017. Aquatic Invasive Species Change Ecosystem Services from the World's Largest Sockeye Salmon Fisheries in Alaska. Prepared for submission to Ecological Economics.

2.2 Introduction

Invasive species pose a threat to the health of aquatic ecosystems worldwide, and effect ecosystem services important to economic sectors such as agriculture, forestry, and fisheries. While most bioeconomic research focuses on current invasions, little research has highlighted the future risk of invasion to intact ecosystems not-yet-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 of taking action, and the fact that people remain unaware when not directly or immediately affected by environmental harm (Doelle, 2003). In this context, aquatic invasive species are especially worrisome because their subsurface nature limits 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 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 (Frésard and Boncoeur, 2006; Knowler, 2005). Deciding which complexities to address and which ones to leave out is a common conundrum for researchers. Economic valuation is most straightforward when the invader has a direct effect on a harvestable resource because the link between ecology and economics can be established through reliable market data (Barbier et al., 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 that establishes linkage between the invader and a harvestable resource, structured expert judgment (SEJ) can fill this knowledge gap (Cooke, 1991). While SEJ is an incomplete substitute for biophysical experimentation, it provides important insights to management. SEJ allows for explicit treatment of uncertainty in cost-benefit analysis and, as such, can inform managers about the economic value of physical

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experimentation aimed at reducing uncertainty (Peterman and Anderson, 1999). SEJ has been widely applied 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 varied expertise. Some approaches use equal weights among experts or a performance-weighted average based on seed (test) questions with known answers (Cooke, 1991). However, especially in cases of high uncertainty that require a diverse group of experts, seed questions can be difficult to frame appropriately (Grigore et al., 2016).[2] Its usefulness was called into question during research applying SEJ to quantify uncertainty in the medical field where experts from various specialized fields were required (Fischer et al., 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 instead uses a multi-method approach to quality-assurance and elimination of inconsistent experts, and then applies equal weighting. Cooke's performance scoring is replaced by a coherence check eliminating illogic judgments. Thus, 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. Yet, probabilistic expert opinion is derived indirectly from estimated individual-specific utility functions (unpublished research). 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

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[2] As discussed, bioeconomic analysis of biological invasions often center around 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 uncertainties is higher. That requires the expert pool to be broad because knowledge needs to be attained from different fields of knowledge (Maestas et al., 2014).

weighting (Maestas et al., 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 can then be integrated into a risk analysis framework. The presented approach allows for a more detailed vetting especially useful when uncertainty is high and expertise varies. Additionally, it avoids some of the issues of Cooke's method.

Economic damage assessments in commercial fisheries have gained attention in recent years as marine and coastal ecosystems face increasing human influence through trade, commerce, and development (Frésard and Boncoeur, 2006; Knowler, 2005). In North America, much of the ecological and economic research on invasion impacts to fisheries has focused on the Great Lakes (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 never be eliminated when invasive species populations have established and irreparably impaired ecosystems (Doelle, 2003). The continued allocation of resources into these impaired systems results in 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. Economic benefits are received on a worldwide scale including global salmon consumers as well as local and national fish harvesters and seafood processors. Wholesale values of Alaska salmon exceeded $1 billion in five years between 1988 and 1995, underpinning the large economic value of Alaska salmon systems (Knapp et al., 2007). As human presence and activity in ecosystems in the Arctic and Subarctic increases, the threat of invasive species increases, particularly for highly productive fisheries in this region (Short et al., 2004). Yet, invasive species protection and prevention have received little attention (Schwörer et al., 2014). Local resource management also remains hampered by insufficient funds for rapid response. This challenge, in part, is related to the inability of agencies to estimate and communicate the potential economic risk to policy-makers and private industry.

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 has recently also been 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 habitat not yet 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 more problematic such as rapid growth, allelopathic chemical production, and phenotypic plasticity, traits that are found in *Elodea spp.* (Erhard et al., 2007; Schultz and Dibble, 2012). Given the urgency of statewide management of elodea, information on the potential economic risk is critical for decision-making; yet, the lack of biophysical evidence relating elodea to salmon abundance and productivity has so far prevented economic analysis (Carey et al., 2016). Expert elicitation related to elodea's potential reproductive effects on salmon found that elodea invasions in salmon habitat are believed to lead to both negative and positive outcomes for sockeye salmon (unpublished research). These results underline the need for a bioeconomic risk analysis as presented here that 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 elodea invasions. The first section of this paper provides background regarding commercial sockeye salmon fisheries in Alaska. In the following section, a bioeconomic market valuation is developed that integrates SEJ-derived growth rates for sockeye salmon (*Oncorhynchus nerka*) with a market demand model that uses published commercial fisheries data (ADFG, 2016a, 2016b). The SEJ approach is justified due to lack of data specifying the biological relationship between elodea and salmon, preventing analysis of structural changes to the stock recruitment relationship for salmon. The model's primary purpose is to inform elodea managers about the future costs and benefits of taking action and as such is a descriptive model.[3] The range of outcomes found 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

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[3] 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).

investment is needed in keeping productive ecosystems free of aquatic invasive species. The paper ends with a discussion of the modeling approach and provides policy implications.

2.3   Background

2.3.1   Elodea ecology, management, and history in Alaska

There are two species of Elodea in Alaska that 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 but not 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. Elodea prefers sand and small gravel substrate in cold, static or slow-moving water to 9 m depth (Riis and Biggs, 2003; Rørslett et al., 1986). Elodea is tolerant of a wide range of environmental conditions and has successfully invaded aquatic ecosystems worldwide (Josefsson, 2011). Cyclical population dynamics have been observed for *E. canadensis* peaking between three and ten years after invasion and declining or even disappearing thereafter (Heikkinen et al., 2009; Mjelde et al., 2012; Simpson, 1984). Sudden collapses remain unexplained but have been observed throughout Europe (Mjelde et al., 2012; Simberloff and Gibbons, 2004). 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 et al., 2011). Natural dispersal includes flooding and wildlife transport (Champion et al., 2014; Spicer and Catling, 1988). In Alaska, elodea reproduces vegetatively with stem fragments surviving desiccation and freeze (Bowmer et al., 1995). Elodea has some of the highest fragmentation and regeneration rates among aquatic invasive plants causing rapid dispersal and severe challenges for mechanical removal (Redekop et al., 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 2.1, 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 2.1, 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).

2.3.2 Commercial sockeye salmon fisheries

Alaska's commercial sockeye salmon fisheries can be regionally divided into five large watersheds (Figure 2.1) (USGS, 2016). 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. There are also commercial sockeye salmon fisheries in Southeast Alaska and the Aleutian Islands that were not part of this study, keeping the focus on regions closest to the currently known elodea infestations. The regions have varying seafood processing capacity, run sizes, harvest levels, and prices. Prices are determined by global market forces; for example, the rapid and sustained growth of the market for farmed salmon has placed downward pressure on the prices for Alaskan salmon since the 1990s. Yet over the past decade, prices have recovered due to marketing efforts aimed at wild and sustainably-caught Alaska salmon, and to disease outbreaks in salmon farms elsewhere (Knapp et al., 2007).[4] In 2014, wild salmon comprised about 30% of global salmon production by volume. Of the wild salmon portion of this global market, Alaska sockeye salmon production took the largest share with 65% in wild sockeye volume of which 37% were 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 et al., 2007). Table 2.1 shows historical wholesale prices for the four main product categories for sockeye salmon—frozen, fresh, canned, and other.[5] Given a globally traded product, variations in price exist and are more or less correlated across regions (Table 2.2).

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

[5] While there are additional subcategories, the analysis focuses on these four categories for which wholesale prices are published (ADFG 2016b).
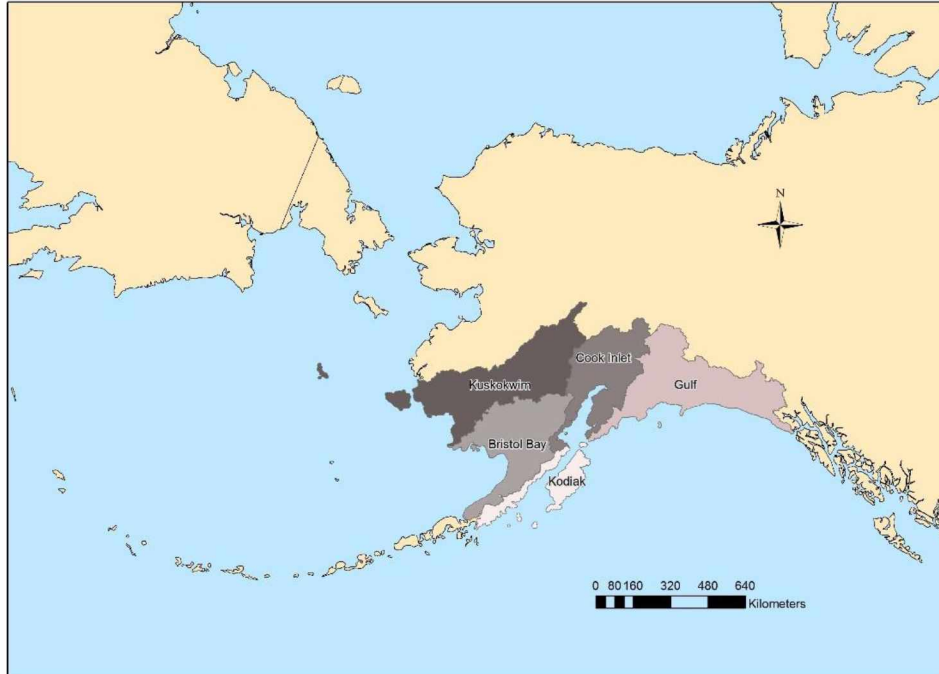
Figure 2.1 Watersheds supporting commercial sockeye salmon fisheries that were part of this study. This study region was selected because elodea is present in the Cook Inlet and Gulf regions.

Table 2.1 Fisheries characteristics by region

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 2.2 Correlation among regional wholesale prices for sockeye salmon

	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 2.3 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 et al., 2007).

Table 2.3 Production shares and processing yield by region

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).

2.4   Methods

The damage assessment approach consisted of two components. The first describes the elicitation, evaluation, and aggregation of expert opinion on the reproductive impacts of elodea on sockeye salmon in Alaska. Two methods were used to accomplish this, a DCM (unpublished research) and SEJ (Cooke, 1991). The second outlines the bioeconomic model used to estimate changes in consumer surplus (Freeman, 2003). This approach followed 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 for estimating potential damages to sockeye salmon fisheries.

2.4.1 Expert judgment

In order to quantify uncertainty about elodea's effects on salmon the approach relied on broad expertise from three areas of knowledge: Pacific salmonids in freshwater habitat, the ecological role of submersed aquatic vegetation, and 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 therefore 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. The appendix details the various fields of expertise for experts who responded to the elicitation (Appendix).

Several attempts following Cooke's method for designing seed questions to score expert performance failed because of the difficulty finding appropriate questions. The challenge was to find questions to known phenomena that experts of all fields could be expected to know, and were relevant to the elicitation. Not only was it difficult to find appropriate questions that were suitable for all experts, but the experts participating in a pretest of the elicitation opted out after realizing that they were being tested. The reason was that the seed question was relevant to salmon biologists but not invasive species experts specializing in aquatic vegetation. Therefore, instead of relying on inappropriate seed questions the DCM and SEJ were used to evaluated experts and test for coherence of expert opinion.

First, the DCM asked experts to choose among hypothetical salmon habitat scenarios that they believed would result in long-term persistence of salmon. The scenarios varied in their description of habitat and invasion characteristics (unpublished research).[6] Based on the DCM

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

data, each expert's probability of choosing invaded over uninvaded habitat for persistent salmon populations was estimated (unpublished research). In a second exercise, a SEJ asked 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).[7] 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). As such, the elicited growth rates apply to the whole population of sockeye salmon and do not specify elodea's effects on specific age-structures. The SEJ asked the following questions:

Q1. Imagine Alaska's sockeye salmon systems would be invaded with Elodea spp. 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 spp.*? 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 spp.?

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.

While the first question 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

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[7] 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.

question tested expert's comprehension of the task and was also used to further eliminate experts from the pool (Speirs-Bridge et al., 2010).

Based on the probability of salmon persistence in elodea-invaded habitat in the DCM and the stated sockeye growth rates in the SEJ the following coherence check was applied. A logical and consistent expert 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. Also logical is an expert who showed a higher than 50:50 chance of persistence in the DCM and stated a positive median growth rate in the SEJ. To the contrary, incoherent experts fell into one of two possible groups: they showed higher than one odds of persistence but judged the median growth rate to be negative, or they indicated that salmon had a less than 50:50 chance of persisting in elodea-invaded habitat but stated a positive median growth rate in the SEJ. This vetting technique further narrowed the sample of experts that formed the joint probability distribution of annual average growth rates in elodea-invaded habitat. Assuming normality, individual expert's interval judgments from Q1 to Q3 were combined applying equal weights (Figure 2.2) (Cooke, 1991).
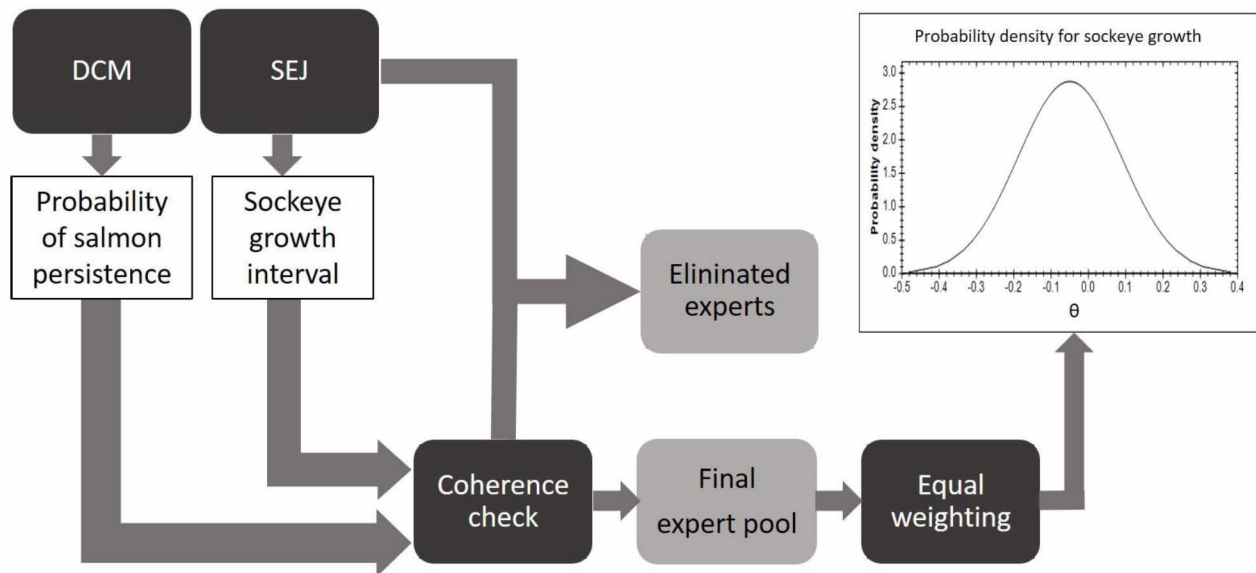
Figure 2.2 Expert vetting process used for aggregating expert opinion on annual average sockeye growth rates in habitat invaded by elodea.

2.4.2 Bioeconomic model

Potential annual damages from elodea to commercial fisheries were estimated in discrete time using a benefit approach to economic valuation of ecosystem services (Freeman, 2003). If

elodea changes the provisioning of ecosystem services—the amount of harvestable sockeye salmon—the introduction of elodea changes the benefits consumer derive from the resource. Consumer surplus is a measure of these benefits and is quantified by the difference between the maximum amount consumers are willing to pay 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 forgone changes 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:

$$\Delta CS_{t+1} = CS_t - CS_{t+1} \tag{2.1}$$

$$= \frac{\gamma}{2}\left(h_t(p'-p_t) - h_{t+1}(p'-p_{t+1})\right)$$

where *y* 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 2.3). The choke price at which demand ceases was equal to *p*. Using the own-price elasticity of demand, ε, the choke price equaled $p' = h_t/\varepsilon + p_t$. Further, harvest in period *t+1* was expressed as a function of SEJ-derived sockeye growth rates θ, thus $h_{t+1} = f(h_t,\theta)$. After substituting and rearranging, Equation 2.1 became

$$\Delta CS_{t+1} = \frac{\gamma}{2}\left[\left(h_t - f(h_t,\theta)\right)\left(\left(\frac{h_t}{\varepsilon} + p_t\right) + \frac{f(h_t,\theta)p_t}{h_t\varepsilon}\right) - p_t h_t \right]. \tag{2.2}$$

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).[8] 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 was 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).

The logistic growth model describes the population dynamics for an entire population of salmon irrespective of age-classes and as such is consistent with the SEJ-derived population growth rates. Even though the logistic growth model is not often used to describe population dynamics in fisheries due to this and other limitations described below (Larkin, 1977), its advantages lie in its simplistic application particularly in data-limited situations (Beverton and Holt, 1957; Haddon, 2011). The logistic growth model differs from commonly used fisheries 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 that is 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 K in the logistic model but would be lacking in an exponential growth model.

Under assumed 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. In addition, while long-term persistence is not guaranteed under the logistic growth model, the model assumes 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). This data showed that landscape-wide spread of an elodea invasion could occur in much longer timeframes compared to the 20-year time horizon considered for persistent salmon populations in invaded habitat (Peterson et al., 2008). Also, 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 elodea's 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

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

(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 2.2 are converted into net present value terms (NPV) such that

$$NPV = \sum_{t=0}^{100} \Delta CS_t \left(1+d\right)^{-t} \qquad (2.3)$$

where d is the real social discount rate and takes into account the public's time preference related to natural capital.9 NPV is a measure for natural capital, from which a constant flow of ecosystem services can be calculated such that

$$NPV_{annual} = NPV \frac{d}{1-\left(1+d\right)^{-100}} . \qquad (2.4)$$

While NPV measures the value of natural capital (Equation 2.3) and is a stock just like wealth, annualized NPV is the constant flow of ecosystem services associated with that natural capital (Equation 2.4). In the same context, if natural capital is wealth, ecosystem services are income. The regional estimates were summed to show combined statewide damages. A sensitivity analysis tested the robustness of the estimate by first measuring the parameter's contribution to variance in the NPV estimate, and second how the maximum and minimum parameter values changed the mean NPV.

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

9 The discount rate accounts for the time value of money or, put differently, the preference related to immediate consumption versus later consumption of a good, called time preference. Consequently, when applying a discount rate, cash flows occurring in the immediate future are of higher value now, than the same cash flows occurring in the distant future or occurring for future generations. Since current stakeholders do not know if future generations will still exist within the time horizon or what their preferences will be, the applied discount rate is uncertain. A discussion of discounting and the environment can be found in Hanley and Spash (1993).

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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. Therefore, the predicted changes 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 multitude of retail products. In addition, retail prices are a reflection of other price factors non-attributable to salmon, such as store location, parking, and availability of other products which result in significant variation in price (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 analysed time horizon. This assumption ignored 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). However, Alaska commercial salmon fisheries are sustainably managed as certified by the Marine Stewardship Council (MSC) (Clark et al., 2006; MSC, 2017). Also, the high permit prices in many of Alaska's commercial salmon fisheries demonstrate that many fisheries create significant economic rent (Knapp et al., 2013).

2.4.3   Model simulation and parameter assumptions

The deterministic nature of the economic valuation approach did not necessitate a simulation approach. However, Monte Carlo simulation was used to estimate NPV for a range of parameter inputs. For example, historical data was used to determine the range of salmon harvests and prices. Due to the deterministic model and contrary to common stochastic modeling, 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 2.3 and 2.4. 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.

Below, the distributional assumptions concerning the uncertain parameters are discussed. 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 Mangle, 1997). 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). In addition, long-term variation of salmon returns is also driven by Pacific climate variability and other factors (Hare et al., 1999).

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 2.1). 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 2.1) (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 2.1). 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 is used to derive estimates of economic benefit. In order to measure changes in consumer surplus caused by a chance salmon catch due to an invasion, 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. However, estimates from elsewhere in North America can serve as a proxy. A variety of sources were consulted that estimated the elasticity of demand for fresh and frozen sockeye salmon in the Pacific Northwest, Oregon, or Canada (DeVoretz, 1982; Johnston and Wood, 1974; Swartz, 1978; Wang, 1976). 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 the latter elasticity estimates as bounds (Table 4.4). There are several arguments that would support higher elasticities $|\varepsilon| > 1$. For instance, the existence of very close substitutes to wild sockeye salmon, such as coho, pink, or chum underpin this argument. Additionally, wild sockeye is 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).

Lastly, the real social discount rate is another key uncertainty that was taken into account by the model. The real 30-year social discount rate recommended by OMB and discount rates used in similar analysis of invasive species risk range between 1% and 6% (OMB, 2016; Rothlisberger et al., 2012). The analysis uses a triangular distribution assuming a most likely rate of 3%, consistent with best practices in financial valuation (Winston and Albright, 2016). A distribution is used rather than a discrete value in order to reflect 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 suggesting the use of multiple discount rates (Arrow et al., 2013; Baumgärtner et al., 2015). The upper bound of 6% reflects real annual rates of return for Alaska's commercial salmon fisheries (Huppert et al., 1996). The lower bound is consistent with recent research suggesting impacts to ecosystem services should be discounted at much lower rates compared to impacts related to manufactured capital (Baumgärtner et al., 2015).[11] Table 4.4 summarizes the model parameter assumptions used in the analysis.

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[11] 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 2.4 Bioeconomic model parameters

Parameter	Units	Region-specific	Specification	Source
Annual average sockeye growth rate, θ	decimal	no	Normal (−0.0522, SD: 0.1388)	This study
Pre-invasion harvest, h_0	lbs	yes	Normal (Table 2.1)	ADFG 2016a
Pre-invasion wholesale price[a], p_0	2015 USD	yes	Lognormal (Table 2.1)	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 (Table 2.1)	ADFG 2016a
Processing yield, γ	decimal	yes	Table 2.3	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 (Table 2.3).

2.5 Results

Following the structure of the outlined methods, this section first presents results associated with the expert elicitation followed by damage estimates. The section closes with a sensitivity analysis of the presented results.

2.5.1 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 intervals 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 in Q4 and were eliminated. The scatterplot in Figure 2.3 A shows how the 39 remaining experts varied in their expert 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 2.3 A). The eight experts were eliminated before aggregating their interval judgments to form a joint and normal probability distribution (Figure 2.3 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 remained cognisant of both elodea's negative and positive growth effects on sockeye salmon.
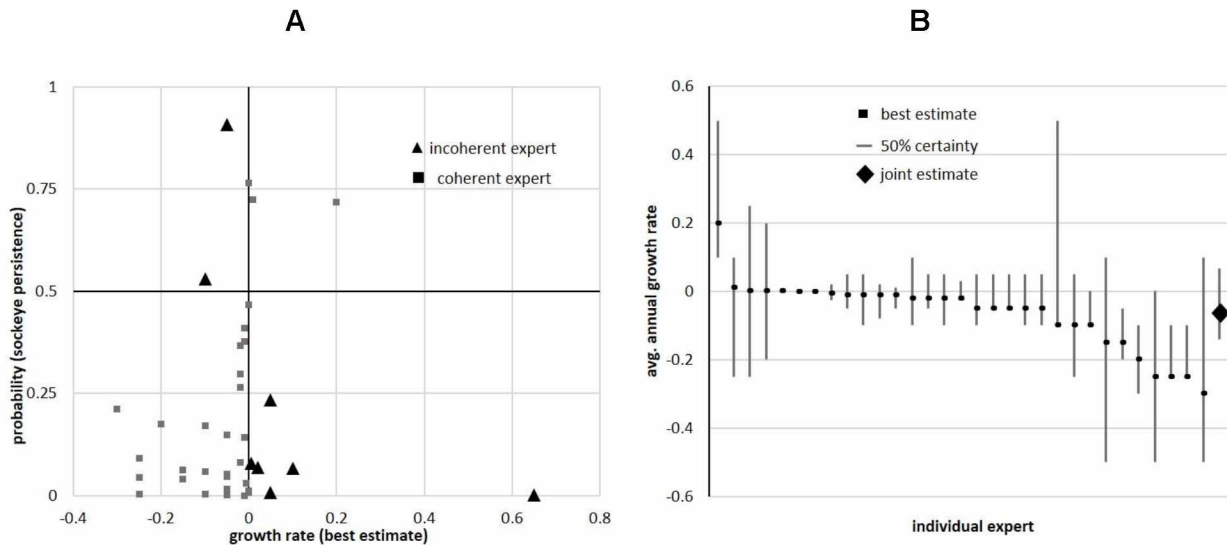
Figure 2.3 Stated annual average sockeye growth rate intervals (25th, mean, and 75th percentile) for sockeye salmon in elodea-invaded habitat by individual experts.

2.5.2 Potential economic loss

The medians of the resulting distributions related to Equation 2.3 and 2.4 are the most probable results. The 90% uncertainty range provides a measure of variation surrounding the median. The following results are in 2015 USD. Figure 2.4 illustrates the non-discounted annual loss in consumer surplus over the 100-year time period for Bristol Bay. Annual loss was not only increasing it is also became more uncertain in future years. Also, the 90% uncertainty bars extended below the horizontal zero damage line, consistent with expert opinion of positive sockeye growth and positive net benefits to consumers.

Equation 2.3 was used to calculate the net present value of potentially lost natural capital which amounted to a median of $3.8 billion for all five regions combined (90% CI: –$4.6 billion in net benefits, $20.0 billion in damages) (Table 2.6). The associated mean NPV was equal to $5.1

billion, indicating that damages were skewed towards positive damages. In addition, a more detailed look at the NPV distribution and 90% uncertainty range revealed that despite the 35% probability of positive ecosystem services (negative damages), the upper uncertainty bounds reflected significant damages. Considering this loss in natural capital, the associated constant annual loss in ecosystem services for all five regions combined amounted to a median loss of $142.3 million annually (90% CI: –$144.4 million in net benefits, $577.3 million in damages) (Table 2.6). Across the five regions, this estimate ranged between a median of $0.1 million in damages in the Kuskokwim and $96.7 million in damages in the Bristol Bay (Table 2.6). 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 loss to a potential elodea invasion ranged between 21% and 43% of past wholesale value (McDowell Group, 2015).
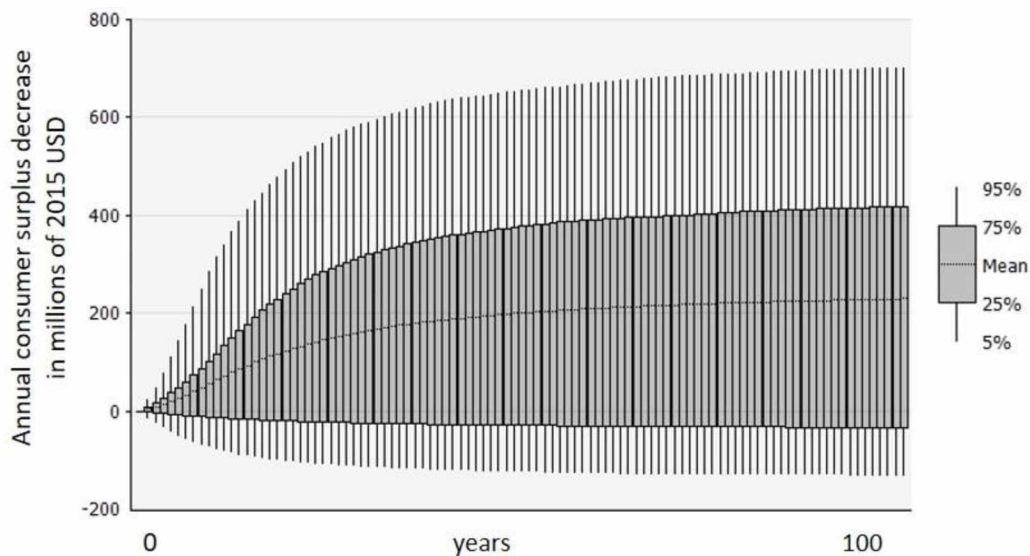
Figure 2.4 Annual non-discounted consumer surplus loss over the next 100 years assuming Bristol Bay is invaded by elodea and remains unmanaged.

Table 2.5 Potential damages to commercial sockeye fisheries by region ($ million)

Region	Change in ecosystem services (NPV$_{annual}$)			Change in natural capital (NPV)		
	Median	5%	95%	Median	5%	95%
Bristol Bay	96.7	−101.0	401.6	2,584.1	−3,175.8	13,957.5
Cook Inlet	18.0	−26.1	95.0	490.2	−834.4	3,196.9
Gulf	13.9	−17.3	56.3	372.7	−547.8	1,920.7
Kodiak	5.9	−8.5	38.8	163.3	−267.7	1,283.5
Kuskokwim[d]	0.1	−0.3	1.0	2.9	−7.8	34.3
Total	141.3	−144.4	577.3	3,795.0	−4,589.5	20,029.7

Figure 2.5 illustrates how ecosystem service loss varies across Alaska's most productive sockeye salmon fisheries. Reasons for the differences are varying regional characteristics discussed above. The Bristol Bay shows the largest economic impact followed by Cook Inlet, Gulf, Kodiak, and Kuskokwim regions (Figure 2.5, Table 2.6). Important to note is that across all regions, the most probable outcomes are showing positive damages.
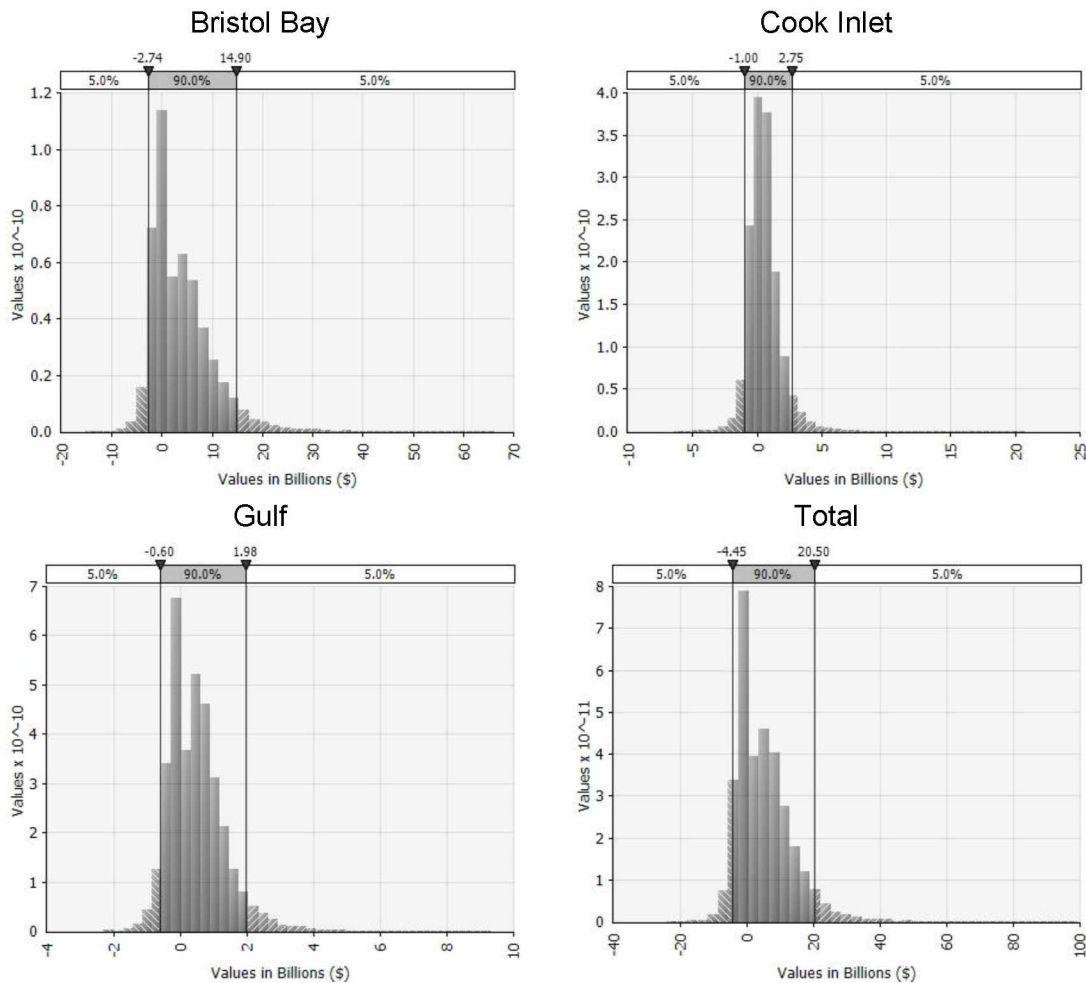
Figure 2.5 NPV distributions for the most important sockeye fisheries and all Alaska sockeye fisheries combined. Dark gray shows 90% certainty range.

2.5.3 Sensitivity analysis

The SEJ-derived annual average sockeye growth rate 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 in the first percentile (-0.37) increased the mean NPV by over $8 billion, while some of the largest growth rates in the 99th percentile (0.27) decreased the mean NPV by $8 billion to -$3.4 billion in net benefits. Additionally, the discount rate and Bristol Bay wholesale price for frozen sockeye product contributed less to the variance compared to the growth rate (Table 2.7). A Bristol Bay price assumption of $18.59/lbs increased NPV by $4.4 billion, whereas $0.82/lbs reduced NPV 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

whole sale prices in other regions not shown (Table 2.7).[12] As expected the sockeye growth rate and discount rate both were negatively correlated with NPV whereas wholesale prices were positively correlated (Figure 2.6). The effect of positive sockeye growth rates on the mean NPV was reduced by the harvest constraint, creating a convexity of the solid line in Figure 2.6 above the 70th input percentile. Initial harvest assumptions were not significantly contributing to variance in NPV.

Table 2.6 Sensitivity of annualized damage estimates to parameter assumptions with the largest influence on simulation outcomes

	% Contribution to variance	Change in mean NPV (billions 2015 USD) [a]	
		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.

Simulation results are also sensitive to assuming different types of sockeye growth underlying elodea's effects on sockeye salmon. Figure 2.6 shows the mean harvest over time for negative growth rates (A) and positive growth rates (B). The linear growth of Scenario 1 results in a sharp and linear drop in harvest, whereas logistic and exponential growth both are non-linear with more and less moderated declines respectively (Figure 2.6). As expected, under linear growth, harvest changes more rapidly causing greater variance in the damage estimates (Table 2.8). Linear growth assumptions also shift the NPV distribution furthest towards positive damages more than doubling the median to $7.9 billion (Table 2.8). The exponential growth assumption also increase the mean NPV to $6.4 billion but less pronounced than linear growth assumptions. The 90% uncertainty bounds are narrowest for assuming logistic growth.

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[12] A test using a triangular distribution with a peak of -4.82 lead to median damages within 0.1% of the shown result.
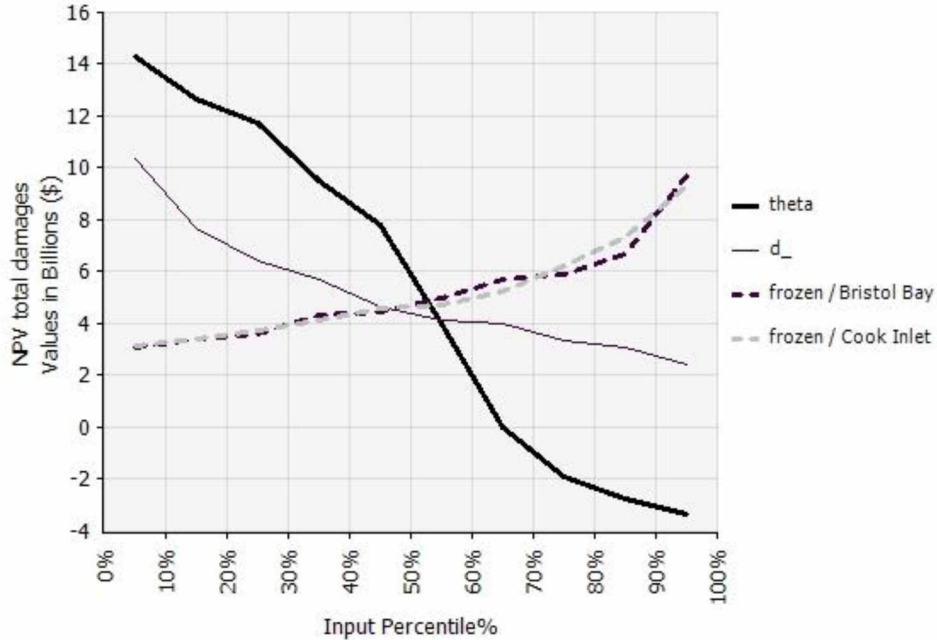
Figure 2.6 Change in mean NPV for all regions combined dependent on percentile changes related to the three parameters contributing the most to variance in the NPV distribution.

2.6   Discussion

This study offers a damage forecast related to elodea's effect on sockeye salmon fisheries that stands in stark contrast 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 (Rosaen et al., 2012; Rothlisberger et al., 2012). In their highest of four scenarios, Rothlisberger et al. (2012) estimated the cumulative damages related to Dreissena mussels invading the Great Lakes through marine shipping at $2.16 billion over the next fifty years. This estimate is $750 million more than the associated benefits related to transportation savings by the shipping industry, and as such offsets most of the invasion damages. In contrast, this study estimated the cumulative mean damages to commercial salmon fisheries in Alaska to amount to $3.09 billion over the next fifty years.[13]

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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.

This study offers several contributions. First it explicitly addresses uncertainty in the predicted damage distributions by applying a unique coherence check for vetting expert opinion. The presented approach is more conducive to a larger expert pool because it does not require probabilistic statements and avoids the use of seed questions, which are often difficult or impossible to frame for experts from different fields. Thus, the multi-method 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 (Clemen, 2008; Hammitt and Zhang, 2013; Morgan, 2014; O'Hagan et al., 2006). Besides the simple application of the equal weights method for post-elicitation, the presented 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, generally found to be a challenge for management (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 publically available data on fish harvest and wholesale prices. This is a more reliable method compared to economic valuation techniques based on hypothetical stated preferences such as contingent valuation methods (Freeman, 2003). Fourth, the study is in contrast to most economic invasive species assessments that estimate damages after substantial and often irreversible injury occurred to native ecosystems (Knowler, 2005; Rothlisberger et al., 2012).

The sensitivity analysis showed that results are robust considering the assumptions made. However, for the following reasons, the median damages could be underestimated. First, the study only includes sockeye salmon, which amounts to over half but not all of the value of Alaska salmon (Knapp et al., 2007)[14]. Second, the analysis leaves out potential effects on other sectors such as recreational or subsistence fisheries, which combined can amount to more than twice the net economic value attributable to commercial salmon fisheries (Duffield et al., 2013). Third, the

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

study does not quantify the effects of elodea on other ecosystem services. For example, there is evidence that elodea affects nutrient cycling (Ozimek et al., 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 (unpublished data). Some of these limitations also underline that the true value of ecosystems cannot solely be expressed in monetary units.

Fourth, potential damages to producers are not accounted for by the framework, ignoring the income effects to fishermen for example. A production function approach, where habitat quality is a direct input into salmon production, could measure welfare changes to producers (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. Lastly, the presented damages also do not include the potential cost of managing elodea, thus, do not provide a full accounting of the social costs of a potential invasion. Additionally, a decision analysis that takes the human-mediated spread via floatplanes into account would further improve region-specific estimates.

Ideally, damage assessments would be based on empirical evidence of economic and ecological changes before and after invasions while controlling for different drivers of ecosystem and human system conditions. However, while the data needs would be enormous, data collection could only occur under experimental settings questioning the validity of the results in practice or after the invasion occurred, making the value of prevention irrelevant. Obtaining expert knowledge provided a feasible workaround to data limitation, while being able to explicitly quantify uncertainty in the estimates. However, it lead to further simplifications in the model. For example, 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 (unpublished research) 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 effects 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). The elicited growth rates were within $\theta \leq 1$, and meant that salmon population dynamics are not believed to be oscillating or unpredictable in the long-term and instead result in smooth population dynamics over the 100-year time horizon (Haddon, 2011). This assumption is consistent with model selection described earlier. 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 upon.

Not surprising is that 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 reduce the range of damages estimated. Additional analysis is required to quantify the expected value of such information aimed at reducing uncertainty in the estimates (Peterman and Anderson, 1999).

2.7 Conclusion

Even though the range of potential damages estimated by this study is large, the most probable damages of $142 million annually suggest that substantial investment is justified to prevent aquatic invasive species from gaining a foothold in Alaska. Considering the attention and investment the invasive species threat in the Great Lakes has received in the past decade, the much larger damage estimate by this study raises the question whether large invasive species management investments are justified in ecosystems that will never return to an unimpaired state. Moreover, study results 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 (Pinsky et al., 2009). With the invasive species problem in its infancy in the Arctic and Subarctic, society still has the opportunity to take prevention seriously.

On a local and regional policy level, this study is able to more broadly inform policy decisions that try to address society's trade-offs related to economic development in the largely intact ecosystems of the Arctic and Subarctic. The introduction of invasive species through economic development can lead to varying effects on a range of stakeholders (Carey et al., 2016; Touza et al., 2014). For example, non-renewable resource development remains a critical economic sector in the Arctic and Subarctic, yet non-renewable development often conflicts with existing ecosystem-based sectors such as fisheries (Larsen and Fondahl, 2014). Policy decisions on such development are more informed if potential costs of invasive species are internalized, showing which stakeholders bear the cost and benefits of the policy decision.

On a different note, the link between the marine and terrestrial sides of salmon ecosystems requires increased collaboration between land management agencies targeting invasive species and fisheries. Not only does the study have potential to raise awareness about the threats of elodea among fishermen and seafood processors, but it can also help design market-based conservation mechanisms providing continued funding to protect productive ecosystems (Engel et al., 2008). Private investment in invasive species management in particular can be useful for cases like elodea management in Alaska, where resource managers tend to have sole responsibility. This sole responsibility can "crowd out" private investment as evident in Alaska where private funding contributes little to active invasive species management with particular funding gaps for prevention (Finnoff et al., 2005; Schwörer et al., 2014).

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2.9 Appendix

Local expertise	Salmon expertise	Other fields of expertise	Qualifications
no	yes	no	Fish biologist
no	no	yes	Fishery Biologist
yes	yes	no	Fishery Biologist III
no	no	yes	Fishery Biologist
yes	yes	no	Fishery Biologist IV
no	yes	no	Fisheries Biologist
yes	yes	no	salmon Chugach Forest
yes	yes	no	Fishery Biologist II
yes	yes	no	Fish and Game Coordinator, Comm Fisheries
no	no	yes	Quantitative ecologist
no	yes	yes	Aquatic ecologist
yes	yes	no	Ecologist, invasive species,
yes	yes	yes	limnologist
no	yes	no	Fishery biologist
yes	yes	no	Fishery Biologist II
yes	yes	no	Fishery Biologist (Kuskokwim)
yes	yes	no	Fisheries Scientist II
yes	yes	no	Cordova Fisheries Biologist
no	yes	no	Fisheries Biologist I
no	yes	yes	wetland ecology, Kenai salmon
no	no	yes	Salmon expert
yes	yes	no	Fishery Biologist II
no	no	yes	Invasive species specialist
yes	yes	no	Fishery Biologist IV
no	yes	yes	conservation ecology
yes	yes	no	salmon in Prince William Sound, and herring, etc.
no	no	yes	Ecologist, invasive species,
no	yes	yes	invasives, aquatic ecosystems
no	yes	no	Fisheries Biologist
yes	yes	no	Fisheries Scientist I
no	yes	no	Fisheries biologist
yes	yes	no	Alaska salmon, freshwater habitat, aquatic ecology
yes	yes	yes	salmon and invasives Columbia River
yes	yes	no	Fishery Biologist III
yes	yes	no	Fishery Biologist III
yes	yes	no	Finfish Research Supervisor
no	no	yes	Mat-Su salmon and pike, invasive species, aquatic ecology
yes	yes	no	Fishery Biologist III
yes	yes	no	Fishery Biologist II
no	no	yes	invasive aquatic plants, limnology, aquatic ecology
yes	yes	no	Fisheries Scientist I
yes	yes	no	Fishery Biologist III
yes	yes	no	Fisheries Scientist II
yes	yes	no	Fishery Biologist III
yes	yes	no	Fisheries biologist

Chapter 3. Aquatic Invasive Plants Alter Recreation Access for Alaska's Floatplane Pilots: an Application of Stated Geographic Preferences to Economic Valuation[15]

3.1 Abstract

This article presents a contingent valuation study for assessing potential recreational damages by Alaska's first known aquatic invasive species, *Elodea spp*. Using data collected through an online mapping tool geared towards pathway analysis, a recreation demand model was estimated using multinomial logit and probit specifications. The lost trip value to the average Alaska floatplane pilot whose destination is an elodea-invaded lake is $185 (95% CI: $157, $211). The result has important policy implications for protecting remote and pristine freshwater resources. It informs not only resource management decisions but also provides an incentive for floatplane pilots to assure the resources they value remain protected from invasive species. This study is the first to estimate ecosystem service loss associated with the floatplane pathway's long-range dispersal of aquatic invasive plants. Important policy implications related to natural resource management and payments for ecosystem services are laid out.

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[15] Schwoerer, T. 2017. Aquatic Invasive Plants Alter Recreation Access for Alaska's Floatplane Pilots: an Application of Stated Geographic Preferences to Economic Valuation. Prepared for submission to Ecological Economics.

3.2 Introduction

Invasive species are an increasing threat to the health of aquatic ecosystems worldwide. Biological invasions are reducing the ecosystem services attained by the public and the commercial sectors dependent on productive ecosystems such as recreation and fisheries (Nunes and van den Bergh, 2004; Rothlisberger et al., 2012). Invasive species in conjunction with human altered ecosystems are also the main contributors to biodiversity loss (MacDougall and Turkington, 2005). Once established, some invasive species cause environmental damage, economic loss, and harm to human health, threatening local livelihoods that depend on healthy ecosystems (Wilgen et al., 2001). The estimated annual management cost of the approximately 50,000 invasive species in the U.S. alone is at least $137 billion in 2012 dollars (Pimentel et al., 2005). Yet that estimate is regarded by many economists as inaccurate because it does not account for adaptations and interactions between society and the environment and does not capture non-market losses (Finnoff et al., 2010). Further, such studies are unable to inform policy makers about the value of prevention and the economic risk of letting invasions spread into still pristine ecosystems such as those found in Alaska. Strategies to prevent new introductions and reduce current and future damages of existing invasive species warrant interdisciplinary approaches to inform policy at local and global scales. The research presented here is aimed at better understanding local values at risk as aquatic invasive species spread to remote waterbodies in Alaska, and underlines the increasing need for informed policy to protect these pristine ecosystems.

Information on the social costs and benefits related to potential management actions is essential for informing policy and efficiently allocating resources (Pearce and Nash, 1981). The application of environmental valuation allows for assessment and integration of non-market values in cost benefit analysis, and is increasingly being used to inform natural resource management decisions (Bockstael et al., 2000). Among the valuation methods used are those which model human behavior. Of those, the random utility model has had a long and successful history of application within the area of recreation demand analysis (McFadden, 1973; Train, 1998). Past studies have used travel cost models (TCM) to estimate benefits derived from sport fishing (Carson et al., 2009; Layman et al., 1996), forest recreation (Bujosa Bestard and Riera Font, 2010; Willis and Garrod, 1991), and for estimating the non-market damages of invasive species (Nunes and van den Bergh, 2004). The application of non-market valuation in the context of aquatic invasive species has been centered around hedonic valuation to estimate the effects of invasions on lake front property values (Halstead et al., 2003; Horsch and Lewis, 2008).

Often, recreation demand models are specified using a combination of revealed and stated preference data (Adamowicz et al., 1994; Englin and Cameron, 1996; Hensher et al., 1999). Capturing revealed preferences on how people decide where to recreate has become more advanced in recent years with the onset of GPS tracking devices and mobile phone records. More traditionally, travel diary surveys are used for this purpose. A common challenge associated with all techniques is the question of how complete the records are (Rieser-Schüssler and Axhausen, 2014). The travel diary approach provides reasonable completeness with low marginal cost over longer data collection periods, but high upfront cost for the researcher developing the data collection tool. An additional hurdle is related to high response burden that can negatively affect response rates (Rieser-Schüssler and Axhausen, 2014).

These approaches are often time consuming because they require elaborate survey designs for the estimation of damages, and resource managers often need the information within a shorter timeframe. The need for timely information is particularly acute for the management of invasive species, as timely action decreases long-term management costs and increases management success (Leung et al., 2002). In these situations, a simplified approach to valuation that ideally combines economic valuation with researching the invasive species pathway can accomplish several objectives at once. This study aims at such a multi-objective approach to data collection. It was motivated by the recent discovery of Alaska's first documented freshwater aquatic invasive plant *Elodea spp.* (elodea) in Anchorage's Lake Hood, the world's busiest floatplane base. Known infestations are primarily in urban lakes and are being distributed by floatplanes to remote destinations across the state where the explosive and dense invasive plant growth creates safety hazards for pilots (Hollander, 2014). The presence of aquatic vegetation at Lake Hood has been a safety concern for pilots and was the primary reason for implementing continued vegetation removal (CH2MHILL, 2005). Also, elodea's explosive and dense plant growth can prevent pilots from accessing places pilots want to land for recreational and other purposes. This study is the first to measure the economic loss related to lost access due to floatplane-introduced aquatic weeds.

Since Alaska is mainly roadless, small single engine propeller planes play a large role in meeting commercial and private transportation needs (Gray, 1980). Alaska has six times as many pilots and 16 times as many aircraft per capita compared to other U.S. states (The Ninety-Nines, 2016). During summer months the landing gear of many single engine planes is converted from wheels or skis to pontoons. A large portion of floatplane operations are associated with small

commercial air carriers that serve backcountry recreationists, remote lodges, and private charter demand to remote residences.

Based on resource managers' need to quickly understand the floatplane pathway and have information on the potential economic damages, the research objectives for this investigation were two-fold. The primary objective was to identify floatplane destinations across the state to inform detection efforts. The secondary objective was to estimate potential recreational use losses for floatplane owners to inform management decisions. The outcomes can then be integrated into a formal risk and decision analysis. For the purpose of this paper, only the analysis pertaining to the damage assessment is presented.

This study developed an online mapping tool to identify flight destinations and to estimate damages using a choice-based recreation demand model. The approach extends exploratory research on the floatplane pathway conducted earlier and borrows from the natural resource damage literature (Carey et al., 2012; Hausman et al., 1995). Results indicate that elodea may result in significant lost trip value for recreational floatplane pilots in Alaska. The article closes by discussing the limitations of the approach and important policy implications.

3.3 Methods

The methodology for this study is structured into three parts. The first describes the survey instrument used to gather geographic preferences from floatplane pilots. The second details how the dataset for empirical analysis was constructed. In specific, publicly available geographic data on recreational hunting success was integrated with the survey data to further describe varying site characteristics. The third specifies the recreation demand model used for empirical analysis.

3.3.1 Data collection

A stratified random sample of 1,015 floatplane-certified pilots residing in Alaska was drawn from the population of 2,625 pilots using the publicly available Airmen Certification Releasable Database published by the U.S. Federal Aviation Administration (FAA). This database includes

the name and physical address of pilots and their certifications (FAA, 2015).[16][17] The sample frame was divided into a rural strata including all 271 rural pilots and several urban strata that were drawn proportionally (Table 3.1). Alaska's main population centers were determined to be in the urban strata and included the Cities of Fairbanks and North Pole, Municipality of Anchorage and cities of Palmer and Wasilla, Kenai Peninsula Borough, and City of Kodiak.

Table 3.1 Stratified random sample

Strata	Population of floatplane pilots	%	Sample	%
Municipality of Anchorage, Cities of Palmer and Wasilla	1,733	66%	548	54%
Kenai Peninsula Borough	227	9%	72	7%
Cities of Fairbanks and North Pole	342	13%	108	11%
City of Kodiak	52	2%	16	2%
Urban total	2,354	90%	744	73%
Rural total	271	10%	271	27%
Total	2,625	100%	1,015	100%

The survey was administered between December 2015 and May 2016. Pilots were first contacted using a letter of invitation which included the survey URL and $2 incentive payment. This was followed by a post card reminder, and finally a third reminder including a paper copy of the survey with a paid mail return option (Dillman, 2007). The hard copy allowed respondents with no or slow internet to respond. As of 2014, 87% of Alaska households had Internet access (U.S. Census Bureau, 2017). The availability of internet should not be expected to influence floatplane flying behavior.

The web survey contained three parts. The survey first asked respondents whether they are familiar with elodea and the safety hazards the plant can create for floatplane operations. For respondents not familiar with elodea, the survey informed pilots where elodea would most likely be expected and made pilots aware of increased risk of turning rudders inoperable due to entanglement. The second and main part included an electronic mapping tool that allowed pilots

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[16] According to the FAA, opt-out rates for not wanting to release personal data in a public database are minimal.

[17] Southeast Alaska was excluded for several reasons. Floatplane bases are almost exclusively in saltwater, minimizing risk of freshwater invasive species transfer. So far, aquatic invasive species have not been found in Southeast Alaska. Only 8% of Alaska's floatplane-rated pilots reside in Southeast Alaska.

to precisely identify their flying destinations and avoid spatial ambiguity with respect to their trip locations. Respondents were asked about their home base and then asked to mark their 2015 first-leg freshwater flight destinations (Figure 3.1). For each destination, pilots were asked to mark the landing spot on an electronic map. Then, a pop-up menu asked the pilot to state the 2015 annual flights to the destination and select one of two statements: 1) *I would **not** land here if dense vegetation in the landing zone*, and 2) *I would land here if dense vegetation in the landing zone. With dense vegetation, how many flights would you still make?* (Figure 3.1). To state frequency of trips, a small drop-down menu was used with the following trip intervals: less than 10, 10-25, 25-50, 50-75, 75-100, 100-200, 200-300, more than 300. The median of each interval was used for empirical analysis. The third and last part of the survey asked questions about the planes and operating cost as well as brief questions on personal demographics.

The TCM in its traditional form measures nonmarket values associated with existing recreation use, but here it is extended to include a set of hypothetical questions where pilots are asked to state the number of trips they would take given site quality changes (Englin and Cameron, 1996). A panel dataset was used for analysis where the pre-invasion actual flight information from 1) above was combined with information on post-invasion contingent behavior stated in 2) above (Englin and Cameron, 1996; Hynes and Greene, 2013). Potential problems with this approach relate to respondents' difficulty of remembering their recreational activity from a year ago, and the hypothetical nature of the stated behavior. The development of the survey instrument was conscious of respondent burden and thus kept the mapping exercise as simple as possible. This approach had obvious trade-offs as it prevented the instrument from becoming more complex—complexity that could have enabled the collection of more detailed information about their destinations, decision making, and flying behavior.

While the approach did not account for an individual pilot's substitution of new landing sites for his/her existing landing sites, it does account for substitution between landing sites each pilot is currently familiar with. Even though the survey instrument did not specifically ask for a second best destination, assuming the pilot's existing landing site becomes invaded, the approach was able to estimate the change in trip demand among the pilot's existing set of destinations. Pilots like to fly to locations with which they are familiar. As a consequence the pattern of substitution favors each pilot's existing (pre-invasion) set of locations. Key informant interviews with a subset of respondents were used to refine the survey and to learn about respondents' answers. For example, pilots mentioned that they would reduce their trips to destinations with

shallow water depth that are more prone to elodea-invasion, and increase trips to lakes with deep water, where elodea is unable to grow. Therefore, contingent post-invasion flying behavior could lead to a downward shift in trip demand for some destinations while it could lead to an upward shift in other destinations.
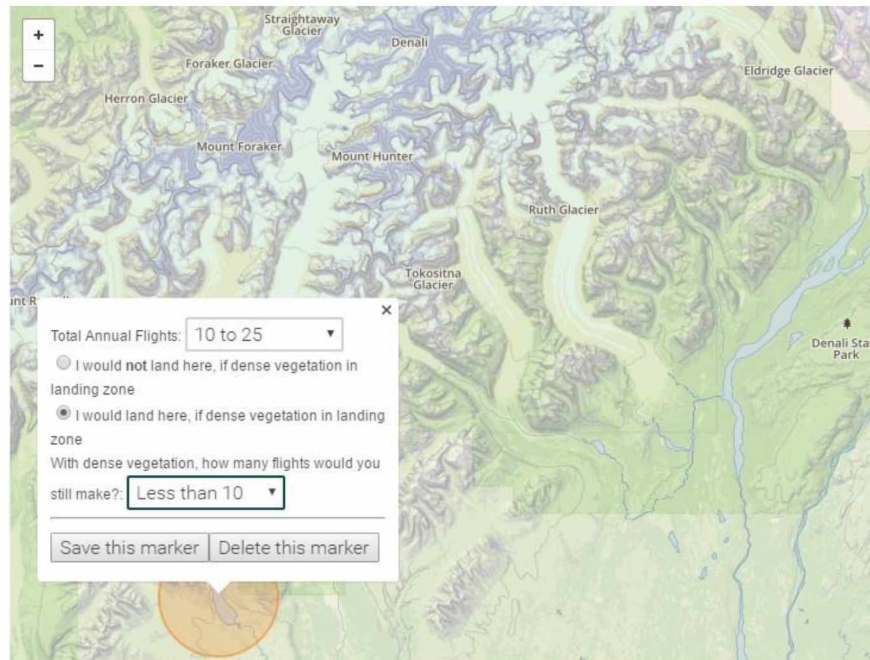
Figure 3.1 Online mapping tool for eliciting floatplane destinations.

Alternative approaches to data collection were not considered because they require more time (e.g. discrete choice experiments) or rely on the recording of recreation activity for a distinct pre and post invasion period (e.g. diaries) (Carson et al., 2009; Hanley et al., 2002). Despite the obvious advantage of discrete choice experiments to predict substitution patterns, they are more complex. This complexity would have placed an additional burden on respondents, particularly for pilots who fly to many destinations. Diaries also require often unknown information on the invasion status of the destinations to distinguish invaded from un-invaded recreation sites.[18] Since the survey's main purpose was not to estimate non-market damages but instead to identify remote floatplane destinations, the decision was made to keep the survey instrument as user-friendly as possible.

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[18] In 2016, only 16 sites were known to have been invaded by elodea in Alaska, only ten of which are accessible via floatplane. Thus, the diary approach would have been unrealistic given the small sample size.

3.3.2 Model specification

The pilot's decision was composed of two-parts.[19] First, the pilot chose where to fly to followed by the number of annual trips to that chosen location. In the contingent post-invasion part, the pilot decided whether he would continue to the elodea-invaded destination, reduce his annual trips, or stop flying to the destination. By using the number of flights as a frequency weight in the estimation process, the decision was reduced to one level.[20] The econometric specification of this decision followed random utility theory (Manski and McFadden, 1981). It defines overall utility of an alternative j to individual n as U_{nj}, comprised of observable utility V_{nj} and the unobservable utility, ε_{nj} thus $U_{nj} = V_{nj} + \varepsilon_{nj}$ (McFadden 1973). The measured component of utility in linear form for individual n was

$$V_j = \beta_{0j} + \beta_{1j}X_{1j} + \beta_{2j}X_{2j} + \beta_{3j}X_{3j} + \beta_{4j}X_{4j} + \beta_5 X_{5j} \qquad (3.1)$$

where β_0 represented the average of all the unobserved sources of utility and $\beta_{1,...,5}$ were coefficients that measured the contribution of attribute $X_{1,...,5}$ to the observed sources of relative utility. The attribute X_1 was a dummy variable that indicated the hypothetical response related to a pilot's contingent post-invasion flying behavior. Attributes X_2 and X_3 were proxies for sheep hunting and moose hunting quality observed in alternative j. The inclusion of hunting quality could explain very inelastic trip demand for destination sites where hunting quality was very high and floatplane access was limited. In other words, the pilot would have continued to fly to the destination despite an elodea-invasion and may have been willing to take more risk during landing or take-off. Lastly, attributes X_4 was the pilot's age and attribute X_5 was the travel cost associated with alternative j.

The choice rule stated that each individual evaluated all alternatives presented to him/her, U_j for $j = 1,...,J$ alternatives in the choice set, compared U_1, U_2, ...,U_J and finally chose the destination alternative with maximum utility max(U_j). The probability of an individual respondent choosing alternative i was equal to the probability that the utility associated with alternative i was equal or greater than the utility of any other alternative, U_j, in the choice set, thus $p_i = p(U_i \geq U_j)$,

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[19] One could argue that there is a third level - flight distance. Respondents indicated small sets of destinations, often falling within one region leaving little variation in distances related to alternative site choices (Table 3.5).

[20] Frequency weights indicate duplicate observations and are integers. If the frequency weight for an observation is equal to three that means that there are three identical observations.

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where i ≠ *j* and *j* ∈ *j* = 1,...,*J*. For example, the model was capable of predicting whether pilots would continue to fly to destinations with high hunting quality despite the occurrence of elodea.

Multinomial logit (MNL) and multinomial probit (MNP) are commonly used to estimate the parameters of models for random utility (Chen et al., 1997; Hausman et al., 1995; Hausman and Wise, 1978; McFadden, 1973). Both MNL and MNP are appropriate for modeling recreation demand because they are models of discrete choice that account for substitution among alternatives. The main difference between the MNL and MNP models lies in the distribution assumption of the unobservable component of utility, ε_{nj}, which leads to different assumptions regarding decision makers' substitution patterns.

In the MNL, the error term is assumed to be independent and identically distributed following a type 1 extreme value distribution and allows the choice probabilities to be easily calculated. It assumes that the ratio of probabilities of any two alternatives cannot change if any other alternative is added or taken away from the set of alternatives in a choice set. Put differently, the pattern of substitution is limited by the Independence of Irrelevant Alternatives (IIA) property. Under IIA, a change in one alternative has the same effect on all other alternatives. Thus, all alternatives are assumed to be equally dissimilar with none being more or less similar to each other (Hausman et al., 1995). As such, when the pilot chose alternative *i* from a set of *J* alternatives, the choice probability equalled the multinomial logit (MNL) specification as follows:

$$p_{ni} = \frac{e^{\beta_n X_{ni}}}{\sum_{j=1}^{J} e^{\beta_n X_{nj}}}$$

(3.2)

where i ≠ *j* and *j* ∈ *j* = 1,...,*J* (McFadden, 1973). Since the IIA assumption can assume a rather unrealistic proportional substitution pattern, the application of MNL to estimate recreational damages deserved particular care.

To test sensitivity of the MNL results, the MNP was used as an alternative approach to relax the IIA assumption. In the MNP, the random component of utility, ε_{nj}, is assumed to be correlated across choices and to follow a multivariate normal distribution. The resulting choice probabilities are given by:

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$$p_{ni} = \int_{-\infty}^{\infty} F_j \left((X_j - X_i)\beta_n + \varepsilon_{nj} \right) d\varepsilon_{nj}$$ (3.3)

where F_j is the joint distribution of the errors. Since the above integral is not closed and is multi-dimensional, estimation of the choice probabilities relies on Monte Carlo simulation techniques such as Gibbs sampling. In contrast to the logit model, the probability ratio of the MNP depends not only on the utility functions for alternatives *i* and *j* but all alternatives, thus relaxing the IIA assumption (Chen et al., 1997).

The welfare changes estimated from either of the two recreation demand models were equal to the total derivative of the utility function (Equation 3.1) with respect to changes in attribute X_1 and X_5, expressed as follows (Hole, 2007):

$$\frac{dX_5}{dX_1} = WTP_1 = -\frac{\beta_1}{\beta_5}$$ (3.4)

Equation 3.4 represents the annual value lost per floatplane trip. If elodea changes accessibility to floatplane destinations, it changes the quality of recreation and other amenities pilots derive from visiting a site. Therefore, the introduction of elodea changes these benefits and changes the ecosystem services consumers derive from a site. Consumer surplus is a measure of these benefits and is identified by the difference between the pre- and post-invasion change in cost that keeps utility—the overall satisfaction of the pilot with the site—unchanged. The per flight loss in trip value can then be aggregated across the population of pilots to reflect the loss in consumer surplus, in other words, the loss in non-market value associated with potential elodea invasions in pilot destinations across Alaska.

For estimating the model, White's robust standard errors were used to make valid statistical inference as data collection possibly caused the explanatory attributes and the error term to not be identically distributed as assumed by the model (White, 1980). For the damage assessment following Equation 3.4, a 95% confidence interval was estimated surrounding the mean using the Krinsky and Robb method with 2000 replications (Hole, 2007; Krinsky and Robb, 1986).

3.3.3 Integrating survey data with other independent variables

Particular care was given to the way the data was formatted for empirical analysis to allow substitution patterns to emerge and proper damage assessment to occur (Hausman et al., 1995). The data was coded as a panel where each panel referred to a set of alternative destinations, one related to pre-invasion and the other to the stated post-invasion stated flights. Each respondent's individual destinations were grouped into eight regions encompassing large watersheds defined by the National Hydrographic Dataset (NHD) (Figure 3.2) (USGS, 2016). This aggregation was necessary for two reasons. First, the data showed more than 700 individual destinations, a number quite large for estimation purposes.[21] Second, the regions closely align with watershed boundaries set for further analysis extending this study to include damages to Alaska's commercial salmon fisheries.[22] A no-fly ninth destination alternative was added. If a respondent stated to reduce or stop flying post-invasion, the no-fly destination alternative accounted for the difference between pre- and post-invasion flights across all destination alternatives. A binary choice variable indicated to which region the pilot flew. Note, within the specific context of discrete choice analysis, the regions would be called recreation sites or destination alternatives. Here the terms alternative and region are used interchangeably. The resulting choice data for each pilot had 18 rows. In the first choice set, there were nine rows (one for each region, including the no-fly region) that describe the flights the pilot took in 2015, and nine rows that show flights in the contingent post-invasion scenario.

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[21] Many econometric software packages limit the number of alternatives in the choice model.

[22] The depicted watersheds encompass freshwater habitat supporting most of Alaska's salmon fisheries.
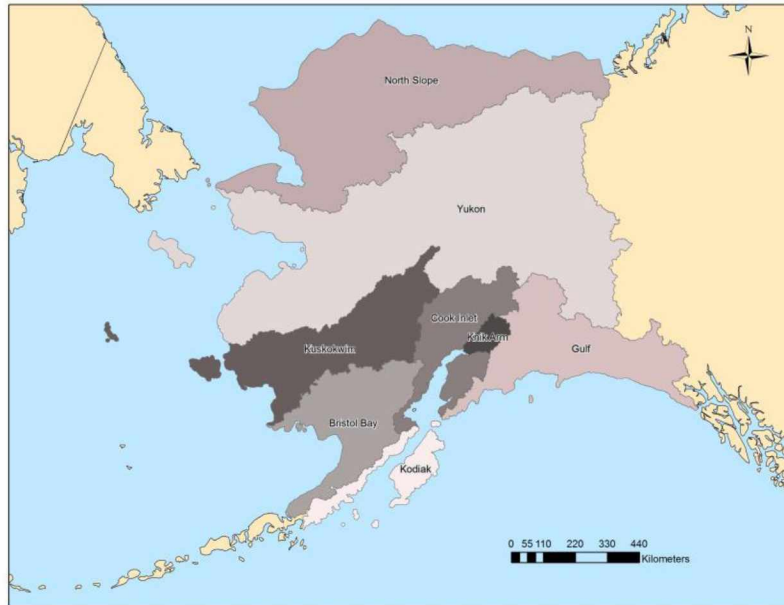
Figure 3.2 The eight regions that form destination alternatives in the recreation demand model.

Estimating the recreation demand model required information on varying destination attributes to explain the choice of recreation destinations. Due to reasons discussed earlier, the survey instrument did not ask about site characteristics or the motivation of pilots. Instead, the approach relied on statewide publically available hunting data to describe the variation in alternative destinations. It is recognized that hunting is only part of what sets one region apart from another and does not describe floatplane activity. Here, the hunting data is solely used as a descriptor of how regions vary. For this purpose data on moose and sheep hunting success by game management unit[23] was used to assign destination attributes related to hunting quality (ADFG, 2016). The level for the hunting quality attributes equalled the mean kill to hunter ratio observed for each individual pilot's destinations within a region (Table 3.2). While hunting success ratios are a good indicator of hunting and wildlife viewing quality and one motivating factor in pilots' decision to fly, there are obviously many more underlying unknown motivational drivers the model was unable to capture. For example, the survey did not collect preferences from the passengers of the responding pilots.

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[23] The Alaska Department of Fish and Game divides Alaska into game management units (GMU) for the purpose of managing game species. These GMUs are aligned with watershed boundaries and are therefore geographic subsets of each region *j*.

Table 3.2 Mean attribute levels by alternative region

Region	Sheep (Success per hunter) [a]	Moose (Success per hunter) [a]	Cost ($) [b]
Gulf	0.24	0.28	474
Knik Arm	0.19	0.16	356
Cook Inlet	0.23	0.19	212
Kodiak	0.00	0.37	1,029
Bristol Bay	0.00	0.28	685
Kuskokwim	0.64	0.59	453
North Slope	0.09	0.39	1,238
Yukon	0.21	0.32	655
Total	0.18	0.29	567

a) Successful kill per hunter for 2015, varies by game management within region. b) One-leg flight cost between home base and respondent destination. Varies by respondent and aircraft type.

The remaining explanatory attributes included pilot age and travel cost. The cost to fly to each alternative region was individual-specific for regions the pilot chose to fly to and estimated for other regions not in the pilot's set of destinations. The stated plane operating cost,[24] pilot's plane type and cruising speed were used to calculate a per km cost for each respondent multiplied by the weighted average of each respondent's Euclidean distances between home base and destinations within region j. Costs associated with destination regions to which the pilot did not fly, were estimated using the pilot's per km cost multiplied by the Euclidean distance between the pilot's home base and centroid of the destination regions not chosen. Table 3.2 shows the mean of the final travel cost attribute levels by region across the weighted respondent pool.

Non-participation in the survey was assumed to be randomly distributed across the population of pilots and was addressed via weighting. Econometric analysis used a frequency weight for each pilot's destination regions for the pre-invasion and post-invasion sets. The frequency weight equalled the number of flights the pilot had taken to each region. The weight was further scaled to the population of pilots in each strata as defined by the sample frame.[25] Since the sample frame did not include information on age, this prevents an adjustment for age.

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[24] Respondents were also asked about their aviation fuel cost, which varies across Alaska, especially between urban and rural areas.

[25] Accounts for the observed proportion of pilots reporting that they did not fly floatplanes in 2015 for each of the strata.

Using flight frequencies as a weight avoided having to model flight allocations among regions and simplified the econometric estimation approach (Hausman et al., 1995).

3.4   Results

Below, the results from the survey with floatplane pilots are presented, followed by the empirical results related to estimating the recreation demand model including the estimation of changes to floatplane trip values.

3.4.1   Survey response

Of the 1,015 initial mailings, fifteen were undeliverable. A total of 444 pilots responded for a response rate of 44%.[26] This high response rate for a mailed invitation to participate in the web-survey may partly be due to heightened awareness of the problem of aquatic invasive species among floatplane pilots. The average web-based respondent took 24 minutes to complete the survey. Considering pilots' awareness of the elodea problem, this length is considered an adequate response burden. A total of 239 pilots report that they flew a floatplane in Alaska in 2015 but only 229 of those provided mapping responses useful for analysis. Of the total respondents, 219 indicated not having flown in 2015, and four respondents did not answer whether or not they flew (Table 3.3). A total of 114 pilots were willing to volunteer regarding monitoring and raising awareness among pilot circles supporting the strong interest among pilots for invasive species prevention and monitoring. Responses from rural areas were proportionally larger, likely due to the oversampling in rural areas at the expense of under sampling in the communities of Anchorage, Wasilla, and Palmer. Responses from other urban areas were proportional (Table 3.3).

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[26] Includes 162 hard copy mail returns.

Table 3.3 Response by strata

	Respondent count	%	Map-response	%	Did not fly	%
Municipality of Anchorage, Matanuska-Susitna Borough	209	47%	127	56%	95	43%
Kenai Peninsula Borough	35	8%	15	4%	19	9%
Fairbanks Northstar Borough	64	14%	33	14%	27	12%
City of Kodiak	6	1%	2	1%	4	2%
Urban total	314	71%	177	75%	145	66%
Rural total	130	27%	44	25%	74	34%
Total	444		221		219	

a) Excludes 233 pilots residing in Southeast Alaska.

Half of the respondents were of retirement age. Respondents' median personal income before taxes in 2015 is $135,000 compared to the most recent statewide median annual earnings of $30,800 (Table 3.5) (U.S. Census Bureau, 2017). Pilots varied most in the number of flights they took in 2015 (Table 3.5). On average pilots reported taking between 30 and 40 flights over a roughly 100 day season with totals ranging from five to over 500 flights.[27] The average respondent's longest flight was 257 km, which is considerably less than the effective aircraft ranges (Table 3.5). On average, pilots carried one to two passengers, and the annual average number of unique destinations to which they flew from their home base is between four and five. The limited number of destinations suggests that most pilots primarily flew to a small number of preferred locations where they were familiar with local conditions. Likewise, there is also a limited number of substitute destinations to which pilots prefer to fly. This result underscores the approach of focusing the economic valuation on existing pre-invasion landing sites rather than new sites The estimated plane operating costs ranged from $0.10/km to $2.97/km with a mean of $0.83/km (Table 3.5). The most frequently flown aircraft among respondents was the Cessna 180 followed by the Piper Super Cub and Cessna 185. A third of all respondents either did not specify an aircraft or selected the "other" category (Table 3.4).

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[27] Key informant interviews showed that flying dates depend on different break-up and ice-up conditions across the state. Due to warmer temperatures observed in recent decades, the season has lengthened and in Anchorage has been 112 days long on average from June 1 to September 20 (Rust's Flying Service personal communication).

Table 3.4 Floatplane characteristics, n=229

Type of single engine plane	Respondent count	Passenger seats	Cruising speed [km/h]	Range [km]	Minimum fetch of destination [a]
Piper PA-17, PA-18, Tailorcraft	49	1	163	493	336 m
Cessna-172 to 206	91	4	253	1325	511 m
DeHavilland DHC-2 Beaver	3	6	230	732	505 m
DeHavilland DHC-3 Otter	0	10	195	1520	645 m
Other and not specified	86	4	216	1030	498 m

a) Estimated using survey responses from this study. Minimum fetch of stated destination waterbodies by airplane type in meters. Fetch is measured by the maximum distance between two points on the perimeter of the waterbody and was estimated using R software (Hollister, 2016).

Table 3.5 Respondent characteristics

	Personal income [a]	2015 avg. # passengers	2015 flights	Pilot age	Number of unique destinations	Max. flight distance (km)	Operating Cost ($/km) [b]
Mean	$ 137,786	1.41	36	58	4.23	257	$ 0.83
Median	$ 135,846	1.00	25	58	3	222	$ 0.75
Mode	$ 135,846	1.00	5	58	1	185	$ 0.78
SD	$ 70,101	1.13	46	11	5	162	$ 0.51
Minimum	$ 25,000	0	5	26	1	3	$ 0.10
Maximum	$ 300,000	6.00	509	94	55	1,000	$ 2.97
Respondent count	229	229	229	229	229	213	229

a) Before taxes. b) Estimated based on cruising speed of plane type and stated operating cost.

Half of the respondents stated that they would no longer have flown to destinations they flew to in 2015 if dense aquatic vegetation would have been in the landing zone (Table 3.6). About 75% of respondents had heard about elodea and reported safety concerns flying to destinations that were shallow and already required caution for landings and take-offs. Follow-up interviews with respondents indicated that pilots identified destinations by taking into account individual lake characteristics such as water depth and terrain features. For example, some pilots considered continuing to land in destinations with larger water depth because elodea invasions would predominately occur in shallower parts of a lake or waterbody. Pilots also mentioned that they would have reduced or eliminated flying to destinations with shallower water depth, as these destinations would be more hazardous to land in, given elodea covered the water surface of the

landing zone.[28] Table 3.6 shows pilot counts for stated changes in flight behavior given elodea invasions would alter accessibility to destinations pilots currently fly to. Scaling survey responses to the population of floatplane certified pilots residing in Alaska, the total number of flights was reduced by two thirds given elodea invaded the landing zones of floatplane destinations identified in the survey (Table 3.6). Key informant interviews also showed that most pilots flew to a destination and then returned to their home base with few flights containing more than one destination after take-off from a home base.[29]

Table 3.6 Recreational pilots' stated change in flight behavior due to invasion, n=229

	Continue flying				Stop flying
	to all their destinations			only to some destinations	
	flight increases to some dest.[a]	no change	flight reductions to some dest.	with flight reductions	
Pilot count (%)	4 (2%)	39 (17%)	36 (16%)	35 (15%)	115 (50%)
Mean % change in annual flights	+120%	0%	-40%	-58%	-100%

a) Flight increases to some destinations are due to flight decreases in other destinations suggesting some degree of substitution.

Through geoprocessing of the destinations respondents reported through the survey, destination characteristics were identified. An important criteria for access via floatplanes is fetch—the maximum uninterrupted water distance between any two points on the perimeter of a waterbody listed in the NHD and excluding glaciers (USGS, 2016). The fetch served as a proxy for accessibility and was used to identify floatplane-accessible waterbodies using the NHD data (Table 3.8). The minimum fetch of waterbodies to which respondents flew was estimated at 336 meters (Hollister, 2016) (Table 3.3).[30] Floatplane accessibility, based on this fetch criteria, differed among regions (Table 3.8). Statewide, about 16% of all waterbodies are accessible by floatplane, given this criteria. The highest proportion of accessible waterbodies, almost half, lay in the Knik

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[28] In addition, weather conditions, pilot skills, and plane models are significant drivers determining access which were not incorporated into the model for reasons discussed earlier.

[29] The potential for introduction of elodea is greatest greatest for the first destination after take-off from urban source locations.

[30] One has to recognize that the pilot's decision to land or not to land on a waterbody is much more complex than fetch, although it is one of the most important features. Additional decision factors include the pilot's flying experience and skill, topography such as tree cover near the lake shore and the surrounding terrain features combined with weather conditions and aircraft type.

Arm region followed by the Gulf and Cook Inlet regions (both 20%). The North Slope and Kuskokwim have similar accessibility (17 and 18%). The Bristol Bay and Kodiak regions have the lowest accessibility with only 10% of waterbodies larger than 336 meters fetch (Table 3.8).

Table 3.7 Total number of flights to destination regions, pre- and post-invasion, scaled to population of pilots

Region	Stated flight count	
	Pre-invasion	Post-invasion
Gulf	2,749	1,654
Knik Arm	7,859	2,343
Cook Inlet	25,036	6,902
Kodiak	135	45
Bristol Bay	4,948	2,212
Kuskokwim	504	186
North Slope	555	260
Yukon	7,155	2,090

Table 3.8 Region characteristics

Region	Waterbody total count [a]	Floatplane accessible [b]	Survey count [e]	Survey % of accessible [c]	Region size in km^2	Accessible/ km^2 [d]
Gulf	51,597	10,510	71	0.7 %	54,366	0.19
Knik Arm	2,019	979	28	2.9 %	12,629	0.08
Cook Inlet	38,165	7,707	187	2.4 %	53,375	0.14
Kodiak	15,271	1,471	41	2.8 %	44,028	0.03
Bristol Bay	126,394	13,086	74	0.6 %	53,297	0.25
Kuskokwim	182,194	30,576	28	0.1 %	75,744	0.40
North Slope	238,274	43,707	93	0.2 %	34,444	1.27
Yukon	360,549	58,033	205	0.4 %	115,544	0.50
Total	1,014,463	166,069	727		443,428	0.37

a) Waterbody count excluding glaciers (USGS, 2016). b) Subset of total count based on floatplane accessibility determined from survey results to equal minimum fetch of 336 m. c) Fourth divided by third column. d) Third divided by sixth column. e) Number of waterbodies respondents identified they landed in.

The survey identified the most floatplane destinations (205) in the Yukon region, which has the largest land mass. Cook Inlet, which is closest to Anchorage where the highest proportion of floatplane pilots reside, showed the second highest destination count (187) (Table 3.8).

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Comparing the count of identified destinations to the subsets of accessible waterbodies based on fetch (Table 3.8 column 4) illustrates the extent to which pilots used each region and revealed the proportion of potential unused destinations. In this context, use rates in Knik Arm, Kodiak and Cook Inlet are higher than those in other regions. Lowest use rate occurred in the Kuskokwim, perhaps since the Alaska Range inhibits flights from Anchorage into this region, and the North Slope perhaps due to the largest distances from urban centers. The density of accessible waterbodies (Table 3.8 column 7) is another characteristic in which regions varied. This index for accessibility illustrates the degree to which pilots would be able to substitute between sites given elodea invasions in their destinations. In this regard, the highest substitutability between sites lay on the North Slope followed by the Yukon region. In the former, there exists more than one accessible waterbody per km^2 whereas in the latter one accessible waterbody exists for every two km^2 (Table 3.8). The destination regions are further described by the observed attribute levels for moose and sheep hunting success as well as flight costs (Table 3.2). The Kuskokwim region has the highest success rates for sheep hunting while the Gulf region has the highest for moose hunting followed by the Yukon and Kuskokwim regions. Flying costs are highest to the North Slope followed by Kodiak, Bristol Bay and the Yukon (Table 3.2).

3.4.2 Empirical results

Multinomial logit and multinomial probit models were fit using maximum likelihood optimization.[31] The coefficients by attribute are shown in Table 3.9 and Table 3.10 for the MNL and MNP models respectively. All coefficients have the expected signs and are statistically significant at the 0.001 level. For calculating the estimated loss in floatplane pilot use values from elodea invasions, statistical significance of the elodea invasion and cost coefficients is of particular importance. This empirical result was supported by more than three quarters of respondents that indicated that they had heard about the spread of elodea in Alaska and were aware of the risk it poses to floatplane safety. Not surprising were the coefficients for moose hunting and sheep hunting success, considering that Alaska has the highest participation rate in wildlife-related recreation by state residents among U.S. states (U.S. Fish and Wildlife Service and U.S. Census Bureau, 2013). The positive coefficient on the age attribute was expected and

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[31]STATA's generalized linear model command (glm of the binomial family with the logit or probit links) was used. This specification results in identical parameter values as using the mlogit or mprobit STATA commands.

reflects that flying is an expensive hobby which is enjoyed by those who are retired and have the disposable income needed to pursue the activity.

The coefficients for the MNL and the MNP models were comparable in sign and magnitude with similar high precision, yet the MNP was more robust than the MNL. This similarity may suggest that the IIA assumption had little consequence as long as sufficient data quality minimizes the amount of unobserved heterogeneity (Hensher et al., 2005). This result was also supported by the consumer surplus changes estimated using both models which again were of similar magnitude (Table 3.11). Additionally, a null model was estimated for both MNL and MNP. In both cases the AIC for the MNL and MNP was equal to 1.14 suggesting that inclusion of the shown covariates results in a better model. Table 3.11 presents the lost trip value per flight to a floatplane destination being elodea-invaded. In order to validate the model, additional willingness to pay (WTP) estimates were calculated for moose hunting and sheep hunting success. In the discussion below, these estimates are compared to two studies containing wildlife-related WTP estimates in Alaska supporting validity of the model (Table 3.11).

Table 3.9 Estimated coefficients applying the MNL for explaining choice of alternative

Attribute	Coefficient	Robust Standard Error	z	p>|z|	95% Confidence Interval	
Elodea invasion	-0.296	0.021	-14.260	0.000	-0.337	-0.256
Cost	-0.002	0.000	-27.770	0.000	-0.002	-0.002
Moose hunting success	1.431	0.127	11.300	0.000	1.183	1.679
Sheep hunting success	2.270	0.078	29.010	0.000	2.117	2.424
Age	0.010	0.001	14.880	0.000	0.009	0.011
Constant	0.398	0.047	8.470	0.000	0.306	0.490
AIC (deviation)	1.0852					
BIC	-1018526					
Log ps likelihood	-53109					

Table 3.10 Estimated coefficients applying the MNP for explaining choice of alternative

Attribute	Coefficient	Robust Standard Error	z	p>|z|	95% Confidence Interval	
Elodea invasion	-0.183	0.012	-15.290	0.000	-0.206	-0.159
Cost	-0.001	0.000	-31.100	0.000	-0.001	-0.001
Moose hunting success	0.836	0.072	11.630	0.000	0.695	0.977
Sheep hunting success	1.279	0.045	28.160	0.000	1.190	1.369
Age	0.006	0.000	14.700	0.000	0.005	0.007
Constant	0.266	0.028	9.440	0.000	0.211	0.321
AIC (deviation)	1.0850					
BIC	-1018552					
Log ps likelihood	-53096					

Table 3.11 Estimated change in consumer surplus per flight

	MNL		MNP	
Attribute	Mean	95% C.I.	Mean	95% C.I.
Elodea invasion	-$178	-$205, -$151	-$185	-$157, -$211
Moose hunting success	$861	$736, $981	$848	$726, $965
Sheep hunting success	$1366	$1215, $1531	$1298	$1162, $1447

3.5 Discussion

This study showed that elodea invasions could significantly affect floatplane pilots' trip values partially resulting in trip reductions and eliminations due to clogged landing zones. Additionally, the applied non-market valuation approach showed that a survey primarily aimed at collecting information on invasive species' pathways can also be used to estimate changes in ecosystem services that are pathway-related. The secondary objective of economic valuation was achieved by combining respondents' stated pre-invasion actual flight information with information on post-invasion contingent behavior, plane operating costs, and other data sources. More than three quarters of all surveyed pilots would either stop flying or reduce flights to destinations they currently fly to, given elodea invades landing zones. This result is not surprising considering that

the average pilot flies to less than five destinations, suggesting pilots prefer a limited number of destinations. Key informant interviews showed that the presence of private property or risk averse flying behavior play a role. For example, exploring unknown destinations comes at a risk for pilots not familiar with water depth and other localized conditions important for flight safety. This fact helps to underscore why the survey focused on collecting data on preferred destinations over hypothetical alternates. Respondents reported having only a small set of destinations to which they frequently fly. Avoiding questions about hypothetical alternate destinations may have helped to reduce the potential for hypothetical bias. With the data at hand, however, there is no way to test for this possibility but it is one aspect where the research could be expanded and test whether this hypothesis is true.

Survey response was much higher than expected considering pilots were first contacted through a mailed invitation. The high response rate is related to the fact that most pilots are aware and concerned about the problem of invasive aquatic species in Alaska. Elodea has received much media coverage throughout the state especially after it was found in Lake Hood. Also, pilots were assured their specific geographic information would not be shared in public, thus their private recreation destinations would remain confidential. This result is reason to believe that pilots revealed accurate geographic information, which was also enabled through the survey's electronic mapping tool and the interactive nature of the survey.

Even though a non-response survey to address specific selection bias was not conducted, the characteristics of the sample and a t-test suggest that the sample is representative of the larger population of pilots. For the t-test, the most recent American Community Survey's five-year estimates of median household income and per-capita income were used to test statistically significant income differences between Census-designated places with non-respondents and respondents (t-test, $p = 0.0008$ and $p = 0.004$ respectively) (U.S. Census Bureau, 2017). This result indicates that based on income, which is an important contributor to whether pilots are able to fly or not, non-respondents are likely similar to respondents.

Advantages of the modeling approach, beyond the mentioned combination of actual pre- and contingent post-invasion behavior, are centered upon integrating existing place-specific data to describe how the destinations vary. This approach reduces the response burden by eliminating additional survey questions that would be necessary to directly link motivational decision variables to destination choice. Since the presented approach does not establish this link, data quality related to location-specific data is of particular importance. Data on hunting success was used

because of its high data quality. Unlike other recreation-based data that is derived from angler and visitor surveys (Fix, 2009; Romberg, 2014), the hunting data reports hunting success through the reported actual kill by specific location. As such, the hunting data is more reliable as it entails specific information about geographic location and the recreation outcome (ADFG, 2016). Additionally, since hunting success was included as a covariate, the non-market values related to hunting were also estimated and compared to historical estimates for model validation.

In specific, comparable consumer surplus values have recently been estimated related to hunting and wildlife viewing considering all means of transportation in Alaska, not just floatplanes as in this study. Per trip estimates range between a mean of $438 ($268) per resident hunter (viewer) and a mean of $765 ($858) per visiting hunter (viewer) (Buckley, 2014). Net economic values for residents hunting bear amounted to $467 per person and trip in 2016 USD again considering all modes of transportation (Miller et al., 1998). This study's higher estimates of $861 for moose and $1366 for sheep hunting success are comparable considering that floatplanes are the most expensive transportation mode. In addition, while this study measured hunting success per-flight, the mentioned studies estimated hunting or wildlife viewing per-person. Considering an average of one to two passengers per flight observed in this study (Table 3.3), the hunting-related WTP estimates presented here are comparable to past research estimates and thus validate the model (Table 3.11).

The welfare losses estimated here are at best lower bounds to the actual economic losses for several reasons. First, this study only looked at a portion of the floatplane sector and has not specified potential use losses to commercial floatplane operators. Second, the preferences and economic values of passengers were not considered. Third, this analysis concentrates on travel cost primarily as relating to airplane operating cost, ignoring the value of time to pilots. Accounting for travel time would generally use a fraction of the wage rate to equal the opportunity cost of time. Yet, one can argue that travel time for recreation has little to do with labor supply decisions, particularly if half the sample is retired.

Since this study only looks at floatplane travel, it prevents estimation of the opportunity cost of time by investigating transportation mode choices that could reveal how people trade-off between cost and time based on differences in observed mode speeds and costs. Yet, for most of the destinations identified by this study, floatplanes are the only transportation option. This limitation likely underestimates the consumer surplus presented because the cost coefficient would have been larger given the consideration of additional costs (Hausman et al., 1995). Fourth,

other use values for other types of recreation and subsistence users were not addressed, in particular ecosystem services that are only received by people who have continued floatplane access. For example, sport fishing, hiking, hunting, and other recreation benefits and local amenities could not be enjoyed without floatplane access to remote water bodies. Finally, non-use values may be held by society and future generations for waterbodies with ecological and cultural significance, thus existence and bequest values are not included.

The geographic scale of Alaska along with the large number of identified floatplane destinations introduces data complexities that are more readily addressed by the data collection and modeling approach presented. However, a few alternative approaches deserve further discussion. In particular, a nested model would have served as a good alternative addressing a complex decision process related to destination choice. While a nesting structure would have relaxed the IIA property and allowed for the estimation of region-specific inclusive values, the demands on data quality are higher. In addition, the nested model could fail to be implemented as it requires inclusive value coefficients to be smaller than one, often necessitating re-specification of the nesting structure which does not always guarantee success (Hausman et al., 1995). Another modeling option presenting itself through the count data is a Poisson or negative binomial specification. Even though these models are used for estimating recreation demand, the application to this damage assessment is limited. The strict distributional assumptions of count data regression are often violated leading to overdispersion, reduced standard errors, and biased welfare estimates and therefore were not considered for this study (Blaine et al., 2015). Lastly, an alternative-specific conditional logit model was specified but was not implemented due to poor fit. The aggregated data and small sample did perhaps not offer enough variance to estimate coefficients specific to each region (McFadden, 1973).

3.6 Conclusions

This work fills an important knowledge gap improving the understanding of significant recreational use losses accruing to floatplane pilots who are believed to be an important vector for long-range dispersal of aquatic invasive species. Thus, estimating user loss is not only informing resource management decision making it also provides incentive estimates for pilots to take extra preventative measures to keep the remote freshwater resources they value in pristine condition. In addition, the estimates can be used for designing market-based conservation mechanisms like payments for ecosystem services that provide continued financing for keeping

pristine ecosystems free of aquatic invaders. The study shows that there are economies of scale associated with multi-objective surveys aimed at integrating biological, economic, and social perspectives into invasive species management decision making. The estimates developed here are intended for further integration into a decision and risk analysis that will evaluate different management options for elodea in Alaska. For increasingly complex management challenges requiring action on multiple species threatening ecosystems in the Arctic and Subarctic, this economic valuation helps quantify risk related to one of the most important long-range dispersal mechanisms for aquatic invasive species.

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Chapter 4. Aquatic Invasive Species from Urban Source Lakes Threaten Remote Ecosystem Services in Alaska: Linking Floatplane Pathway Dynamics with Bioeconomic Risk Analysis[1]

4.1 Abstract

This risk analysis links biology and economics to analyse management decisions for Alaska's first submerged aquatic invasive plant, which floatplanes are introducing into remote water bodies. The approach integrates an ecological metapopulation model describing elodea's spatial spread and population dynamics with market valuation and structured expert judgment to assess effects on fisheries. Those effects are most likely to be negative but in some instances, can be positive; this approach accounts for the full range of potential effects. Further, the analysis applies contingent valuation to estimate losses for floatplane pilots unable to fly into remote destinations after elodea was introduced. The most probable economic loss to commercial fisheries and recreational floatplane pilots is $97 million per year, with a 5% chance that combined losses exceed $456 million annually. The analysis describes how loss varies among stakeholders and regions, with 94% of total statewide losses accruing to the most valuable wild sockeye salmon fishery in the Bristol Bay. Upfront management of all existing invasions is found to be the optimal management strategy for minimizing long-term losses. Even though the range of future economic loss is large, the certainty of long-term damages favors investments to eradicate current invasions and prevent new arrivals. The study serves as a critical first step toward risk management aimed at protecting productive ecosystems of national and global significance.

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4.2   Introduction

Invasive species are an increasing threat to the health of aquatic ecosystems worldwide. Biological invasions can affect livelihoods in economic sectors such as fisheries and recreation that depend on productive ecosystems (Nunes and van den Bergh, 2004; Rothlisberger et al., 2012). Most economic research on the impacts of invasive species focuses on estimating damages from existing invasions, but there has been little research that takes a forward looking approach—predicting future consequences for ecosystems that remain free of invasive species (Jeschke et al., 2014). Estimating financial damages from existing invasions can lead to more public awareness, but such studies are less relevant for management, because they do not evaluate the future consequences of management decisions. Most importantly, they are unable to inform decision-makers about the value of preventing new arrivals or limiting the further spread of existing invaders. This lack of damage forecasting can result in the failure to protect the most valuable ecosystems, and can also lead to waste of money and resources (Doelle, 2003). For example, investments to reduce damages in already impaired ecosystems likely have lower social returns than investments to prevent harmful invasions in pristine ecosystems (Finnoff et al., 2007).

Comprehensive bioeconomic risk analysis can guide management decisions and make economic impact assessments more relevant to management agencies (Lodge et al., 2016). Critical components of such analyses include forecasting costs and benefits over an ecologically relevant period and across spatially-explicit regions, capturing the population dynamics of the invader and related changes in market and non-market values (Shogren et al., 2006; Lodge et al., 2016). Incorporating spatial dimensions into risk analysis aids management decisions about biological invasions, yet most bioeconomic models relevant for management have yet to incorporate spatial aspects (Lodge et al., 2016). Furthermore, when the invader is being dispersed by humans, bioeconomic models can better predict risk if they account for broad-scale spread based on human behavior (Epanchin-Niell and Hastings, 2010). Since intervention can alter the spread of the invader, a model for invasive species management needs to incorporate these social-ecological feedbacks. This integration then makes it possible to evaluate management decisions across regions (Finnoff et al., 2010; Holmes et al., 2010). Few studies have integrated all of the above elements to guide current resource management decisions that are often limited by the availability of local data (Lodge et al., 2016; Maguire, 2004). Some researchers have tried to overcome the lack of location-specific economic values by using less sophisticated approaches, such as benefit transfer techniques (Holmes et al., 2010).

This study was motivated by the recent discovery of Alaska's first documented submerged freshwater aquatic invasive plant, *Elodea spp.* (elodea). The plant was found in Anchorage's Lake Hood, the world's busiest floatplane base, where it created a pathway to spread to remote freshwater landing sites across the state (Hollander, 2015). Since Alaska has vast freshwater resources that support the world's largest wild salmon fisheries, the spread of elodea raises concern about effects on local salmon fisheries (Carey et al., 2016). Also, the explosive and dense invasive plant growth creates safety hazards for pilots, and can prevent them from getting access to private property and recreational opportunities (CH2MHILL, 2005). It is interesting to note that elodea has been observed to collapse and disappear in its non-native range—so management alternatives require a closer look to quantify the trade-offs related to delayed or no action (Simberloff and Gibbons, 2004).

Given the need for statewide management action, quantitative information on the risk of elodea to Alaska's economy is critical for decision-making. Another motive for this study is the need for more sophisticated tools to inform active risk management in Alaska. This research could serve as a step toward a more pro-active risk management approach for elodea, other invasive species yet undiscovered, or new arrivals. Currently, state and federal resource management agencies rely on an invasiveness ranking system that provides little insight for decision-making (Carlson et al., 2008). Given the relative infancy of the invasive species problem in Alaska, the state has a short window of opportunity to efficiently manage biological invasions (Carlson and Shephard, 2007; Schwörer et al., 2014).

This research uses a spatially-explicit simulation approach, integrating human-ecological feedbacks related to population and pathway dynamics, management actions, and valuation of ecosystem services. The approach allows for region-specific predictions of future outcomes for multiple stakeholders, and also accounts for uncertainty. It uses optimization to find management alternatives that minimize future damages. Data on floatplane flight patterns is used to parameterize a metapopulation model that describes the region-wide spread of the aquatic invasive plant, including potential population crashes (Levins, 1969). Metapopulation models have been successfully applied in describing freshwater dispersal of aquatic invasive species (Facon and David, 2006). This framework is particularly suited for modeling invasion dynamics in spatially fragmented environments such as freshwater which are often subject to demographic stochasticity that can lead to colonization followed by extinction (Hanski, 1991; Levins, 1969). The bioeconomic analysis further integrates structured expert judgment with market-based economic

valuation (Cooke, 1991; Freeman, 2003), to simulate effects of invasive species on commercial fisheries (unpublished research). Further, flight data informs a recreation-demand model (Hausman et al., 1995) that estimates non-market damages accruing to pilots (unpublished research).

This research will inform resource managers about the potential range of future economic damages to fisheries and recreation uses, and provides guidance on when and where to intervene. Other objectives include developing a tool that can be used for risk management of new arrivals associated with the floatplane pathway, and evaluating investments to manage existing invasions and prevent further spread. Below the article first describes the ecology of elodea and provides background information on the floatplane pathway for dispersal and on the economic status of Alaska's commercial salmon fisheries. The methods section outlines the framework for quantitative risk analysis, followed by a description of the biological and economic parameters used for empirical estimation. The results include region and stakeholder-specific damage estimates for the no action base-case and recommendations for action. A sensitivity analysis looks into the robustness of the results, followed by a discussion of policy implications and concluding remarks.

4.3   Background

4.3.1   Elodea ecology and management

There are two species of elodea in Alaska *Elodea canadensis* (Canadian waterweed) and *E. nuttallii* (Nuttall's waterweed). A hybrid of the two species is also believed to have established in Alaska (Les and Tippery 2013; Thum 2015 personal communication). This article refer to these species as elodea. Elodea is native to North America except Alaska (Cook and Urmi-König, 1985). Elodea prefers sand and small gravel substrate in cold, static or slow-moving water to 9 m depth (Riis and Biggs, 2003; Rørslett et al., 1986). Elodea is tolerant of a wide range of environmental conditions and has successfully invaded aquatic ecosystems worldwide (Josefsson, 2011). Cyclical population dynamics have been observed for *E. canadensis* peaking between three and ten years after invasion and declining or even disappearing thereafter (Heikkinen et al., 2009; Mjelde et al., 2012; Simpson, 1984). These sudden collapses remain unexplained but have been observed throughout Europe (Mjelde et al., 2012; Simberloff and Gibbons, 2004). Great Britain has the longest recorded invasion of these two species, where landscape-wide spread started in

the 1950s and 1960s. The rate of elodea spread in Great Britain has slowed in recent years suggesting that the plant has reached its ecological limit (Figure 4.1) (NBN, 2015).

A. Elodea canadensis

B. Elodea nuttallii
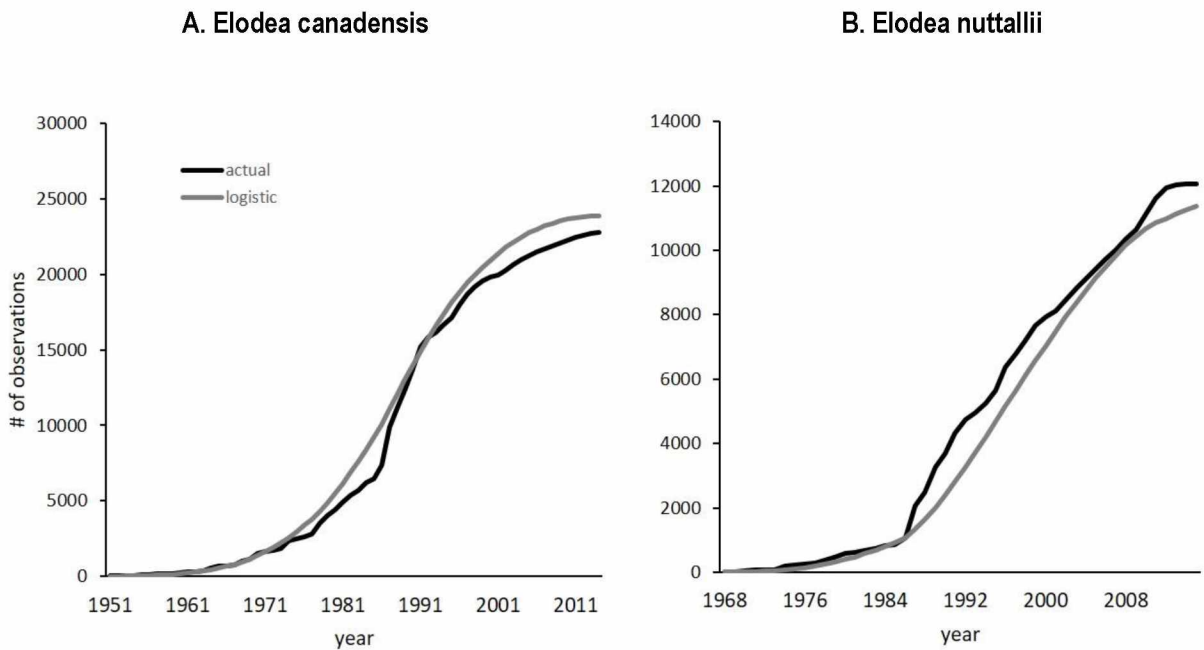
Figure 4.1 Elodea's historical spread in Great Britain and fitted logistic growth.

Common human-related paths for introducing elodea include disposing elodea—used as an aquarium plant—into the natural environment, boats, and floatplanes (Sinnott, 2013; Strecker et al., 2011). Natural means of dispersal include flooding and wildlife transport (Champion et al., 2014; Spicer and Catling, 1988). In Alaska, elodea reproduces vegetatively, with stem fragments surviving desiccation and freezing (Bowmer et al., 1995). Elodea has some of the highest fragmentation and regeneration rates among aquatic invasive plants, causing rapid dispersal and severe challenges for mechanical removal (Redekop et al., 2016). Possible management actions include draining and drying, herbicides, introducing herbaceous fish, and mechanical removal by suction dredging or pulling by hand (Hussner et al., 2017). For eradicating elodea, Fluridone and Diquat are the most effective herbicides, while mechanical methods cause populations to rapidly spread (Josefsson, 2011). In Alaska, Fluridone and Diquat have eradicated elodea in three water bodies (Morton, 2016). At concentrations around 6 ppb, Fluridone selectively removes elodea with few non-target effects (Kamarianos et al., 1989; Schneider, 2000). The use of a mechanical harvester to remove elodea was also tested but deemed too time consuming and expensive (Lane, 2014).

In Alaska, elodea was discovered in Fairbanks (Figure 4.2, Yukon) in 2010, drawing attention to an already established—but until then largely ignored—invasion in Cordova (Figure 4.2, Gulf). New infestations have been found every year since 2010. Aquarium dumps are considered the main pathway near urban locations, while floatplanes are the most likely means 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 4.2, Cook Inlet), the world's largest seaplane base (Hollander, 2015). The discovery of elodea 90 river miles downstream from an unmanaged infestation in Fairbanks (Yukon region) was likely caused by flooding (Friedman, 2015). Many of the infested locations are also home to the five species of Pacific salmon occurring in Alaska.
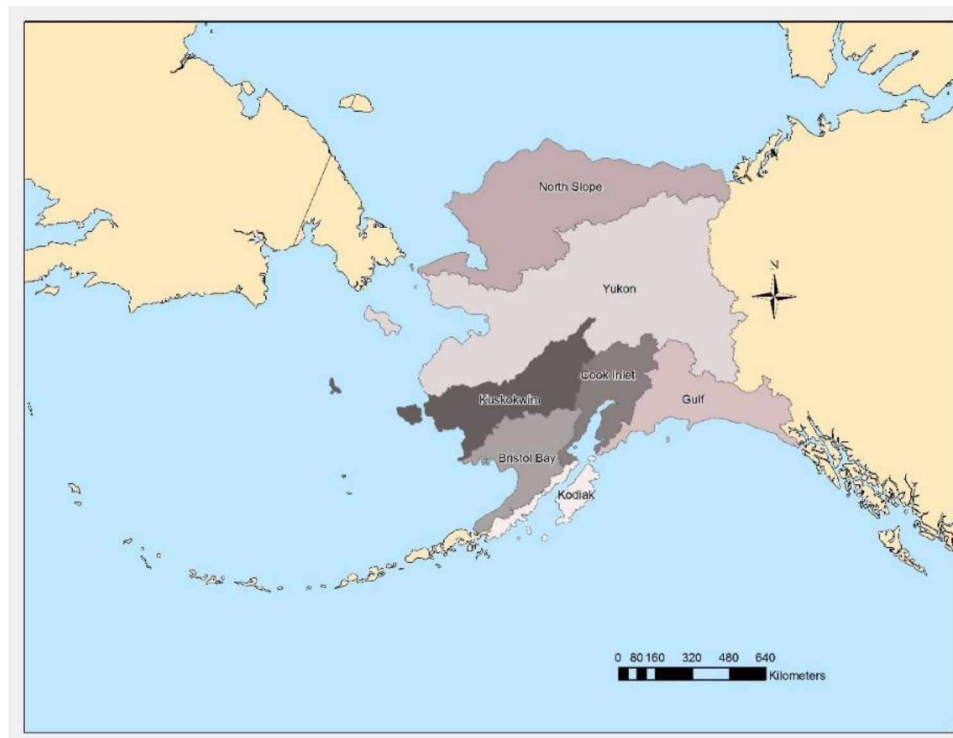
Figure 4.2 Study regions encompassing Alaska's large watersheds.

4.3.2 Elodea's impact on salmon

Sockeye salmon occur across all regions of Alaska, and occupy a wide range of rearing and breeding habitat (ADFG, 2016a). For example, sockeye populations have adapted to

spawning in environments ranging from shallow streams and slow-moving rivers to beaches of large lakes, where they spawn along shorelines, or in deeper water (Hilborn et al., 2003).

Understanding the effects of invasive macrophytes on fishes is complex and an ongoing field of research (Schultz and Dibble, 2012). Very little research specifically describes the effects of elodea on salmon. In its native range, elodea has been found to encroach on spawning sites of chinook salmon (*Oncorhynchus tshawytscha*) (Merz et al., 2008). Previous research by the author used expert elicitation applying a multi-method approach to account for uncertainty in elodea's effects on salmon. The elicitation found that low levels of dissolved oxygen associated with collapsing elodea populations are the primary concern for salmon in their freshwater life stages (Spicer and Catling, 1988). These effects are more concerning for sockeye salmon (*Oncorhynchus nerka*), which spawn in slow-moving streams and shallow water more suitable for elodea, than for lake spawners, which prefer deeper waters (Braun and Reynolds, 2014; Dodds and Biggs, 2002). An additional concern arises because elodea provides habitat for piscivorous predators, particularly northern pike (*Esox lucius*), considered invasive in the Cook Inlet region (Casselman and Lewis, 1996; Sepulveda et al., 2014).

The elicitation first involved a discrete choice experiment (DCM, n=56) followed by structured expert judgment (SEJ, n=44) (unpublished research). The DCM showed experts discrete environmental scenarios, with a yes-or-no question format that asked them about whether salmon persist based on a set of habitat characteristics. The SEJ focused on sockeye salmon only and asked experts to state intervals for the annual average sockeye growth rates to be expected in elodea-invaded habitat. The DCM data can be used to calculate the probability of an expert choosing salmon persistence for elodea-invaded habitat. The scatterplot in Figure 4.3 A shows each expert's probability of sockeye persistence as estimated by the DCM (vertical axis) and the expert's best estimate for the annual average sockeye growth rate elicited in the SEJ (horizontal axis). Eight incoherent experts were eliminated before aggregating the remaining experts' judgments using equal weights to form a joint and normal probability distribution (Figure 4.3 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 assumption is consistent with research that finds mixed effects of invasive macrophytes on fish (Schultz and Dibble, 2012). This distribution of the combined expert opinion remained cognisant of both elodea's negative and positive growth effects on sockeye salmon.
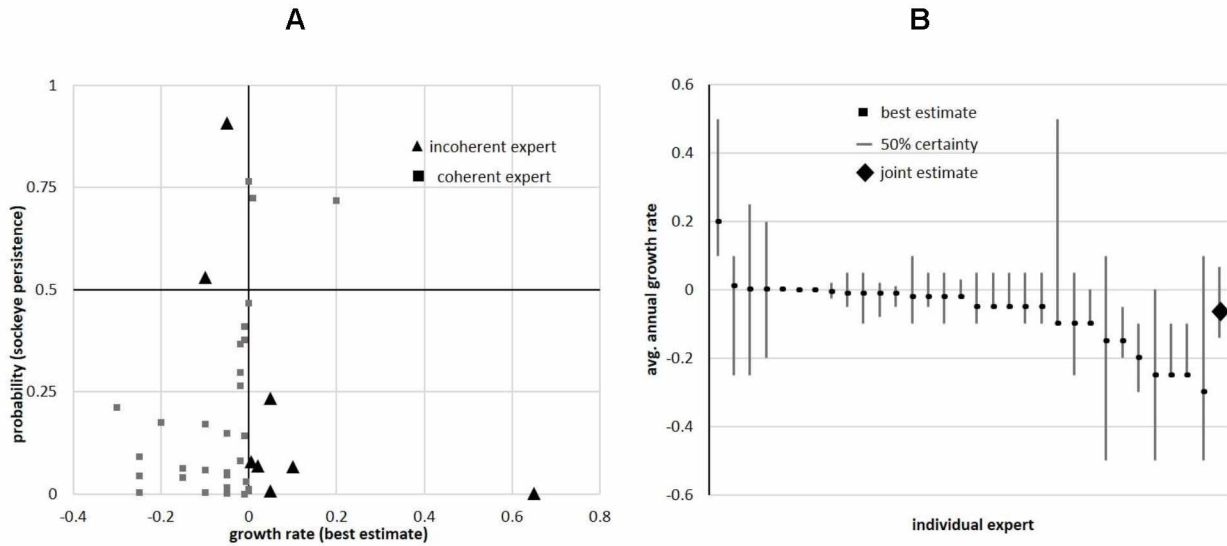
Figure 4.3 Stated annual average sockeye growth rate intervals (25th, mean, and 75th percentile) for sockeye salmon in elodea-invaded habitat by individual expert.

4.3.3 Commercial sockeye salmon fisheries

In 2014, wild salmon comprised about 30% of global salmon production by volume. Of the wild salmon share, Alaska sockeye salmon made up 65%, with 37% from Bristol Bay alone (McDowell Group, 2015). Alaska's commercial sockeye salmon fisheries can be divided regionally into five large watersheds (Figure 4.2) (USGS, 2016). 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 the watersheds supporting the Copper and Bering River fishing districts. There are also commercial sockeye salmon fisheries in Southeast Alaska and the Aleutian Islands that were not included in this study, to keep the focus on regions closest to the currently known elodea infestations. Sockeye salmon exist in the Yukon and North Slope regions, too, but their contribution to the commercial sockeye salmon catch is not significant (ADFG 2016b).

While Alaska's wild sockeye salmon support the world's largest and most valuable commercial salmon fisheries, all species of Pacific salmon are important for the state's subsistence and sport fisheries. In the Bristol Bay region, for example, the net economic value of

subsistence fisheries amounts to 68% of total economic market and non-market value estimated for all fisheries combined, while commercial and sport fishing amount to 27% and 5% respectively (Duffield et al., 2013). People across Alaska depend on the diversity of salmon species. For example, in the Yukon region, local livelihoods critically depend on all species of Pacific salmon except sockeye (Brown et al., 2015). But data on sport and subsistence fisheries are limited, so this analysis focuses on the commercial sockeye salmon fisheries, for which reliable data on catch and prices are available (ADFG, 2016b).

Global market forces determine prices for sockeye salmon. For example, the rapid and sustained growth of salmon farming in the 1990s depressed world-wide prices for salmon and caused prices for wild Alaska salmon to plummet. But over the past decade, prices recovered due to marketing efforts promoting wild and sustainably-caught Alaska salmon, and to disease outbreaks in salmon farms elsewhere (Knapp et al., 2007).[2] Because the Bristol Bay sockeye salmon fishery is so large, it can be argued that Alaska sockeye production plays a price-influencing role globally (Knapp et al., 2007). Table 4.1 shows historical wholesale prices for the four main product categories for sockeye salmon—frozen, fresh, canned, and other.[3] Given a globally traded product, regional variations in price exist and are more or less correlated across regions (Table 4.2). Table 4.3 shows region-specific seafood processing 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 et al., 2007).

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

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

Table 4.1 Historical pre-invasion sockeye harvest and wholesale prices

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 4.2 Correlation among regional wholesale prices for sockeye salmon products

	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: Alaska Department of Fish and Game, Commercial Operators Annual Reports.

Table 4.3 Sockeye production shares and processing yields by region

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, 2016c; 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).

4.3.4 Floatplane pathway

Since Alaska is mainly roadless, small single-engine propeller planes play a key role in commercial and private transportation (Gray, 1980). Alaska has six times as many pilots and 16 times as many aircraft per capita as other U.S. states (The Ninety-Nines, 2016). During summer months, pilots convert the landing gear of many single-engine planes from wheels or skis to pontoons. Many floatplane operations are associated with small commercial air carriers that serve backcountry recreational users, remote lodges, and private charter demand to remote residences. A survey of 1,015 of the 2,625 floatplane certified pilots living in Alaska asked questions about pilots' home bases and all 2015 freshwater destinations where they flew on the first leg of their flights (unpublished research).

Key informant interviews also showed that most pilots flew to a destination and returned to their home base, with few flights including more than one destination after take-off. The potential for introduction of elodea is greatest for the first destination after take-off from urban source locations. The survey identified flight frequencies to over 700 landing sites, 80 of which are floatplane bases (Table 4.4 and 4.5, and Figure 4.4). About 57% of all floatplane flights to freshwater destinations originate from the primary freshwater floatplane hubs in each region identified by the highest number of flight operations (Table 4.5). This result underlines the importance of these seven floatplane hubs for elodea management. The hubs are in urban regional centers where elodea has already been discovered or is more likely to occur (Carey et al., 2016).

Table 4.4 Floatplane landing site characteristics

Regional floatplane hub, city, region	Hub size (acres), a^{ihub}	Median size of destination (acres), a^i	Annual avg. flights/ destination	Number of destinations, L^i	Count [a] I_i^i
Shannon's Pond, Dillingham, Bristol Bay	31	3666	216	74	0
Lake Hood, Anchorage, Cook Inlet	270	185	180	215	3
Hangar Lake, Bethel, Kuskokwim	137	916	42	28	0
Eyak Lake, Cordova, Gulf	2495	381	49	71	3
Lilly Lake, Kodiak, Kodiak[c]	15	307	145	41	0
Float Pond, Bettles, North Slope	155	828	24	93	0
Float Pond, Fairbanks, Yukon	136	336	205	205	0

a) Count of currently known elodea invaded water bodies that are floatplane destinations in each region. Count does not include floatplane hub.

Half the respondents said they would no longer fly to destinations they flew to in 2015, if dense aquatic vegetation was in the landing zone (Table 4.6). That finding is supported by the Lake Hood floatplane base's aquatic management plan, listing safety concerns as the primary reason for continued aquatic vegetation management (CH2MHILL, 2005). The survey also asked respondents what they knew about elodea and informed pilots about the risk elodea poses to their safety. About 75% of respondents had heard about elodea, and reported safety concerns about flying to waterbodies that are shallow and already require caution in landing. Follow-up interviews with respondents indicate that during the survey pilots identified their destination lakes by taking into account individual lake characteristics when asked whether they would land if dense aquatic vegetation covered the lake's landing zone. For example, water depth and terrain features surrounding lakes play a role when dense aquatic vegetation changes landing conditions. The shallower the lake, the denser the aquatic vegetation can become, influencing the aircraft's maneuverability and speed during take-off. In addition, surrounding terrain, predominant weather conditions, pilot skills, and plane models are significant drivers determining whether pilots could still fly to an elodea-invaded waterbody. These additional factors determine whether elodea reduced the margin of safety to a point, where other unfavorable factors make it impossible to safely land and take-off.

Table 4.5 Floatplane pathway between regional floatplane hubs and freshwater destinations in seven regions [a]

Regional floatplane hub, city, region	Number of 2015 flights to region of destination, v^i							
	Bristol Bay	Cook Inlet	Kusko kwim	Gulf	Kodiak	North Slope	Yukon	Total
Shannon's Pond, Dillingham, Bristol Bay	3,450	17	280	0	0	0	0	3,747
Lake Hood, Anchorage, Cook Inlet	1,903	25,382	105	580	0	0	206	28,176[b]
Hangar Lake, Bethel, Kuskokwim	117	0	170	0	0	0	79	366
Eyak Lake, Cordova, Gulf	0	0	0	463	58	0	0	521
Lilly Lake, Kodiak, Kodiak[c]	0	34	0	0	2,934	0	0	2,968
Float Pond, Bettles, North Slope	0	0	0	0	0	458	1,624	2,082
Float Pond, Fairbanks, Yukon	19	112	27	36	0	944	5,812	6,950
Other	10,497	13,161	583	2,411	2,939	786	3,903	34,280
Total	15,986	38,706	1,165	3,490	5,931	2,188	11,624	79,090

a) Weighted flight estimates based on survey responses observed in each strata (unpublished research). b) The only available data to validate this estimate are FAA operation counts at Lake Hood. However, the FAA does not distinguish flights based on landing gear, preventing a count of floatplane flights. Total Lake Hood operations count during open water between June 1 and September 1 was 35,140 (FAA 2016). The FAA count includes flights that are immediate returns to Lake Hood after take-off (without a destination) and counts flights to saltwater destinations. Therefore, the estimate of 28,176 floatplane flights to freshwater destinations is reasonable. c) The most frequently used freshwater floatplane hub on Kodiak Island; many are in saltwater.

Table 4.6 Recreational pilots' stated change in flight behavior due to elodea-invaded destinations (n=229)

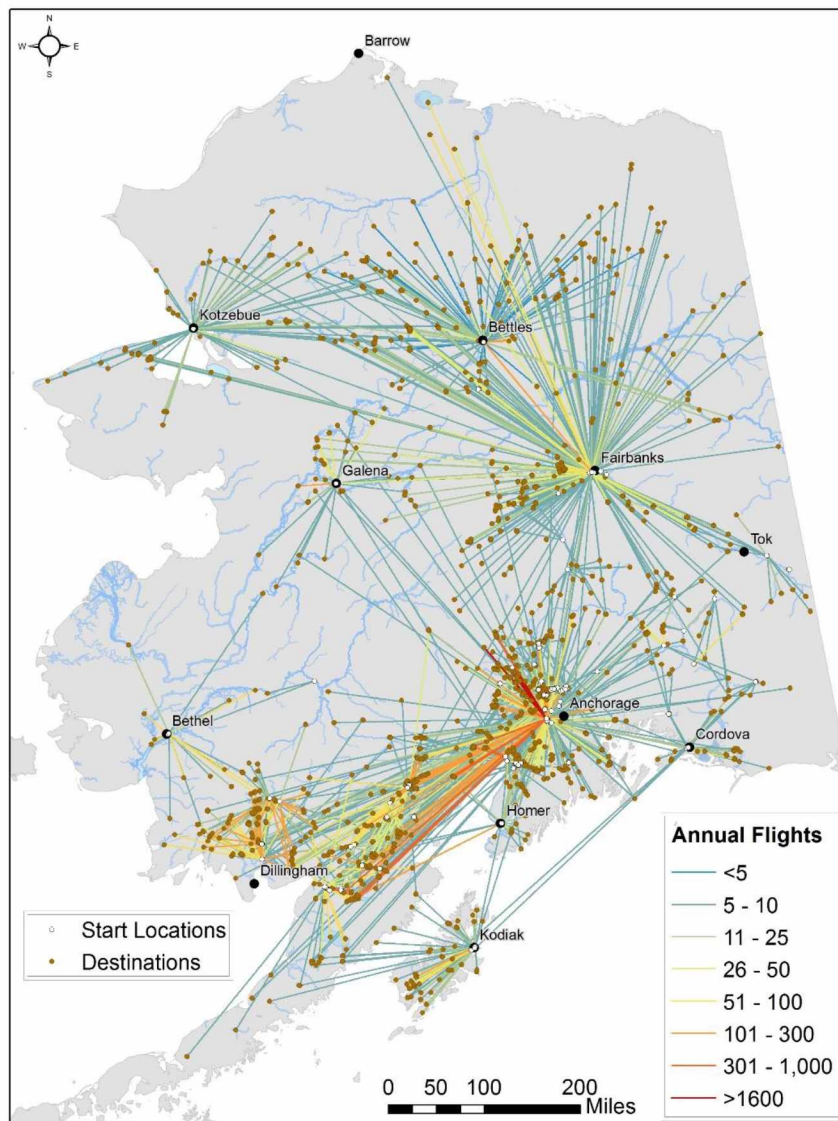|	Continue flying			Stop flying
	to all their destinations		only to some destinations	
	without flight reduction	with flight reductions	with flight reductions	
Pilot count (%)	43 (19%)	36 (16%)	35 (15%)	115 (50%)
Mean % change in annual flights	0%	-40%	-58%	-100%

Figure 4.4 Floatplanes' first-leg flight paths between freshwater start and destination locations. Data from a survey with pilots about their 2015 flights.

4.4 Methods

The study estimated potential annual damages to commercial fisheries from elodea in discrete time, using a benefit approach to economic valuation of ecosystem services (Freeman, 2003). If elodea changes the provisioning of ecosystem services—that is, the amount of harvestable sockeye salmon—it also changes the benefits consumers derive from the resource. Similarly, if floatplanes carry invasive elodea into remote water bodies, these destinations can become inaccessible, forcing pilots to change destinations or stop flying. These changes can in turn reduce recreation benefits people get from visiting the remote sites. Consumer surplus provides a measure of these benefits. Consumer surplus is 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 the consumer. If elodea reduces the harvest of sockeye, prices will increase and consequently diminish consumer surplus, all else equal. Similarly, if the invasion of elodea in floatplane destinations leads to fewer visits because planes can no longer land safely, the difference between how many visits to a site there are before and after elodea is introduced explains the loss in consumer surplus.

The study estimated potential economic losses to commercial sockeye salmon fisheries using an approach that has been applied to fisheries in the invasive species context (Rothlisberger et al., 2012). The study measured the recreational-user loss accruing to floatplane pilots using the previously mentioned survey data from pilots, applied to a recreation demand model (Hausman and Wise, 1978). Here, both of these economic valuation studies were integrated to form a spatially and temporally explicit risk analysis that forecasts potential future damages and informs resource managers about optimal decision-making (Holmes et al., 2010).

Further, the study modeled the landscape-wide introduction of elodea from urban source lakes into remote floatplane destinations using data on floatplane flight frequencies (Table 4.5). Flight data were used to estimate region-specific colonization rates. The spatial modeling approach used a modified structured metapopulation model that accounted for elodea's within-patch population dynamics (Hastings and Wolin, 1989; Levins, 1969). This framework was extended to incorporate how colonization rates change, given management action in specific regional floatplane hubs from which elodea is being spread within and across regions.

Below, the first part describes the structured metapopulation model and its management extension. The second part integrates the economic valuation of market loss to commercial fisheries and non-market loss to floatplane pilots. The third part summarizes the biological and economic parameters applied and explains the simulation approach used to account for uncertainty in model assumptions.

4.4.1　Spread dynamics

The bioeconomic model simulated the floatplane-related spread of elodea in discrete-time, using a finite metapopulation model consisting of seven regions (Figure 4.2) (Facon and David, 2006; Levins, 1969). In the metapopulation literature, the regions are often called patches, which this article uses interchangeably (Hastings and Wolin, 1989). The main reason for using seven regions is that commercial fisheries data is fisheries-specific and is aggregated across salmon populations originating from different nursery lakes and streams. As a consequence, the origin of a fishery's catch is mostly unknown, which prevented a lake-specific risk analysis (Barclay et al., 2014). Also, elodea is more likely to naturally spread within a watershed, given its vegetative reproduction through fragmentation and natural downstream dispersal, underpinning a spatial scale at the watershed level. Finally, while the model was less computationally demanding using seven regions, the broad regional context still provided insights for elodea management.

Following the traditional metapopulation approach, patches were either empty (state $\beta = 0$, where elodea was absent or too rare to be detected) or occupied (state $\beta = 1$, elodea detected). Patch occupancy was determined by colonization and extinction rates. Since colonization success was directly linked to propagule pressure (Schreiber and Lloyd-Smith, 2009), floatplane flight frequencies in Table 4.5 were used to proxy region-specific colonization rates, c^i. The region-specific colonization rates equalled the number of flights to region i that originated from elodea-invaded floatplane hubs, v_e (Table 4.5), over the total number of annual flights, v, to destinations within region i, or

$$c^i = \frac{\sum_{i=1}^{7} v^i{}_e}{\sum_{i=1}^{7} v^i}$$

, for regions i = 1,...,7.[4]   (4.1)

If a region was occupied in year t, there was a probability, e_{t+1}, that elodea would have gone extinct in year t+1. If the patch was unoccupied, the probability it was colonized in year t+1 was $c^i_{t+1} P_t$ where P_t was the proportion of patches occupied in year t. Evidence elsewhere in elodea's non-native range suggested that elodea populations can disappear across broad landscapes (Edwards et al., 2006; Hüssner et al., 2014; Mjelde et al., 2012; Simberloff and Gibbons, 2004). Therefore, the metapopulation approach was well suited to describe the synchronous gain and loss of elodea within each patch.

During time interval [t, t+1], each patch showed one of the following four transitions in β: remaining empty (0 → 0), newly occupied (0 → 1), newly extinct (1 → 0), and remaining occupied (1 → 1). For the first two transitions mentioned,

$$\beta^i{}_{t+1} = \begin{cases} 1 & \text{if } u^i{}_{t+1} < c^i{}_{t+1}P_t \\ 0 & \text{otherwise} \end{cases}$$
,   (4.2)

where u was a random variable described by a uniform distribution bounded by zero and one. If the patch was occupied the previous year, then

$$\beta^i{}_{t+1} = \begin{cases} 0 & \text{if } u^i{}_{t+1} < e_{t+1} \\ 1 & \text{otherwise} \end{cases}$$
.   (4.3)

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4 It is recognized that colonization depends on more factors than described by this fraction. For example, colonization rates are affected by flight distance, the likelihood of elodea being entangled in a floatplane pontoon's rudder, fragment lengths, and other factors. To some degree, flight distance plays less of a role because of elodea's high tolerance to desiccation (Barrat-Segretain and Cellot, 2007) and unusually high regeneration capacity for stem fragments of less than 1 cm (Redekop et al., 2016).

4.4.2 Incorporating management

In order to incorporate the effects of management actions (including the option of no action), management in year t was described using vector $M_t = [m^1_t, ..., m^7_t]$ for regions $i = 1,...,7$ with $m^i_t = \begin{cases} 1 & \text{if action} \\ 0 & \text{otherwise} \end{cases}$. Since management altered the state of a patch, β, a directional effects factor was introduced that depends on the state of the patch and management action, thus $\eta = f(M, \beta)$. The purpose of η was solely to reflect management action reversing elodea's ecological effects and returning the ecosystem to its pre-invasion state. The few non-target effects for native aquatic plants and fish related to Fluridone treatments of aquatic systems suggested that reversibility was reasonable to assume (Madsen et al., 2002). The directional factor took one of three values: the patch was never occupied ($\eta = 0$), occupied ($\eta = 1$), or recovered ($\eta = -1$). Note, once a patch was occupied by elodea and treated afterwards, that patch was either in recovery or was re-occupied. Consequently, the colonization rates became a function of management or expressed as $c^i_{t+1} = f(v^i_e(M_t), v_i)$.[5]

The transitions for $\eta = f(M, \beta)$ during time interval [t, $t+1$] were as follows. If the patch remained unoccupied, β remained ($0 \rightarrow 0$), and the patch was not colonized prior to year t, η remained ($0 \rightarrow 0$), or η remains in recovery ($-1 \rightarrow -1$) if the patch was recovering. If the patch was newly colonized, thus β switched from ($0 \rightarrow 1$), and management occurred in $t+1$, then η switched from ($0 \rightarrow -1$), or η switched from ($-1 \rightarrow -1$) if the patch was recovering. If the patch was newly extinct, thus β switched from ($1 \rightarrow 0$), and the patch was occupied and unmanaged in t, η switched from ($1 \rightarrow -1$), or η remained ($-1 \rightarrow -1$) if the patch was recovering. If the patch remained occupied, β remained ($1 \rightarrow 1$), and there was no management, η remained ($1 \rightarrow 1$), or η switched from ($1 \rightarrow -1$) if there was management in $t+1$. Mathematically summarizing the above equals the following statement:

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[5] Colonization rates were determined by the model using the flight data and depend on which hubs are occupied by elodea.

$$\eta^i_{t+1} = \begin{cases} 1 & \text{if m}^i_{t+1} = 0 \text{ and } \beta^i_{t+1} = 1 \\ -1 & \text{if m}^i_{t+1} = 1 \text{ and } \beta^i_{t+1} = 1 \\ & \text{or } \beta^i_{t+1} = 0 \text{ and } \beta^i_t = 0 \text{ and } \eta^i_t = -1 \\ & \text{or } \beta^i_{t+1} = 0 \text{ and } \beta^i_t = 1 \\ 0 & \text{otherwise} \end{cases}$$

. (4.4)

4.4.3 Integrating ecosystem services

4.4.3.1 Loss to commercial fisheries

The functional response of harvest to an elodea invasion was represented by $h^i_{t+1} = f(h^i_t, \theta)$, where h^i_t is the region-specific harvest of sockeye salmon in year t and θ is the annual average growth rate of sockeye salmon in elodea-invaded habitat. Consistent with common practice in fisheries modeling, harvest was assumed to be proportional to stock size and fishing effort (Haddon, 2011).[6] Year-by-year changes in harvest were modeled using density-dependent population dynamics in logistic form such that harvest levels at *t+1* equalled

$$h^i_{t+1} = h^i_t \left(1 + \eta^i_{t+1} \theta \left(1 - \frac{h^i_t}{K^i} \right) \right) \text{ s.t. } 0 \leq K^i$$

, (4.5)

where K was set to be the historical maximum harvest. Note, the directional effects factor, η, reverses the sockeye growth rate, θ. Assume for a moment that elodea has negative consequences for sockeye growth, $\theta < 0$, Equation 4.5 then results in a logistically declining salmon harvest without elodea treatment and over time recovering sockeye harvest after elodea treatment occurred.

The logistic growth model is fitting for this application for several reasons. Due to the seasonal reproduction of salmon, the discrete time model with an annual time-step is well suited for modeling the seasonal growth changes in salmon (Haddon, 2011). The logistic growth model

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[6] Under this assumption the catch-ability of the fishing fleet does not change over time or stock size.

also describes the population dynamics for an entire population of salmon irrespective of age-classes and as such is consistent with θ, which was derived through expert elicitation that asked about growth rates pertaining to entire salmon populations irrespective of age-classes (unpublished research). Even though the logistic growth model is not often used to describe population dynamics in fisheries, due to a number of limitations (Larkin, 1977), its advantages lie in its simplicity, particularly in data-limited situations (Beverton and Holt, 1957; Haddon, 2011). The logistic growth model differs from commonly used fisheries 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 that is supported by the encroachment effects of elodea observed on spawning adult salmon (Merz et al., 2008).

In addition, while long-term persistence is not guaranteed under the logistic growth model, the model assumed that despite environmental perturbation salmon populations can persist long-term. The invasion of elodea in the British Isles recently reached its ecological limit, 65 years after it was introduced (Figure 4.1) (NBN, 2015). These data showed that landscape-wide spread of an elodea invasion could occur in longer time frames, compared to the 20-year time horizon considered for persistent salmon populations in invaded habitat (Peterson et al., 2008). The effects of elodea on salmon in elodea's invasive range may manifest themselves over a longer time frame without immediate catastrophic outcomes, if the effects on salmon in elodea's native range are a precursor (Merz et al., 2008). Moreover, the boom-and-bust cycle of elodea populations can temporarily lead to more or less pronounced biological effects for different life stages that in the long term average out (Simberloff and Gibbons, 2004). For these reasons, the logistic growth model was used to describe the biological relationship between elodea and salmon, and the 100-year time horizon was used to reflect the likely long-term incremental changes in ecosystem services. Bioeconomic modeling for invasive species emphasizes a long time horizon because longer time spans are most relevant for measuring how people are affected by environmental change and how management intervenes in biophysical processes (Leung et al., 2002).

The model calculated the changes 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 (Marshallian) demand function (Freeman, 2003). Since the expert-derived sockeye growth rates ranged from negative to positive, 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 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:

$$\Delta CSF_{t+1}{}^i = \frac{\gamma^i}{2}\left[\left(h^i{}_t - f(h^i{}_0, h^i{}_t, K^i, \theta, \eta^i{}_{t+1})\right)\left(\left(\frac{h^i{}_t}{\varepsilon}p^i{}_t\right) + \frac{f(h^i{}_0, h^i{}_t, K^i, \theta, \eta^i{}_{t+1})}{h^i{}_t \varepsilon}\right) - p^i{}_t h^i{}_t\right], \text{(4.6)}$$

where γ^i was the region-specific processing yield, p^i was the real (inflation-adjusted) per lb wholesale price for sockeye salmon in 2015 USD received by Alaska primary processors in region i, $p^i{}_0$ and $h^i{}_0$ were the historical pre-invasion sockeye whole sale price and catch respectively, and ε was the own-price elasticity of sockeye salmon demand. Prices were weighted by sockeye product ratios commonly observed in the Alaska processing sector (Table 4.6).

4.4.3.2 Loss to pilots

The non-market loss to floatplane pilots was directly linked to the spread dynamics described above. While a traditional Levin's metapopulation model accounts for the spread of elodea across regions (patches), it ignores elodea's within-patch dynamics (Levins, 1969). For pilots that would mean all destinations within a region would be invaded simultaneously. For this research, the structured metapopulation model addressing within-patch dynamics was more appropriate because it described how floatplanes over time introduce elodea to a growing number of floatplane destinations within a region (Hastings and Wolin, 1989).[7] Long-term observations of elodea's landscape-scale colonization in Great Britain suggest that the logistic growth model described elodea's landscape-wide spread well (Figure 4.1).

Mathematically, the number of landing-spots invaded within a patch in year $t+1$ was expressed using the logistic function as

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[7] The process of an invader establishing a population in a remote patch before colonizing the remaining landscape of the patch is also known as the beachhead effect (Deines et al., 2005).

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$$l^i_{t+1} = l^i_t \left(1 + c^i_{t+1} \left(1 - \frac{l^i_t}{L^i} \right) \right) \quad \text{s.t.} \quad l^i_{t+1} = \begin{cases} 0 & \text{if } \eta_{t+1} = 0 \text{ or} -1 \\ 1 \le l^i_{t+1} & \text{otherwise} \end{cases}$$

(4.7)

where l^i_t was the number of floatplane destinations invaded in year t in region i and L^i was the total number of floatplane landing-spots in region i (Table 4.2). Equation 4.7 assumes simultaneous treatment of invaded floatplane destinations is possible within a region. Management success using Fluridone to eradicate elodea in Alaska suggest that this assumption was realistic (Morton, 2016). Thus, the constraint in Equation 4.7 states that no landing spots are invaded once treatment occurs. In addition, Equation 4.7 assumes that one landing spot is colonized in the first year in which elodea is introduced, with more landing spots being colonized within the region in subsequent years, until treatment occurs.

Welfare changes accruing to recreational floatplane pilots were estimated using the flight data and a multinomial probit recreation demand model (unpublished research). When a simulated floatplane destination became invaded, the marginal user-loss per flight accruing to recreational floatplane pilots was w. The annual loss to floatplane pilots was then expressed as follows

$$\Delta CSP^i_{t+1} = l^i_{t+1} \frac{\sum_{i=1}^{7} v^i_r}{L^i} w,$$

(4.8)

where the fraction was equal to the annual average number of recreational flights per destination, v_r. The management cost associated with eradicating elodea in year t in each region was equal to $C^i_t = s\,(l^i_t \cdot a^i + a^{ihub})$, where s was the per-acre cost of Fluridone, a^i was the region-specific average floatplane destination size in acres, and a^{ihub} was the size in acres for the regional floatplane hub.

4.4.4   Management alternatives

The management approach was aimed at eradicating elodea in Alaska. The management decision determines when to treat and where to treat in order to minimize long-term losses. The

combined loss to commercial fisheries and floatplane pilots was expressed in net present value (NPV) calculated over a 100-year time horizon. Summed across regions, the NPV was

$$NPV = \sum_{t=0}^{100} \sum_{i=1}^{7} \left(\Delta CSF_t^i + \Delta CSP_t^i + C_{t*}^{\ i} \right) \left(1+d \right)^{-t} ,$$

(4.9)

where d is the social discount rate and $t*$ is the year in which the elodea manager decides to treat. The constant annualized loss in ecosystem services was estimated as follows,

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

(4.10)

Economic values are often expressed as either stocks or flows. For example, a person's wealth is a stock, while that person's income is a flow. Similarly, the economic valuation of natural resources measures the loss in natural capital as the cumulative loss related to an impaired ecosystem (Equation 4.9). In contrast, this cumulative loss can be expressed as a constant annual loss in ecosystem services (Equation 4.10). This measure of loss in ecosystem services is often easier to comprehend, because fisheries data is often published annually, and as such, provides relative scale (ADFG, 2016b).

The model estimated losses for two management alternatives: no action and immediate action. The management decision was expressed by $m_t^i = 0$ for $t = 1,...,100$ and i for $1,...7$. For the immediate action alternative, the manager's optimization problem becomes min NPV s.t. $M(t)$, where management M is a function of time when action is taken, assuming each region is managed one year at a time. The optimization uses the OptQuest[8] algorithm to find the optimal order in which management should occur across the seven regions to minimize Equation (4.9) (Glover et al., 1996; Palisade Corporation, 2016a). In addition, the no action and immediate action alternatives were both described using two cases. The first case was the *base-case* and reflects current state of knowledge about which regions were currently invaded, thus $\beta_1 = 1$ for Cook Inlet and Gulf. The second case was the *worst-case* and was hypothetical assuming all regions were already colonized in year one, thus $\beta_1 = 1$ for $i = 1,...,7$.

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[8] OptQuest is a search engine that combined different search algorithms such as Tabu search, scatter search, integer programming, and neural networks. It is not a genetic algorithm used in other Palisade software (Glover et al., 1996; Palisade Corporation, 2016c)

4.4.5 Model simulation and parameter assumptions

Monte Carlo simulation was used to estimate Equations 4.9 and 4.10 for a range of uncertain parameter inputs, some of which were described by distributions. Due to the deterministic economic model, the simulation held colonization parameters fixed over the model's time horizon. In contrast, elodea's extinction probability changed randomly in each time-step.

The simulation tested up to 10,000 possible input assumptions for each uncertain parameter, generating a distribution for Equations 4.9 and 4.10. The simulation stopped when there was a 95% chance that the mean NPV was within ±3% tolerance of its true value (Palisade Corporation, 2016c).[9] Below, the distributional assumptions concerning the uncertain parameters for ecological and human dimensions are discussed.

4.4.5.1 Ecological dimensions

Uncertain parameters include the expert-elicited annual average growth rate for sockeye salmon, θ, for which a normal distribution was used (Normal(-0.052,0.138)[10] (unpublished research). A normal distribution was suitable for this purpose because many unknown ecological processes that average out over a large sample are likely at play in elodea-invaded habitat (Hilborn and Mangle, 1997). This joint distribution represents the uncertainty in elodea's overall effect on sockeye salmon and reflects varying opinions thereof. There is a 0.35 probability of observing positive growth in elodea-invaded habitat. This assumption is consistent with research that finds mixed effects of invasive macrophytes on fish (Schultz and Dibble, 2012).

To describe the variation of pre-invasion historical sockeye salmon harvest, region-specific commercial sockeye harvest records in pounds landed from 2006 to 2015 were used to fit a uniform distribution (Table 4.1). For the purpose of testing different model assumptions surrounding historical harvest, this non-informative distribution was found to best accommodate this purpose across regions. 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). In addition, long-term variation of salmon returns is also driven by Pacific climate variability and other factors (Hare et al., 1999).

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[9] Sampling type: Latin Hypercube, random number generator: Mersenne Twister.
[10] N(mean, SD)

The assumptions surrounding the extinction rate for elodea deserve particular attention, because simulated extinction events reduced statewide damages and management costs. Because elodea was only recently discovered in Alaska, local elodea populations have not yet been observed to decline or go extinct. Data from Norway, where elodea is growing in similar climatic conditions, served as a proxy for estimating extinction rates.[11] In 2012, among the 47 elodea-invaded lakes in Norway, *E. canadensis* disappeared from three lakes for a mean extinction probability of 0.0638 (Mjelde et al., 2012). Since the reasons for sudden collapse of elodea populations were unknown and likely related to random environmental conditions, the model drew extinction probabilities randomly from a beta distribution for each year across the time horizon (Ripa and Lundberg, 2000; Simberloff and Gibbons, 2004).[12] Specifically, the beta distribution was defined as Beta(0.002,0.0297) restricted to [0, 0.5].[13] For each year, the model drew an extinction probability from the beta distribution, which through the random draws, u^i, applied to each region differently (Equation 4.3). The model assumed independent extinction events between years that were uncorrelated (Ripa and Lundberg, 2000). The beta distribution was truncated at a maximum threshold of 0.5 to lower the probability of a region-wide elodea extinction event.[14] Probabilistic predictions in ecological models were often chosen to be subject to thresholds that allow models to show more realistic outcomes. If lack of data prevents model calibration, these thresholds can be arbitrarily chosen, as was the case here (Guisan and Zimmermann 2000). If the beta distribution did not have a threshold, management costs would be lower, as region-wide extinction would be more likely. For this reason, the threshold allowed management costs to be more conservative. The analysis did not account for other costs related to management, such as monitoring (Frid et al., 2013).

4.4.5.2 Human dimensions

Pre-invasion wholesale prices, p_0, were modeled using the lognormal distribution which is commonly used in economics to describe the distribution of income, wealth, and prices (Table 4.7) (Aitchison and Brown, 1976). The correlation of prices among regions was taken into account

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[11] No data are available from disappearing elodea populations in Germany and New Zealand (Edwards et al., 2006; Hüssner et al., 2014).

[12] The beta distribution is commonly used to model population mortality in ecological models, particularly in research on infectious disease (Pollett et al., 2010), conservation biology (Wilcox and Possingham, 2002) and aquatic plant mortality (Muneepeerakul et al., 2007).

[13] Parameters of the beta distribution are $\alpha = 0.002$ and $\beta = 0.0297$. The corresponding mean is $\alpha/(\alpha+\beta) = 0.0631$.

[14] Note, the extinction probability is not region-specific, yet the uniform draws, u^i, are region-specific (Equation 4.3).

based on estimated Spearman's rank-order correlation coefficients observed between 2000 and 2015 (Table 2.1). The model generated rank-correlated pairs of prices for two regions at a time, following induced rank correlation (Iman and Conover, 1982; Palisade Corporation, 2016b).

In order to measure changes in consumer surplus caused by an invasion-related change in salmon catch, the approach relies on assumptions surrounding the responsiveness of demand to price changes, measured by the own-price elasticity of demand (Freeman, 2003). Unfortunately, there are no specific estimates of own-price elasticities for Alaska sockeye salmon. However, estimates from elsewhere in North America can serve as a proxy. There are a variety of sources that estimated the elasticity of demand for fresh and frozen sockeye salmon in the Pacific Northwest, Oregon, or Canada (DeVoretz, 1982; Johnston and Wood, 1974; Swartz, 1978; Wang, 1976). 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 the latter elasticity estimates as bounds (Table 4.7). There are several arguments that would support higher elasticities $|\varepsilon| > 1$. For instance, the existence of very close substitutes for wild sockeye salmon—such as coho—underpin this argument. Additionally, wild sockeye is 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).

Management costs of aquatic plants vary by many factors, most significantly by the type of removal method, species, abundance, and management goal. Additional factors are site-specific, such as the extent of invasion (partial vs. full lake treatment)[15], water depth, water volume, remoteness, water flow and related herbicide dissipation, and herbicide formulation (pellet vs. liquid) (Schardt 2014 personal communication). Compared to herbicides, mechanical removal is much more costly and less effective for submerged aquatic plants like elodea (Hussner et al., 2017). The per-acre cost of mechanical removal ranges between $12,000 and $20,000 in 2015 USD, and due to its poor record of success for elodea it was not considered in this analysis (Johnson 2013; Lane 2014, Schardt 2014 personal communication). Using historical expenses for treating *Hydrilla verticillata* (hydrilla) with Fluridone between 1980 and 2002, a Weibull

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[15] Partial lake treatments often require the use of a contact herbicide such as Diquat to prevent localized elodea populations from spreading throughout a lake, adding to the per-acre cost (Morton et al., 2014).

distribution was fitted to the inflation-adjusted per-acre cost (Weibull(9.709,907.14).[16] Since hydrilla is primarily treated with Fluridone, at similar concentrations to elodea, the mean per-acre cost of $861 in 2015 USD is comparable for the treatment of elodea.[17] The observed costs were comparable to treatment costs in Alaska, but treatment in more remote locations may result in higher costs not accounted for by the model (Morton et al., 2014). Table 4.7 summarizes the model parameter assumptions the analysis used.

Lastly, the real social discount rate is another key uncertainty accounted for by the model. The real 30-year social discount rate recommended by the Office of Management and Budget, and discount rates used in similar analysis of invasive species risk, range between 1% and 6% (OMB, 2016; Rothlisberger et al., 2012). The analysis uses a triangular distribution assuming a most likely rate of 3%, consistent with best practices in financial valuation (Winston and Albright, 2016). A distribution is used rather than a discrete value, to reflect 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, suggesting the use of multiple discount rates (Arrow et al., 2013; Baumgärtner et al., 2015). The upper bound of 6% reflects real annual rates of return for Alaska's commercial salmon fisheries (Huppert et al., 1996).[18] Although many valuation studies focus on social welfare, the private investments at risk would justify the use of a private discount rate that reflects the source of capital and risk. The lower bound is consistent with recent research suggesting impacts to ecosystem services should be discounted at much lower rates, compared to impacts related to manufactured capital (Baumgärtner et al., 2015).

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[16] Hydrilla and elodea are treated using similar concentrations of Fluridone. Weibull(α,β).

[17] This timeframe was used rather than including 2003-2013. Between 2003 and 2014, two massive hurricanes added to cost as well as a change of management occurred (Shuler 2015 personal communication).

[18] 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 4.7 Model parameters used for analysis

Parameter	Units (region-specific)		Distribution or value	Source
Spatial dynamics				
Colonization rate, c	decimal	(yes)	(0, 1)	Model-determined
Extinction rate, e	decimal	(no)	Beta (0.002, 0.02 97)[a]	Mjelde et al. 2012
Proportion of colonized patches, P	decimal	(n/a)	(0, 1)	Model-determined
Patch state before management, β	binary	(yes)	0 or 1	Model-determined
Vector of management actions, M	binary	(yes)	0 or 1	Model-determined
Patch state after management, η	ternary	(yes)	0, 1, or -1	Model-determined
Random variable, u	decimal	(yes)	Uni (0, 1)	This study
Floatplanes				
Floatplane destinations, L^i	sites	(yes)	Table 4.4	Unpublished research
Pre-invasion destination count, l^i	sites	(yes)	Table 4.4	Unpublished research
Mean surface size of floatplane destinations, a^i	acres	(yes)	Table 4.4	This study
User loss per flight, w	2015 USD	(no)	Normal (185, 13.78)	Unpublished research
Surface size floatplane hub, $a^{i\text{-}base}$	acres	(yes)	Table 4.4	This study
Commercial fisheries				
Annual average sockeye growth rate, θ	decimal	(no)	Normal (-0.05, 0.149)	Unpublished research
Pre-invasion harvest, h_0	lbs	(yes)	Uniform (Table 4.1)	ADFG 2016a
Pre-invasion wholesale price for sockeye salmon products [b], p	2015 USD	(yes)	Lognormal (Table 4.1)	ADFG 2016b
Own-price elasticity of demand, ε	decimal	(no)	Uni (-12.78, -1.472)	Wang 1976; DeVoretz 1982
Ecological limit of sockeye harvest, K	lbs	(yes)	(Table 4.1 max harvest)	Unpublished research
Processing yield, γ	decimal	(yes)	(Table 4.3)	Knapp et al. 2007
Management				
Herbicide cost, s	2015 USD	(no)	Weibull (9.71, 907)	Schardt 2014
Discount rate, d	decimal	(no)	Tri (0.01, 0.03, 0.06)	Rothlisberger et al. 2012; OMB 2016

a) Truncated at 0.5. b) Weighted by the region-specific product amounts for frozen, canned, fresh, and other Table 4.3).

4.5   Results

Simulation results are presented for the no action and action alternatives, where the latter is aimed at minimizing long-term damages. Each of the alternatives assumed a base-case of

currently known elodea infestations (state of knowledge) and a hypothetical worst-case that assumed all regions were currently colonized by elodea. This latter case provided an upper bound to damages and acknowledged more uncertainty about the true state of elodea invasion in Alaska. Lastly, a sensitivity analysis looked into the robustness of the results. All monetary values are in real (inflation-adjusted) 2015 USD.

Before discussing the findings in detail, it's useful to look at the big picture: what did the model tell us about the economic risk of elodea invasions given the two management alternatives and assumptions about the state of knowledge where elodea colonized. Table 4.8 summarizes the mean statewide loss in ecosystem services, a measure of constant annual loss for the four resulting scenarios. Assuming the currently known state of invasion is the true state of invasion, then immediate action is minimizing long-term damages to fisheries and pilots by reducing the constant annual loss in ecosystem services by 88% from $124.6 million to $14.7 million annually (Table 4.8). Assuming elodea is currently much more widely distributed across Alaska and has colonized all seven study regions, then constant annual loss would be 43% larger than the $124.6 million per year estimated in the base-case. Immediate action would again reduce those losses by more than four fifth. The following sections each describes the four scenarios outlined in Table 4.8 in more detail.

Table 4.8 Constant annual loss in ecosystem services by management alternative and state of knowledge ($million of 2015 USD)

State of knowledge	Management alternative	
	No action	Immediate action
Base case (currently known invasions)	124.6	14.7
Worst-case (hypothetically all regions invaded)	177.7	25.0

4.5.1 No action alternative

4.5.1.1 Base-case

Given elodea's spatial spread dynamics, the parameterized metapopulation model predicted invasion of the seven regions over a 100-year time horizon, assuming no action was taken to intervene in elodea's floatplane-introduced spread. In this context, the probability of invasion varied over time and among regions, because it depended on varying floatplane-related

colonization rates across regions and random extinction events. Figure 4.5 shows the model's predictions, where existing invasions in the Cook Inlet and Gulf regions were forecast to remain across the time horizon, with a slightly lower invasion probability in year 100 due to the chance of extinction in these regions. The Kuskokwim and Bristol Bay regions had a higher than one in two chance of being invaded in year 10, but were forecast to see elodea invasions in year 50.
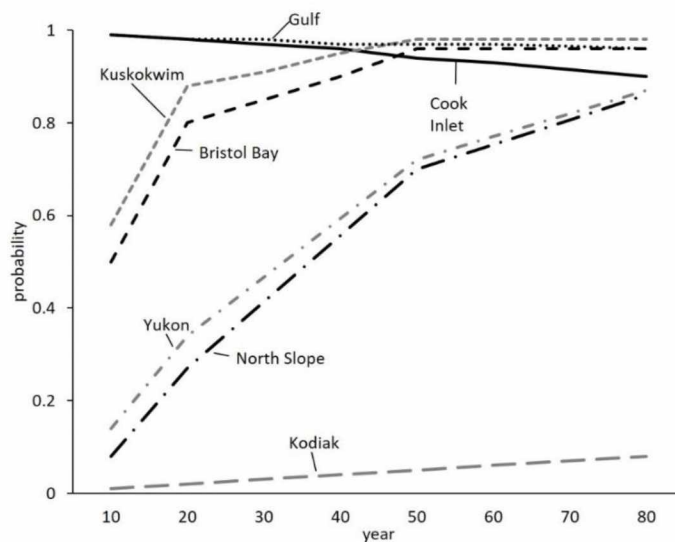

Figure 4.5 Probability of invasion by region over time, no action base-case

Floatplane-related introductions of elodea in the Yukon and North Slope regions are increasingly likely in the next 100 years. The probability of introduction in year 100 is estimated at 85%. It should be noted that the true probability of elodea invasion—considering all possible pathways—is higher in the Yukon region than simulated here. In 2016, there were several unmanaged elodea infestations in the Yukon region. These elodea populations are not currently in floatplane destinations, but they are still a source of elodea, transported by river current to new locations that could be used by floatplanes (Friedman, 2015). Since this study did not address other vectors, probability of introduction based on floatplanes only, underestimated the true probability of introduction considering all vectors.

The Kodiak region showed low probabilities of floatplane-introductions throughout the time horizon. This simulation result is consistent with Kodiak's insular floatplane operations that comprise mostly of intra-regional flights rather than flights to other regions (Figure 4.4). This is largely due to the surrounding topography, including the high peaks of the Aleutian Range to the north. Also, since Kodiak is an island in the Gulf of Alaska, a much larger proportion of Kodiak's floatplane operations occur in saltwater compared to those other regions. These saltwater flights

were not part of the survey because saltwater provides a natural risk buffer to the spread of elodea, which is intolerant to saltwater (Cook and Urmi-König, 1985).

Figure 4.6 A illustrates the harvest dynamics depicted in Equation 4.5 summed across all regions. Figure 4.6 B shows the number of floatplane destinations invaded over time as described by Equation 4.7 and summed across all regions. For both fisheries and pilot destinations, the range of uncertainty increased across the time horizon. At first glance it may seem that sockeye harvests were more uncertain than the number of landing sites invaded by elodea until year 10. This is shown by the standard deviation for fisheries harvest being larger than for floatplane destinations within the first ten years. This outcome is solely due to more uncertainty being captured by the model for the harvest dynamics. Specifically, post-invasion sockeye harvest levels and annual average sockeye growth rates were described by probability distributions accounting for uncertainty in those parameters (Table 4.7). In contrast, the colonization rates (flight ratios described in Equation 4.7) take on discrete values, ignoring uncertainty in pilot flying behavior. [19]

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[19] A probabilistic pathway model or probabilistic recreation demand model could have accounted for the uncertainty in landing-site invasion dynamics (Stanaway et al., 2011; Timar and Phaneuf, 2009). The analysis did not use such approaches for reasons discussed later.

A. Fisheries harvest

B. Invaded floatplane destinations
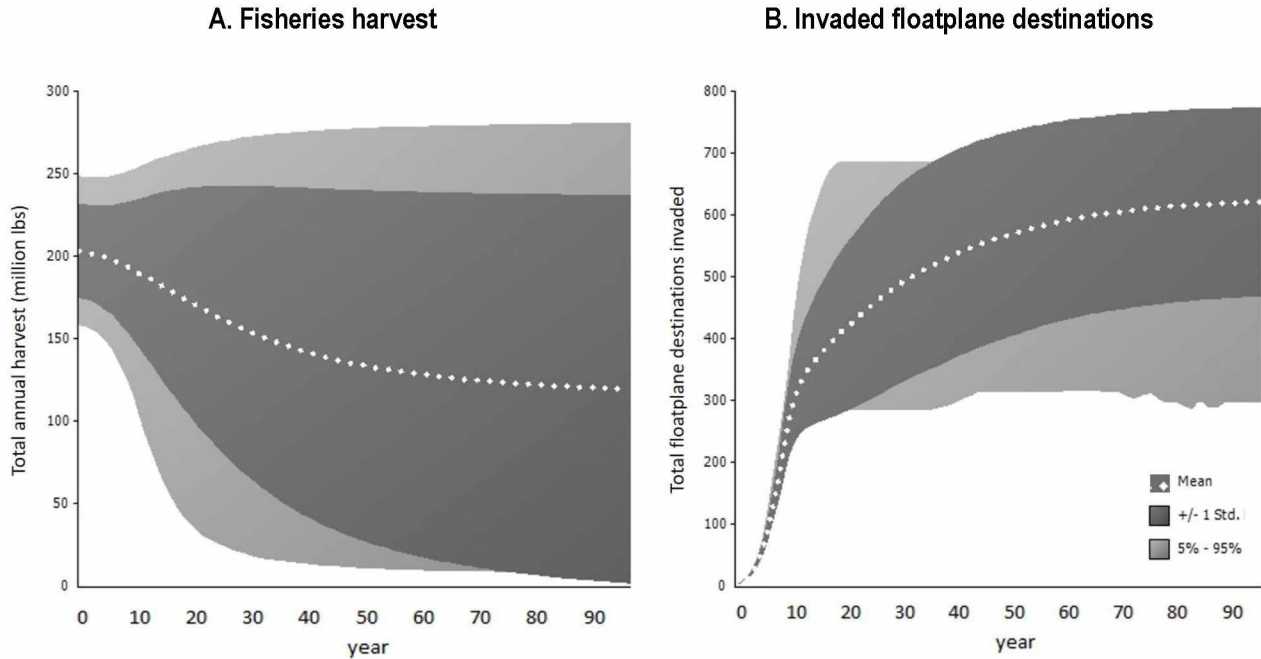
Figure 4.6 Uncertainty range for sockeye harvest (A) and plane destinations (B), no action base-case.

Applying Equation 4.9, the statewide cumulative loss to both fisheries and pilots amounted to a median— the most probable—cumulative loss of $2.6 billion in year 100 (90% CI: –$3.1 billion in net benefits; $16.4 billion in damages) (Table 4.9). The associated cumulative mean loss was $4.3 billion, indicating that the damage distribution was skewed. Figure 4.7 shows the distributions for cumulative losses for fisheries and pilots separately. Most of the loss (94%) was in the fisheries sector (mean cumulative loss $3.8 billion) versus loss to pilots ($250 million) (Table 4.10). Losses for both fisheries and pilots were highly skewed toward higher damages (Figure 4.7). Applying Equation 4.10, the most probable total constant annual loss equaled $97 million (90% CI: –$98 million in net benefits; $457 million in damages) (Table 4.9).

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A. Loss to fisheries

B. Loss to pilots
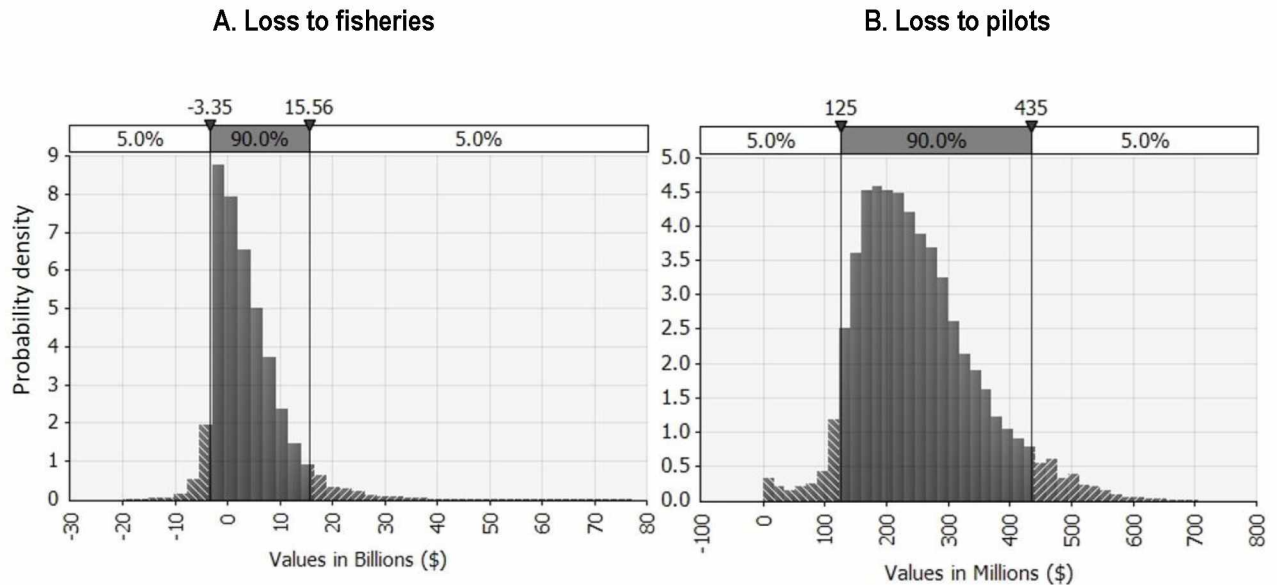
Figure 4.7 Distributions of future cumulative losses to fisheries (A) and pilots (B) for the no action base-case. Note differences in scale of horizontal and vertical axes.

Simulation results showed that the economic risk from elodea invasion not only varied among resource user groups but also varied across regions. Overall, Bristol Bay would bear the greatest risk (63%), followed by Cook Inlet (22%) and Gulf (12%) (Table 4.10). This outcome is mainly related to the projected fisheries damages and the high economic value of the Bristol Bay commercial sockeye fishery. Consequently, two thirds of statewide fisheries-related losses were projected to be in the Bristol Bay region, followed by Cook Inlet and Gulf with 19% and 12% respectively. This result is not surprising, given the varying run sizes and wholesale values of the regional sockeye salmon fisheries (Tables 4.1). Losses to pilots were projected to be greatest for pilots flying to the Cook Inlet region (70%), followed by pilots who fly to the Bristol Bay (22%), Yukon (9%), and Gulf (6%).

Table 4.9 Constant annual and cumulative losses for the no action base-case ($million of 2015 USD)

Region	Constant annual loss in ecosystem services (annualized NPV)			Future cumulative loss in natural capital (NPV over 100-year period)		
	Median	5%	95%	Median	5%	95%
Bristol Bay	51.2	–66.0	303.6	1,335.2	–2,122.9	11,049.9
Cook Inlet	22.4	–20.4	100.9	605.4	–631.0	3,448.3
Kuskokwim	0.2	0.0	0.9	5.9	–1.2	32.0
Gulf	13.5	–16.6	56.3	372.5	–515.0	1,964.2
Kodiak	0.5	–3.6	16.8	12.1	–118.8	564.3
North Slope	0.1	0.0	0.3	3.0	0.0	10.7
Yukon	0.7	0.0	1.6	18.5	0.0	61.0
Total[a]	97.3	–97.7	456.5	2,564.1	–3,142.5	16,405.6

a) Totals do not sum to individual values per region since the results depict distributions rather than discrete values. Annual NPV mean: $124.6 million, NPV mean: $4.03 billion.

Table 4.10 Cum. mean losses to fisheries and pilots, no action base-case ($million of 2015 USD)

Region	Fisheries loss		Pilots user loss		Total loss	
	Loss	%	Loss	%	Loss	%
Bristol Bay	2,481.6	66%	54.2	22%	2,535.8	63%
Cook Inlet	724.2	19%	174.8	70%	899.0	22%
Kuskokwim	4.9	0%	4.5	2%	9.4	0%
Gulf	471.9	12%	15.7	6%	487.6	12%
Kodiak	95.9	3%	0.6	0%	96.5	2%
North Slope	0.0	0%	3.8	2%	3.8	0%
Yukon	0.0	0%	22.6	9%	22.6	1%
Total	3,778.5	100%	249.8	100%	4,028.3	100%

4.5.1.2 Worst-case

In the worst-case scenario—assuming that elodea invaded all regions in year one—projected future cumulative mean loss increased by $1 billion statewide, again concentrated in the fisheries sector (Table 4.11). Compared to the base-case, fisheries-related loss in the Kodiak region increased more than five-fold and in Bristol Bay 20%. Projected pilots' losses increased very sharply in the Kodiak region and three-fold in the Yukon and North Slope regions. The larger

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loss estimates for Kodiak's fisheries and pilots are due to the large proportion of intra-region flights originating from Kodiak's main freshwater floatplane hub, as discussed earlier, and illustrated in Figure 4.4. This somewhat insular flight pattern leads to a reduced risk of elodea being transferred into the region, but once it is introduced leads to much larger losses.

Table 4.11 Cum. mean losses to fisheries and pilots, no action worst-case ($million of 2015 USD)

Region	Fisheries loss		Pilot user loss		Total loss	
	Loss	%	Loss	%	Loss	%
Bristol Bay	3,065.9	64%	66.9	23%	3,132.8	63%
Cook Inlet	724.6	15%	175.2	61%	899.8	22%
Kuskokwim	6.7	0%	6.2	2%	12.9	0%
Gulf	473.3	10%	15.9	6%	489.2	12%
Kodiak	533.2	11%	23.9	8%	557.1	2%
North Slope	0.0	0%	10.9	4%	10.9	0%
Yukon	0.0	0%	57.4	20%	57.4	1%
Total	4,803.7	100%	288.0	100%	5,091.7	100%

4.5.2 Action alternative

Under the action alternative, managers are assumed to minimize long-term damages by deciding when and where to eradicate elodea, under the constraint that agencies have resources to treat a single region in any given year. While this alternative is also somewhat hypothetical, it illustrates the importance of distinguishing between region-specific risk in statewide decision-making, and helps managers prioritize action to fight elodea.

4.5.2.1 When to take action

Figure 4.8 A suggests that the optimal time to take action is in the first year, where mean loss is minimized at $1.7 million with a 5% chance of exceeding $9.6 million and a 5% chance of exceeding $4.8 million in net benefits. The future cumulative mean loss and its 90% uncertainty range increase the longer management action is delayed (Figure 4.8 A). Figure 4.8 B shows the mean loss to fisheries and pilots, including the management cost to be expected if the elodea managers take action. Management costs are larger in the first 50 years compared to the second 50, because of the higher chance elodea populations would go extinct in the distant future,

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reducing later management costs. The upfront mean management cost of $2.3 million (90% CI: $1.8 million, 2.7 million) to treat currently invaded water bodies in Cook Inlet and Gulf is insignificant, compared to the avoided cumulative mean loss of $4 billion. The benefits of immediate action outweigh the costs by several orders of magnitude.

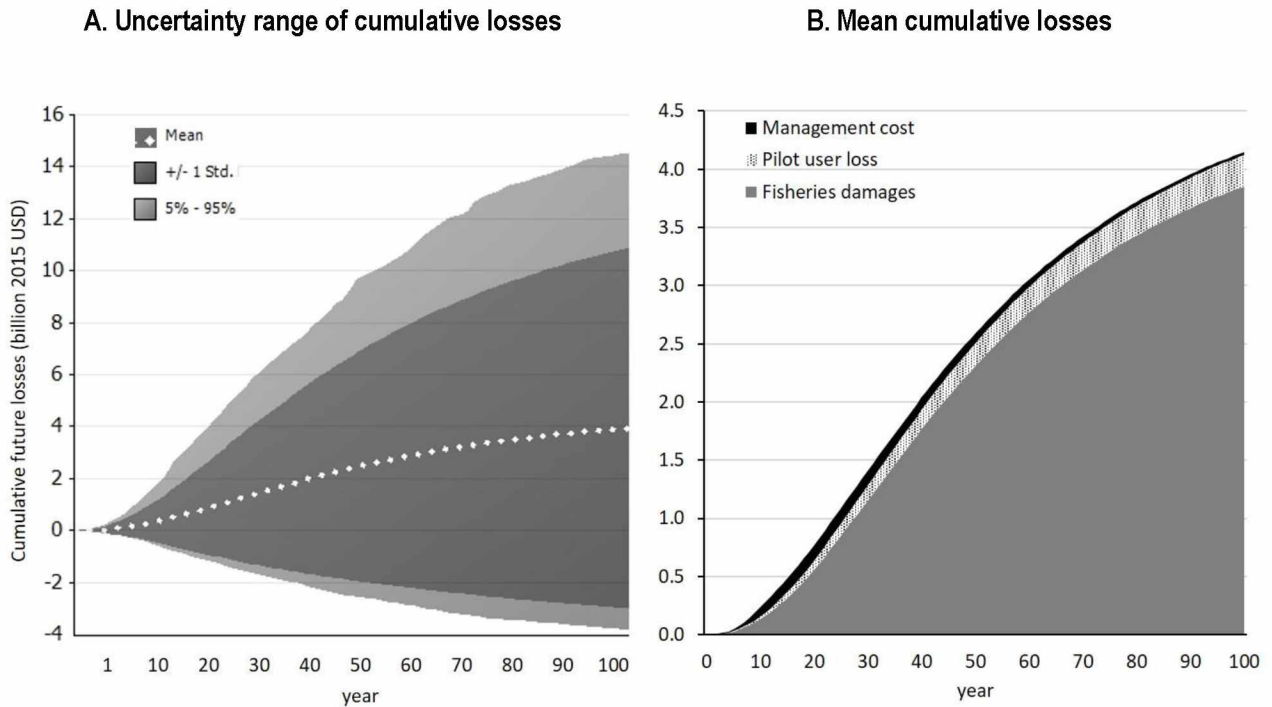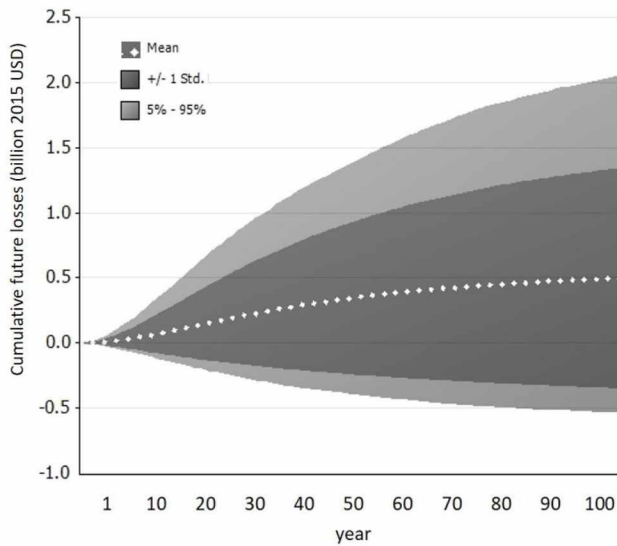**A. Uncertainty range of cumulative losses**   **B. Mean cumulative losses**

Figure 4.8 Uncertainty range of cum. losses (A) and mean cum. losses (B) for fisheries and pilots including management cost. Note differences in scale of horizontal and vertical axes.

4.5.2.2 *Where to take action*

An additional question regarding immediate action is where to manage first, assuming management agencies are only able to manage one region at a time. Considering the base-case, optimal management would first target invaded water bodies in the Cook Inlet region, and then those in the Gulf region. This result is consistent with what management agencies actually decided to do when they treated Lake Hood (Cook Inlet) in 2015 (DNR, 2015). However, more action is required. Figure 4.9 illustrates the cost of delaying management of invaded water bodies in the Gulf region, assuming management in Cook Inlet preceded action in the Gulf region. The mean statewide damages associated with not taking action in Gulf were forecast to amount to $40 million in year 10 and $500 million in year 100 (Figure 4.9).

A. Uncertainty range of cumulative losses
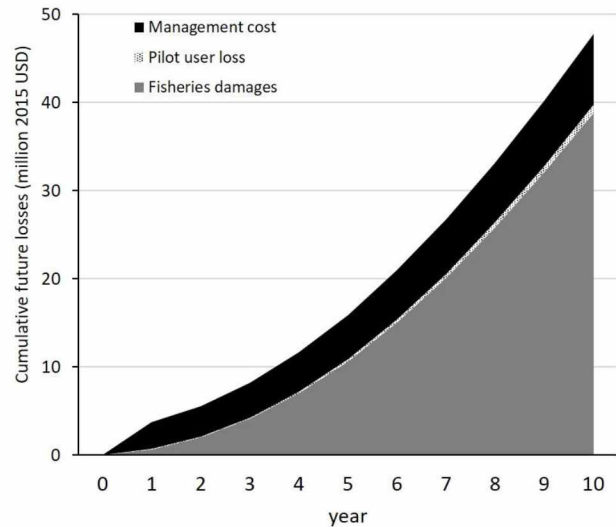
B. Mean cumulative losses

Figure 4.9 Uncertainty range of cumulative future losses if Gulf remains unmanaged (A) and associated mean cumulative losses to fisheries and pilots, including management cost (B). Note differences in scale of horizontal and vertical axes.

Management cost in Gulf in year 1 was estimated at $3 million, increasing to $8 million in year 10 (Figure 4.9 B). The year 1 estimate includes treatment of elodea in Eyak Lake, the region's floatplane hub, at a cost of $2 million. The projected management cost was based on average lake size and did not account for the cost associated with remote site access. For treating remote water bodies in Gulf—such as Martin Lake, for example—the estimated cost was likely underestimated. Regardless, the optimal management outcome would not change, even assuming larger cost.

Under the worst-case, assuming all regions were invaded, the model was used to establish an optimal management schedule. The result does not suggest a region-by-region treatment schedule to be better than immediate action in all regions. Such an exercise simply illustrates in another way which regions carry the largest risk of elodea transmission into high-value areas. Table 4.12 shows the optimal treatment schedule calculated by the model, and treatment schedules under other forms of prioritization. For the optimal management schedule, the highest priority for eradication would be given the Bristol Bay region. This result is not surprising, considering that the economic risk from elodea invasions is highest for that region. Interesting to note, under this worst-case, the priority order between Cook Inlet and Gulf changes, placing Gulf ahead of Cook Inlet. This result outlines once more the importance of spatially explicit

models that cover spread dynamics, but also the need to account for the influence of management.

Table 4.12 Evaluation of management strategies, hubs treated one year at a time, immediate action worst-case ($million 2015 USD)

Region	Treatment schedule (year)		
	Optimal as determined by model	Total flights	Flights to other regions
Bristol Bay	1	3	4
Cook Inlet	3	1	1
Kuskokwim	6	7	5
Gulf	2	6	7
Kodiak	4	4	6
North Slope	5	5	3
Yukon	7	2	2
Median cumulative loss	14.7	33.5	52.5

Managers could also use other ways to prioritize action across regions. For example, the prioritization might be based on the total number of flights originating from each hub. Under this management schedule, the median damages double. Similarly, basing prioritization on the number of flights to other regions triples damages (Table 4.12). This result shows the utility of quantitative bioeconomic risk analysis to management decision-making.

4.5.3 Sensitivity analysis

Given the above results, fisheries-related parameters most influenced the damage estimate. For the no action base-case, the annual average growth rate for sockeye salmon in elodea-invaded habitat, θ, contributed nearly half to the variance in the loss estimate. Much less influential were the discount rate (7%), and the pre-invasion Bristol Bay wholesale price for frozen sockeye products (<1%) (Table 4.13). The pre-invasion Bristol Bay harvest assumption and the pre-invasion price assumptions for other regions were also less influential (<1%). The contribution of the annual average growth rate to variance is related to the high range of uncertainty in expert-derived sockeye growth rates. There was a strong negative correlation between the growth rate and loss estimate (Table 4.13). The lowest growth rate of –0.12 increased the mean cumulative loss by $6 billion to $10 billion. The highest growth rate of 0.07 had the same magnitude but in the opposite direction, decreasing the mean cumulative loss to $2.1 billion in net benefits (Table

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4.13). As expected, simulation outcomes also varied assuming different discount rates. Large discount rates lead to future damages being discounted more than damages that occurred sooner (Table 4.13). With Bristol Bay being the largest sockeye salmon fishery in Alaska—and with frozen product its main line of business—the contribution to variance of Bristol Bay frozen-product prices is not surprising. A price assumption of $18.59/lb increased the mean cumulative loss by $3.4 billion to a total of $7.4 billion, whereas a price of $0.82/lb reduced mean losses by $1.7 billion to a total of $2.3 billion (Table 4.13).

Table 4.13 Sensitivity to parameter assumptions, no action base-case

	% Contribution to variance	Correlation (Spearman Rank)	Mean cumulative loss (NPV billion USD) [a]	
			Lowest input assumption	Highest input assumption
Annual average sockeye growth rate, θ	46%	–0.86	10.03	–2.1
Discount rate, d	7%	–0.16	8	1.8
Price for frozen product in Bristol Bay	<1%	0.11	2.3	7.4

a) The NPV mean was $4.03 billion. All losses are calculated holding all other parameters constant at their mean levels.

The analysis also looked at how sensitivities in the no action management alternative varied from those in the immediate action alternative (Figure 4.10). In particular, the annual average growth rate influenced the loss estimate differently in the no action alternative (Figure 4.10 A) than it did under immediate action (Figure 4.10 B). Recall that the sockeye growth rate was drawn from a normal distribution, with a 35% probability of elodea having positive growth outcomes. In the no action alternative, where losses accumulated over a 100-year period, these positive growth rates had a lower effect ($0–$2 billion) compared to negative growth rates ($0, $10 billion) (Figure 4.10 A).

By contrast, under immediate action, positive growth rates resulted in forgone benefits to commercial fisheries of between $0 and $3 billion (Figure 4.10 B). These losses were a consequence of treating elodea and eliminating chances of elodea benefitting salmon growth in the future, assuming elodea had solely positive effects on salmon. This result highlighted the double-edged sword of elodea management for fisheries, and underlined the importance of accounting for uncertainty in the sockeye-growth parameter. Under immediate action, the sensitivity to other parameter assumptions was also slightly different. The uniform distribution draws and elasticity of demand had the second and third highest influence on the mean loss estimate, whereas these had much less influence in the no action alternative. The influence of

the uniform distribution draws suggests that loss estimates were sensitive to where elodea was colonizing in the first year—a simulation effect that averaged out over a longer time horizon in the no action alternative. Due to the shorter time horizon under immediate action, the responsiveness of demand was also more influential than for example, pre-invasion price assumptions. If demand is more inelastic ($-2 < \varepsilon < -1$), meaning large changes in harvest resulted in large changes in price, it leads to higher losses (Figure 4.10).
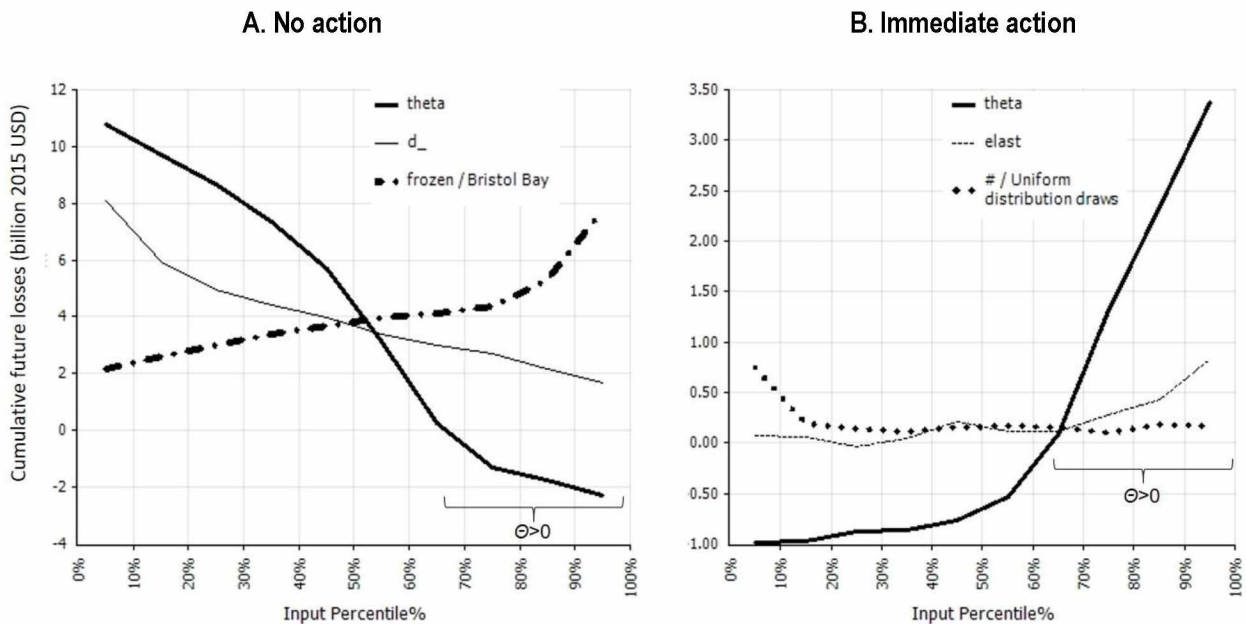
A. No action

B. Immediate action

Figure 4.10 Sensitivity analysis for no action (A) and immediate action (B). Note differences in scale of horizontal and vertical axes.

4.6 Discussion

Ideally, damage assessments like the one presented here would be based on empirical evidence of economic and ecological changes before and after invasions, while controlling for different drivers of ecosystem and human-system conditions. Such data would allow for a detailed look into how the ecosystem and the economy adapt to changes in ecological conditions driven by an invasion and resulting changes in prices, harvested quantities, and income to stakeholders. Also, such data would allow for data-driven validation of the developed model. While the data needs would be enormous, data collection could only occur under experimental settings, bringing into question the validity of the results in practice and the purpose of forecasting. In such situations, the impacts of an invasion over time will always be subject to great uncertainty. Integrating as much information on ecological and economic dynamics within a spatial context is

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desirable but simplifications in model design will have to be made for the results to be tractable, particularly within a local management decision context. Formal expert elicitation, while not a panacea for biophysical experimentation, provides a feasible work-around to data limitation and lets researchers account for uncertainty.

This study quantified the risk that pilots create for themselves and other stakeholders—endogenous risk—by integrating spatially-explicit ecological models with benefit cost analysis and expert elicitation. The model design focused on being relevant to local stakeholders and local management decisions. The year-by-year changes to environmental and economic conditions were treated deterministically in order for results to remain amenable and enabling an easy integration of ecological and economic modules. Alternative approaches to the analysis of endogenous risk, use a real options framework, which applies financial option pricing to resource management problems under uncertainty (Finnoff et al., 2010). The real option framework has been found to provide more accurate risk estimates that are often reduced and narrowed compared to other approaches (Finnoff and Shogren, 2004).

Similarly, this study showed that loss estimates can be narrowed and reduced by incorporating the human-mediated spread and spatially explicit population dynamics related to the invader. Figure 4.11 compares the cumulative 100-year loss to fisheries, not accounting for spread dynamics (unpublished research), with the fisheries loss that acknowledges the chance of elodea colonization and collapse. The median cumulative loss disregarding these additional factors amounts to $3.8 billion (90% CI: −$4.5 billion, $20.5 billion). This study reduced and narrowed the cumulative median loss by $1.4 billion to $2.4 billion (90%CI: −$3.5 billion, $16 billion) (Figure 4.11) and underlined the importance of integrating pathway dynamics and specifying invasive species traits in bioeconomic risk modeling.

The metapopulation framework allowed simple integration of trait-specific characteristics such as elodea's possible collapse, floatplane pathway, and management interventions that change the pathway. Alternative modeling approaches that address spatial spread could have used the recreation demand model (random utility model) directly for estimating the colonization probability through the floatplane data (Timar and Phaneuf, 2009). Additionally, gravity models have also been used for this purpose. However, these models would have prevented the simple integration of elodea's population dynamics, particularly species-specific traits such as landscape-wide population collapse. For this reason, the metapopulation approach was used for its simple implementation and integration.
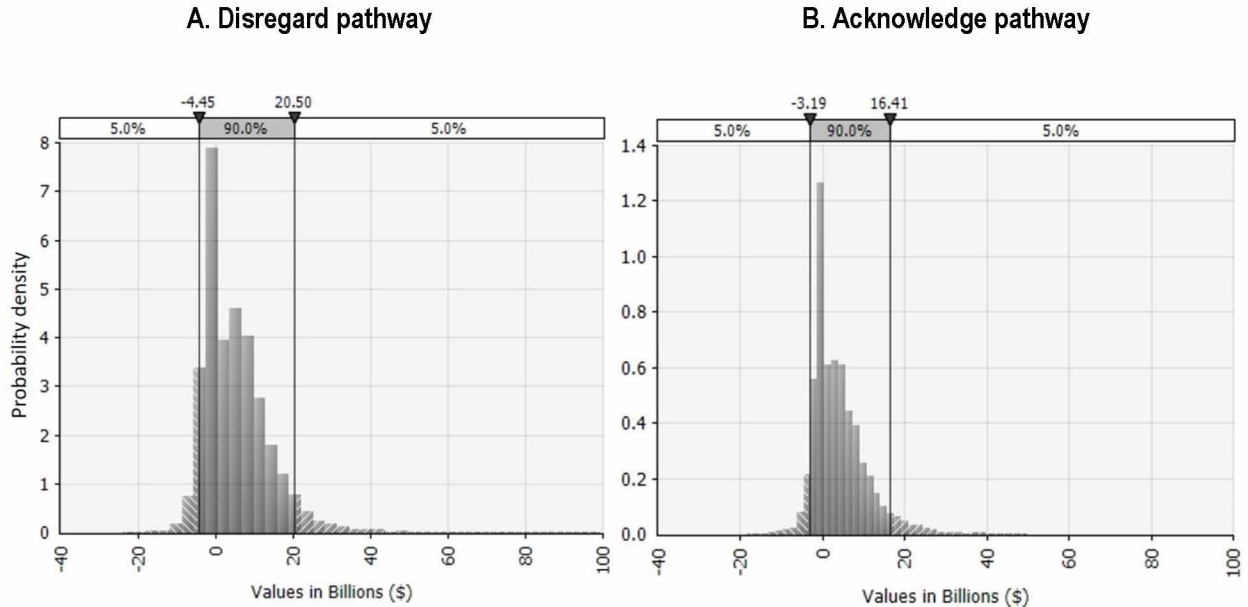
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A. Disregard pathway **B. Acknowledge pathway**

Figure 4.11 Cum. loss without (A) and with pathway dynamics (B), no action base-case.

The sensitivity analysis showed that the damage estimates were robust to parameter assumptions. However, there were several factors that would have resulted in higher or lower damages than presented. Higher damages would have been expected if the welfare changes to other salmon fisheries like subsistence and sport salmon fisheries would have been included. Sockeye salmon make up 26% of Alaska's commercial salmon catch and over half the value of that catch (Knapp et al., 2007). Since Alaska-specific economic data on the non-market value of subsistence and sport fisheries are rare, the region-specific risk to fisheries was skewed toward regions that have commercial sockeye fisheries. There is, however, evidence that the net economic value of sport and subsistence fisheries can be more than twice as large as that of commercial fisheries (Duffield et al., 2013). The model's focus on commercial sockeye fisheries particularly affected risk estimates for the Yukon region, where salmon species other than sockeye are supporting livelihoods (Brown et al., 2015). In addition, the economic risk to floatplane pilots calculated for the Yukon region was likely underestimated, given that there are existing unmanaged elodea invasions that are not yet known to be in the floatplane pathway but which may eventually spread there.

Additional reasons for underestimating risk relate to the fact that the model only accounted for consumer values ignoring affected producer values. For example, loss to commercial

floatplane operators and the loss of income to fishermen remained unaccounted. The model would have estimated larger damages if it accounted for downstream effects within the supply chains related to the lost salmon harvest. For example, almost all Bristol Bay processors are from Washington state, and many supplies for the seafood processing that takes place in Alaska is purchased outside Alaska. Approximately one-third of Bristol Bay fishermen and two-thirds of processing workers are from other West Coast states, suggesting broad ripple effects in the economy that this study did not analyse (Knapp et al., 2013). However, the early stages of the elodea invasion justify not incorporating downstream effects yet (Lodge et al., 2016). Therefore, investigating impacts to two sectors of the economy that are most likely affected is valid particularly since the elodea infestation has not yet resulted in economy-wide impacts.

Moreover, effects of elodea on other ecosystem services are likely already present in Alaska but were not captured here. For example, there is evidence that elodea affects nutrient cycling (Ozimek et al., 1993), reduces lake-front property values by up to 16% (Zhang and Boyle, 2010), and has severe effects on biodiversity (Mjelde et al., 2012). Given, these economic impacts were not incorporated into the model, the calculated estimates are lower than the true impacts to the economy. In addition, these welfare effects are likely distributed differently than the fisheries values that drive the presented results. The potentially varying distribution of other welfare effects could change the prioritization of treatment among regions as well.

Also, it is recognized that the spatial prioritization for a hypothetical region-by-region treatment schedule may not fully capture the need of resource managers tasked with eradicating elodea. The estimated prioritization schedule depended on the model's floatplane pathway dynamics and the way those where modeled. The model does not capture the absolute probability of colonization as would have been accomplished by a probabilistic model where the measure of risk would have been related to the actual flight frequencies (propagule pressure) (Stanaway et al., 2011). Instead, the model used flight proportions from elodea infested lakes to set discrete region-specific colonization rates (Equation 4.1). While this approach is easily integrated into the existing model it had shortcomings that resulted in the risk for the Gulf region being overestimated. The Gulf region showed flight frequencies that are low compared to other regions (Table 4.5). In addition, the Gulf region is bound by high mountain ranges and ocean that form a natural buffer for elodea dispersal through natural and human-related pathways. Floatplane traffic is consequently constrained by these topographic boundaries which could be strategically used by

management to combat invasive species. These topographic attributes, however, did not enter the model (Wilen, 2007).

Lastly, it is important to note that any economic benefits related to management need to be viewed as being simplified. In specific, the approach assumed that management action is a perfect substitute for environmental quality—that is, society can achieve pre-invasion environmental quality by avoiding the damages. However, this relationship is rarely straightforward, especially when some aspects of avoided cost cannot be offset by management actions (Hanley and Spash, 1993). For example, the partial irreversibility of non-target effects related to herbicide treatment (extirpation of other native plants for example) would result in additional ecological costs and lower environmental quality compared to the pre-invasion state. Such conditions were not accounted for.

Other aspects of the approach taken may have resulted in overestimating the true potential damages. These factors mainly relate to the deterministic modeling approach which ignored how the environment and economy respond to an elodea invasion. For example, the model did not capture that salmon could adapt to elodea by straying to new habitat. Similarly, fishermen could adapt to lower harvest levels through technological or institutional change. If the model would account for these adaptations, the estimated loss would be lower and elodea's effects on salmon would be more moderate throughout the model's time horizon. In addition, the expert elicitation did not collect information on whether experts truly believed elodea could lead to extirpated salmon populations. In the DCM, experts selected scenarios they believed resulted in either salmon being extirpated or persisting and similarly the SEJ-elicited growth rates that could lead to extirpation over any given time horizon. For most experts this binary extreme outcome response was not problematic. Four out of 25 experts who commented after the elicitation wrote that they believed in elodea resulting in moderate change to salmon health rather than a catastrophic outcome. Two thirds of all experts rated elodea's overall effect on salmonid persistence as moderately negative (unpublished research).

A different modeling approach that would add year-by-year stochasticity to the effect of elodea on salmon could moderate the influence of elodea on salmon further and result in less catastrophic outcomes over the 100-year time horizon. However, it is important to note that other aspects of the model already moderate the potential salmon extirpation effect of elodea over time. First, the model's 100-year time horizon was chosen because of its ecological relevance in

illustrating possible short-term collapse and moderate long-term changes in salmon abundance.[20] Moreover, the spatial dispersal via floatplanes resulted in varying probabilities of introduction across fisheries. Finally, elodea's chances of collapse were explicitly accounted for and indirectly moderated elodea's effect on salmon over time. Analysis depicted in Figure 4.12 shows that the chance of salmon extirpation was increasing across the 100-year time horizon and varied among regions. However, collapse of any salmon populations in the study regions was far from certain. For example, salmon populations in the Bristol Bay reached a probability of extirpation equal to 0.2 in year 100, assuming no action was taken (Figure 4.12).
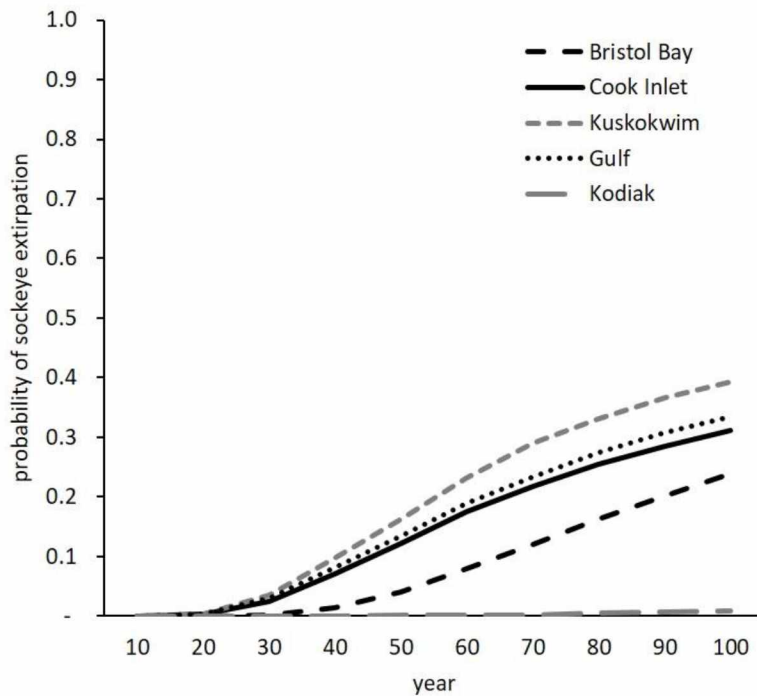

Figure 4.12 Probability of sockeye extirpation, no action base-case

Extensions of this research could develop a species distribution model that is both probabilistic in nature and includes habitat suitability (Luizza et al., 2016). This integration could also be used to more closely analyse the transition probabilities between introduction, establishment, spread, and impact—invasion steps that if accounted for improve predictions for elodea's spatial spread (Muirhead et al., 2011). Such extension could also assess the probability of successfully eradicating elodea from Alaska, a valuable piece of information for current

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[20] The model's 100-year time horizon is also consistent with bioeconomic research on invasions (Lodge et al., 2016).

management investments (Spring and Cacho, 2015). While the current analysis sacrificed some of this spatial detail, it was able to account for important spatial and temporal dynamics affecting fisheries on the one hand and floatplane pilots on the other—which offered novel comparisons between affected resource user groups. Despite higher resolution and added capabilities, however, any model is limited by the number of other invasion pathways it can incorporate. Most importantly, as long as river currents can further distribute elodea across the Yukon region, that region may continue to be a source of elodea for other regions as well. Since floatplane destinations in the Yukon region are currently elodea-free, the damages discussed here did not fully account for that risk.

4.7   Conclusion

Upfront management action on aquatic invasive species can have large long-term benefits for the protection of highly productive ecosystems. This simulation study empirically estimated the potential future damages to commercial sockeye salmon fisheries and the potential user loss to recreational floatplane pilots, and weighed these damages against the potential cost of management. Results show that if no action is taken to eradicate existing elodea invasions in the state, the median annual loss in ecosystem services amounts to $97 million (90% CI: $-97 million, 456 million). Even though the range of the damage estimate is large, the median estimate suggests that substantial investment is necessary to prevent aquatic invasive species from establishing in Alaska. Establishing funding mechanisms that allow early detection and rapid response are essential.

On a national scale, considering the attention the threat of invasive species has received elsewhere, this study raises an important point. Bioeconomic research has shown that preventing biological invasions produces greater benefit for society than managing invasions once they are established. This fact raises the question of whether past investments to manage invasive species were optimally allocated to ecosystems that will never return to an unimpaired state, or whether such investments would be better directed toward preventing damage to some of the most productive ecosystems that are of national and global significance. With the invasive species problem in its infancy in the Arctic and Subarctic, society still has the opportunity to achieve large returns on investment—but the window of opportunity is quickly closing.

Moreover, the study showed that estimating financial damages for different users is important for engaging with stakeholders that are affected but contribute to spread of the invasion. Financial damage estimates can create incentives for market-based conservation mechanisms (Engel et al., 2008). Private investment in invasive species management in particular can be useful for cases like this one, where resource managers tend to have sole responsibility. This sole responsibility can "crowd out" private investment, as is evident in Alaska, where private funding so far has contributed little to active invasive species management. There are particular funding gaps for preventing the spread of existing invaders or preventing new arrivals (Finnoff et al., 2005; Schwörer et al., 2014). In addition, region-specific risk estimates inform optimal management across large landscapes. The presentation of local economic data as achieved by this study, is often directly linked to whether managers think the model results are reliable, and whether local stakeholders trust the estimates. While benefit-transfer methods may bridge this gap, they often cannot provide what's needed (Holmes et al., 2010).

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General Conclusion

This bioeconomic risk analysis serves as a new tool and stepping stone towards a more proactive risk management approach for elodea and other invasive species yet to arrive in Alaska. It combines expert elicitation with economic valuation and ecological modeling to quantify economic risk of elodea and evaluate uncertainty regarding management action. The results show that social science can significantly contribute to the parameterization of ecological models, especially if ecological processes are driven by human dispersal. In addition, bioeconomic information goes well beyond what relative risk scores are able to report. Expert elicitation results show that experts believe high dissolved oxygen levels are twice as important for sustaining salmonids in elodea-invaded habitat as they are for salmonids occupying uninvaded habitat. The median probability of experts choosing invaded over uninvaded habitat for persistent salmonids is 0.041 (mean 0.21) indicating that experts are highly concerned about elodea invading salmon habitat. This concern particular relates to elodea's boom and bust cycles that cause fluctuations in dissolved oxygen.

The most probable economic loss to commercial fisheries and recreational floatplane pilots is $97 million per year, with a 5% chance that combined losses exceed $456 million annually. Using non-market valuation, the lost trip value to the average Alaska floatplane pilot whose destination is an elodea-invaded lake is $185 (95% CI: $157, $211). These estimates show that even though the range of future economic loss is large, the certainty of long-term damages favors investments to eradicate current invasions and prevent new arrivals. Upfront management of all existing invasions is found to be the optimal management strategy for minimizing long-term loss.

Financial measures of risk have the advantage of communicating risk in a way that is familiar to a broader audience compared to more commonly used relative risk scores. Even more importantly, bioeconomic risk analysis is capable of incentivising stakeholders to behave in ways that assures the resources they value remain protected from invasive species. This incentive is of particular importance for stakeholders who play a direct role in the dispersal of the invader, in this case floatplane pilots. Such incentives can help inhibit invasion spread and are especially useful to communicate in the early stages of an invasion such as the case with elodea in Alaska. It is also important to recognize that stakeholders are more likely to trust the estimates if they are

derived from local data and therefore able to capture variation in local environmental and social conditions as presented here.

This study's region and stakeholder-specific analysis also recognizes the importance of whose values count when it comes to policy-making (Martinez-Alier, 2001). The establishment of elodea in the Arctic and Subarctic illustrates that these regions are no longer immune to the invasive species threat. As new transportation corridors open and economic development pressure rises, invasive species will more easily find old and new ways to being introduced in remote ecosystems (CAFF, 2013; Heikkinen et al., 2009). In this context, addressing society's trade-offs in its decision-making becomes increasingly important. For example, non-renewable resource development remains a critical economic sector in the Arctic and Subarctic, yet non-renewable development often conflicts with existing ecosystem-based sectors such as fisheries (Larsen and Fondahl, 2014). Policy decisions on such development are more informed if potential costs of invasive species introductions are internalized, showing which stakeholders bear the cost and benefits of the policy decision (Lázaro-Touza and Atkinson, 2013).

Moreover, an approach to economic valuation that is locally relevant can assist in the design of market-based conservation mechanisms providing continued funding to protect productive ecosystems (Engel et al., 2008). Private investment in invasive species management in particular can be useful for cases like elodea management in Alaska, where resource managers tend to have sole responsibility. This sole responsibility can "crowd out" private investment as evident in Alaska where private funding contributes less than 1% to active invasive species management with particular funding gaps for prevention (Finnoff et al., 2005; Schwörer et al., 2014).

Results from this study suggest that future invasive species investments may be better directed towards preventing damage to some of the most productive and intact ecosystems of national and global significance (Pinsky et al., 2009). Considering the attention and investment the invasive species threat in the Great Lakes has received in the past decade, the much larger damage estimate by this study raises the question whether large invasive species management investments are justified in ecosystems that will never return to an unimpaired state. Yet, the reality of allocation is always more complex as investments to manage invasive species compete with an array of other agency management goals, such as agricultural and wildlife management. Also, as a society, our investments in managing invasive species compete with investments for broad social goals—such as funding for children's health and education. With the aquatic invasive

species problem in its infancy in the Arctic and Subarctic, society still has the opportunity to achieve large returns on investment—but the window of opportunity is quickly closing.

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Appendix

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Institutional Review Board

909 N Koyukuk Dr. Suite 212, P.O. Box 757270, Fairbanks, Alaska 99775-7270

January 25, 2016

To: Joseph Little
               Principal Investigator

From: University of Alaska Fairbanks IRB

Re: [612464-5] A Decision Analysis for Management of Elodea in Alaska: Expert Elicitation

Thank you for submitting the Amendment/Modification referenced below. The submission was handled by Exempt Review. The Office of Research Integrity has determined that the proposed research qualifies for exemption from the requirements of 45 CFR 46. This exemption does not waive the researchers' responsibility to adhere to basic ethical principles for the responsible conduct of research and discipline specific professional standards.

Title:	A Decision Analysis for Management of Elodea in Alaska: Expert Elicitation
Received:	January 17, 2016
Exemption Category:	2
Effective Date:	January 25, 2016

This action is included on the February 3, 2016 IRB Agenda.

Prior to making substantive changes to the scope of research, research tools, or personnel involved on the project, please contact the Office of Research Integrity to determine whether or not additional review is required. Additional review is not required for small editorial changes to improve the clarity or readability of the research tools or other documents.

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DATE: June 9, 2016

TO: Joseph Little
FROM: University of Alaska Anchorage IRB

PROJECT TITLE: [612464-11] A Decision Analysis for Management of Elodea in Alaska: Expert
                    Elicitation
SUBMISSION TYPE: Continuing Review/Progress Report

ACTION: APPROVED
DECISION DATE: June 9, 2016
EXPIRATION DATE: March 23, 2017

This letter is in response to your request for continued Institutional Review Board (IRB) approval of your
research project.

This project was originally reviewed by the IRB in *March 2015*. Your progress report states that you have
had no problems with data collection, there were minor changes to your protocols, and you would like an
extension of IRB approval. Your request is hereby granted.

Should data collection extend beyond the expiration date of this letter, please submit another Continuing
Review Report (Progress Report) for continuation of IRB approval, or a Final Report after you have
completed your project. These forms are available on IRBNet.

On behalf of the entire Board, I wish you continued success with your study.

Sharilyn Mumaw, M.P.A.

Research Integrity & Compliance Officer

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