

1 Quantifying the cost of cultural bias in conservation
2 decision-making

3

4 **1 Abstract**

5 Human systems shape not only ecological data collection, but also perspectives and assumptions made
6 during model building, generating uncertainty about how dominant value systems and cultural bias limit
7 ecological inference. Understanding how this uncertainty propagates in conservation decision-making requires
8 translation beyond abstract statistical measures and toward performance on real-world objectives. Here we
9 develop a quantitative framework combining uncertainty quantification and decision theory to understand
10 the value of reducing uncertainty generated by cultural bias for a decision maker. We demonstrate this
11 framework in the context of decision-making in a multi-species dynamical system in the Columbia River
12 basin (CRB), where the Pacific lamprey – an ancient, foundational species in the CRB – modulates salmonid
13 ocean survival both as a parasite of salmonids and a predation buffer against marine mammals. Despite its
14 critical ecological role in the CRB and its high cultural value for Columbia basin Indigenous peoples, the
15 Pacific lamprey has faced a precipitous decline in the last century, largely stemming from Euro-American
16 cultural bias. Asymmetric measurement error and observation of local, rather than global, properties of
17 the system limit understanding of density-dependence in species interactions, and subsequently evaluation
18 of management actions. We quantify the cost of lamprey uncertainty in units relevant for a decision maker,
19 demonstrating that the value of information around overlooked species can be considerable. These results
20 highlight how Situated Modeling in ecological management can be used to interrogate how modeling as a
21 process and practice is contextualized.

22 **2 Introduction**

23 Building an ecological model is an active exercise of bringing about the world (Schlüter et al., 2025). Yet
24 this world-making process is limited, as models tend to exist where the light is shining (Figure 1), often

reflecting what is known and where the data is, rather than what is unknown. The presence or absence of parameters and processes in a model can reflect dominant systems of knowledge production, dominant societal values, human perceptions of species charisma and value, and cultural bias (Hughes et al., 2021; Silver et al., 2022; Stoudt et al., 2022). For decision-makers, uncertainties that are known and articulated already strain management of ecological systems (Polasky et al., 2011), yet understanding how cultural bias and systems of power generate uncertainties that propagate in conservation decisions remain largely unexplored.

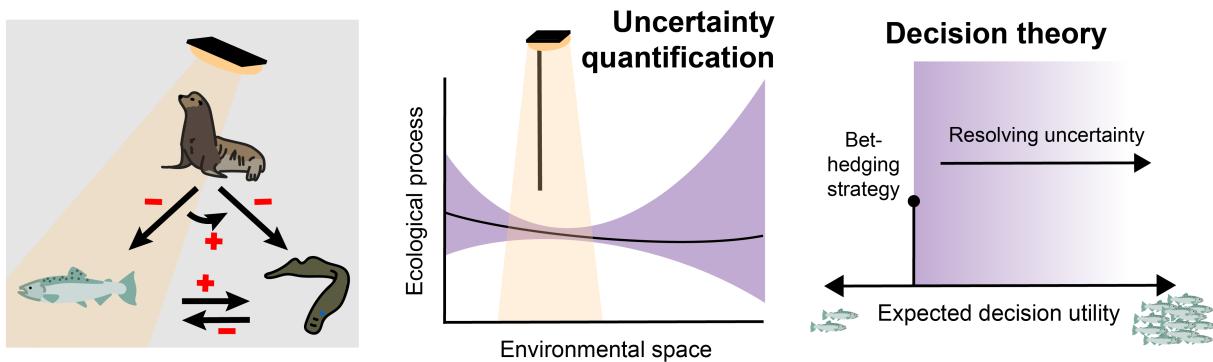


Figure 1: What is the cost of looking only under a lamp-post for a scientific solution, simply because that's where the light is? Here we present a methodological framework combining uncertainty quantification and decision theory that can be used to quantify the cost of cultural bias to a decision-maker.

The Columbia River Basin (CRB) provides a fruitful setting to quantify the cost of cultural bias in conservation decision-making (Box 1). Over the past few decades, the endangered, migratory Pacific salmon has faced increased predation pressure by California sea lions traveling into the Columbia River (Wargo Rub et al., 2019). This conflict between two federally protected and broadly beloved species has strained decision-making, ultimately precipitating an amendment to the Marine Mammal Protection Act to allow legal euthanasia of these sea lions. Although the Columbia River salmon fisheries are among the most intensely managed and heavily studied fisheries in the world, one relatively understudied fish species – the Pacific lamprey – may play a role in restoring balance in this system (Figure 1).

The Pacific lamprey is an ancient, jawless fish that nearly all extant species in the CRB have co-evolved alongside (Close et al., 2002). Importantly, the Pacific lamprey holds high cultural and spiritual value for CRB Indigenous peoples, and as a high value prey item for marine mammals, the lamprey may relieve predation pressure on salmon (Columbia River Inter-Tribal Fish Commission, 2011). Despite this value, however, Pacific lamprey has been driven to near extinction over the last century, largely due to cultural bias and exclusion by Euro-American society and management (Box 1). While modern management is reconciling with this history and increasing investment in lamprey restoration (Clemens et al., 2017), the legacy of nearly

47 a century of neglect is reflected in the data. Most data about salmon-lamprey-sea lion interactions come from
 48 observation systems designed for salmon, not lamprey (Kostow, 2002), and understanding global, density-
 49 dependent dynamics is challenging, since observations are limited to a parametric space where lamprey are
 50 at much lower abundance than historic levels (Figure 2; Figure S1).

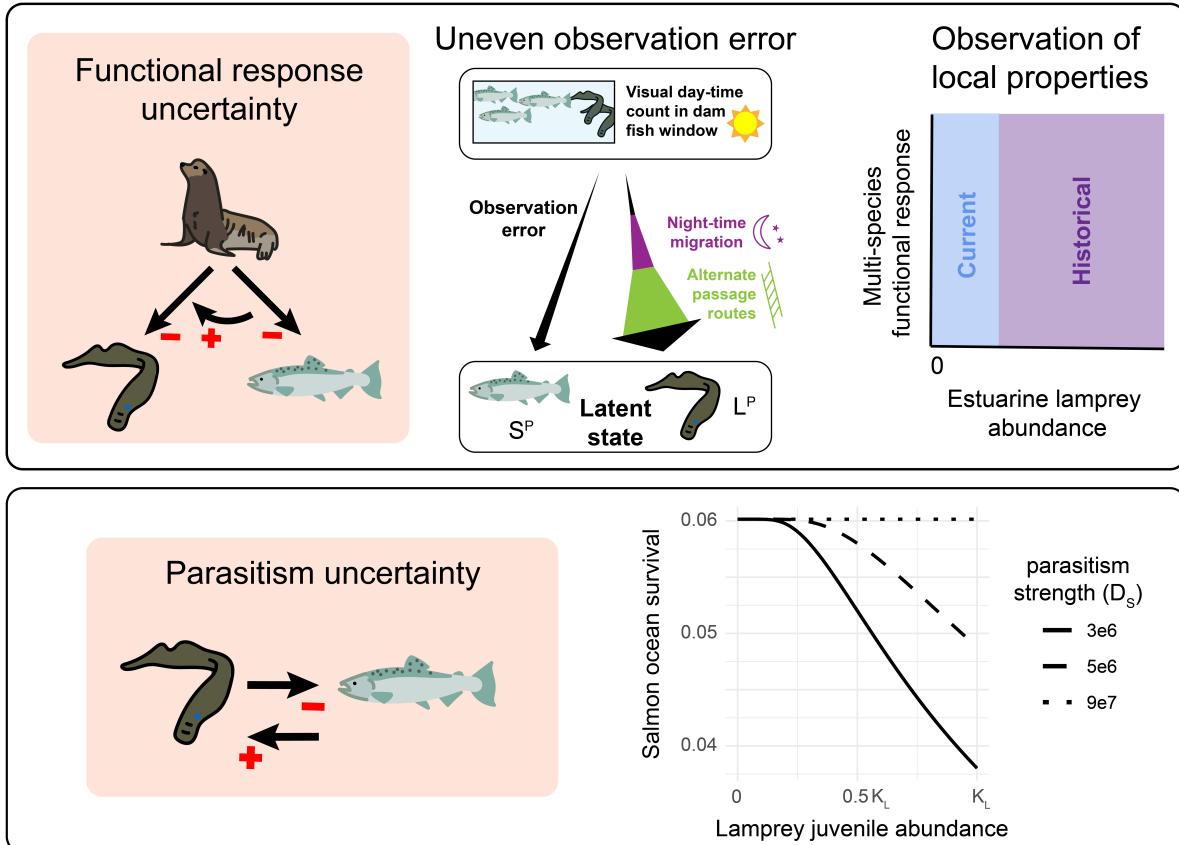


Figure 2: Two sources of parametric uncertainty considered in the decision problem: **A.** Multi-species functional response uncertainty, derived from 1) uneven observation error of the true abundance of fish passing through the dam (S^P and L^P for salmon and lamprey, respectively) and 2) observation of local properties of the density-dependent multi-species functional response (i.e., observation space limited to low Pacific lamprey estuarine abundance, E_L). **B.** Parasitism uncertainty, or an unknown rate at which salmon ocean survival (proportion of juvenile salmon returning the estuary, E_S/J_S) declines with juvenile lamprey abundance (J_L). The parameter D_S describes this rate, and values are selected to cover the universe of possibilities, from a commensal lamprey-salmon marine relationship ($D_S = 9e7$), to a scenario where salmon ocean survival declines to 0.04 at high lamprey densities ($D_S = 3e6$).

51 Like all ecological observations, data reflecting salmon-lamprey-sea lion interactions are an opportunistic
 52 window into a complex, likely non-linear system, generating statistical uncertainty in ecological inference.
 53 Yet these windows of opportunity are not neutral and have been shaped by human systems, and therefore
 54 statistical uncertainty can be artifacts of human bias (Figure 1). Translating the cost of this bias for decision-
 55 makers requires moving beyond abstract statistical scores and towards measurements on real-world objectives

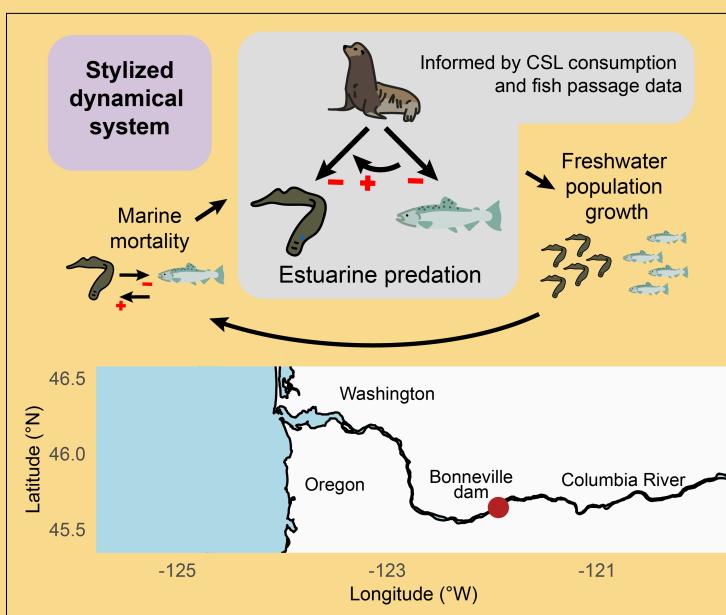
56 (Boettiger, 2022). While the ecology and conservation literature provides little guidance on how to approach
57 such a problem, we can draw from decision-theoretic methods to measure the cost of cultural bias in units
58 relevant for a decision maker.

59 In this study, we quantify the extent to which historical cultural bias against the Pacific lamprey impedes
60 decision-making in the CRB. We first quantify uncertainty in the multi-species functional response (MSFR),
61 or the functional form describing the rate of California sea lion predation as a function of the abundance
62 of Pacific lamprey and spring Chinook salmon the Columbia River estuary (Rosenbaum et al., 2024). This
63 Bayesian model quantifies global uncertainty in the MSFR and is developed to consider how systems of
64 knowledge production have generated asymmetries in the observation-generating processes between fish
65 species (Carlen et al., 2024) (Figure 2). In the context of decision theory, uncertainty matters when it
66 affects the choice of management action (McCarthy & Possingham, 2007). The importance of uncertainty
67 can be quantified as the Value of Information (VoI), or the degree to which unresolved uncertainty affects
68 performance on management objectives, measured in the utility of the decision maker (Runge et al., 2011).
69 We then embed the quantified MSFR uncertainty into a decision model to quantify the value of resolving
70 uncertainty related to the lamprey's role in modulating salmon survival as both a parasite and predation offset
71 for salmon (Figures 1-2). This value of resolving uncertainty - Value of Information - can be considered in the
72 inverse, as the cost of a knowledge gap generated as an outcome of cultural bias. Through illustration with
73 this Pacific lamprey case study, we provide a demonstrate a rigorous, quantitative approach to understanding
74 the cost of cultural bias in conservation decision-making, moving from legacies of neglect reflected in data
75 to performance on decision objectives.

Box 1. Pacific lamprey, Chinook salmon, and California sea lions in the Columbia River Basin

Construction of hydroelectric dams along the Columbia River has dramatically altered flow regimes and fish passage, particularly for Endangered Species Act (ESA) protected migratory Pacific salmonids of high cultural and economic value. While millions of dollars have been invested in freshwater habitat restoration and fish ladder construction, in the past few decades these fish have faced a new source of mortality: pinnipeds like California sea lions that have learned to travel to natural pinch points like dams and fish ladders to consume these fish by the thousands. The number of pinnipeds at these predation hotspots is increasing, due to recovery efforts related to the Marine Mammal Protection Act (MMPA) and ocean warming events that have shifted the geographic range of marine mammals in the California Current (Wargo Rub et al., 2019). To mitigate the effects on salmon stocks at risk of extinction, the MMPA was amended in 2018 to authorize states and tribes to lethally remove these sea lions, yet these new conditions have strained decision-making processes intended to maximize salmonid returns to the Columbia River Basin (CRB).

An underacknowledged piece of uncertainty that may impede these decisions is the role of Pacific lamprey in modulating salmonid survival and salmonid-pinniped interactions. The Pacific lamprey, an ancient, foundational species in the CRB serves as a predation buffer for upstream migrating adult salmon from marine mammals, as the species is extraordinarily rich in fats and relatively easy to capture (CRITFC, 2011; Roffe and Matte, 1984). The Pacific lamprey may also decrease salmonid survival in the marine environment, as the species plays a parasitic role in its adult stage, though the impact of parasitic attack wounds on salmonid fitness and survival is not well characterized (Beamish 1980; Weitkamp et al., 2015).



Despite its critical ecological role in the CRB and its high cultural value for Columbia basin Indigenous peoples (Close et al., 2002; 2004), the Pacific lamprey has faced a precipitous decline in the last century, stemming in part from Euro-American cultural bias and association with invasive lamprey in the Laurentian Great Lakes.

[L]amprey are considered pests or trash fish by the dominant society, the result of which is the development of eradication programs or at best, a management policy of benign neglect (Close 2004).

While attention toward Pacific lamprey decline has increased in the last decade—largely due to advocacy, research, and knowledge generated by the Columbia River Inter-Tribal Fish Commission—the legacy of this bias persists in data. Since

Pacific lamprey abundance is low relative to historic levels, understanding density-dependence in the lamprey-salmonid-sea lion functional response is difficult, as only local, rather than global, properties of this functional response are observed. Additionally, most data on lamprey are collected incidental to monitoring of salmonids, where the design and efficiency of the data collection effort is not always adequate for lampreys, resulting in amplified observation error for Pacific lamprey (Kostow. 2002; Tidwell et al., 2022).

76

77 3 Results

78 3.1 Multi-species dynamical system

79 We first built a stylized model of a Chinook salmon and Pacific lamprey dynamical system throughout their
80 lifecycles as anadromous fish, including estuarine predation by California sea lions (CSL), freshwater popula-
81 tion growth, and marine mortality (Box 1). We modeled Chinook salmon and Pacific lamprey interactions
82 in 1) the marine environment through a density-dependent host-parasite relationship and 2) the estuarine

83 environment through a density-dependent, multi-species functional response (MSFR), where the rate of Cal-
84 ifornia sea lion consumption is a function of the abundance of lamprey and salmon in the prey community.
85 These two lamprey and salmon interactions were used represent the rate at which lamprey modulate salmon
86 survival as both a parasite of salmon and a predation offset for salmon. The parameter values used to
87 describe freshwater population growth and marine mortality were guided by historical observations and are
88 described in Table S1, whereas the MSFR parameters were directly estimated with data.

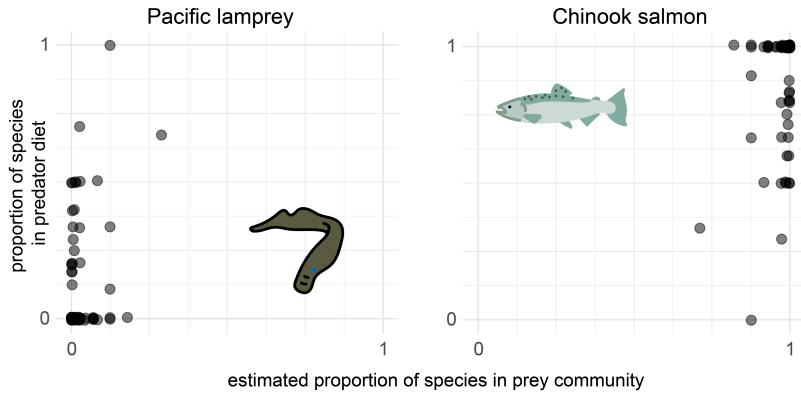
89 **3.2 Quantified multi-species functional response uncertainty**

90 To quantify uncertainty in the California sea lion (CSL) multi-species functional response (MSFR) (Equations
91 1-2), we developed a Bayesian model that relates CSL prey consumption data from gastro-intestinal diet
92 analysis to the observed count of fish passing through Bonneville dam. The posterior distribution was used
93 to quantify parametric uncertainty in the species-specific, density-dependent attack rates, b_i , species-specific
94 handling times, h_i , and MSFR exponent, q in Equations 1-2 (Table S2, Figure S2).

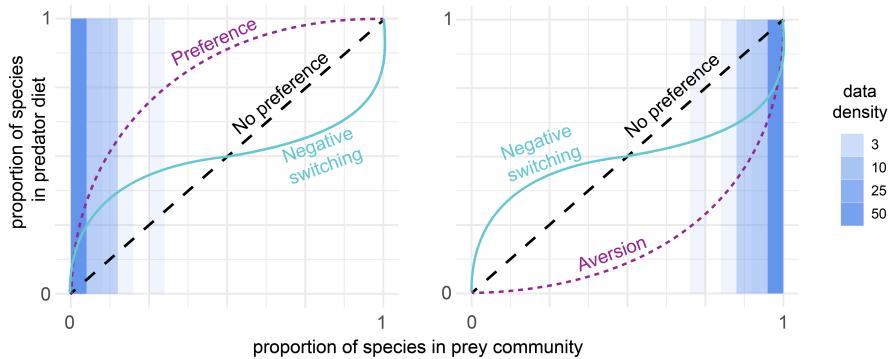
95 The Bayesian model was used to estimate abundance of prey available to the predator below Bonneville
96 dam by accounting for error in observing the abundance of fish passing through the dam and imperfect dam
97 passage efficiency (Figure 3A, Figure S3, Table S2). Across most sampled time points, the abundance of
98 Pacific lamprey was less than 10% of the abundance of Chinook salmon (Figure 3A). Yet despite this low
99 abundance, Pacific lamprey were frequently over-represented in the CSL's diet (Figure 3A).

100 The relatively low abundance of lamprey in the prey community limited observation of global proper-
101 ties of the multi-species functional response, creating high parametric uncertainty in model regions with
102 high lamprey density (Figure 3B-C). This observation of local properties of the density-dependent MSFR
103 prevented distinction between a global preference for lamprey, where lamprey are favored at all densities,
104 and negative switching, where lamprey switch from being over-represented to under-represented in the diet
105 of CSLs as lamprey density increases (Figure 3B-C). The model's posterior samples captured this global
106 uncertainty (Figure 3C; Table S2; Figure S2).

A. Estimated fish prey availability



B. Conceptual multi-species functional responses



C. Estimated multi-species functional response

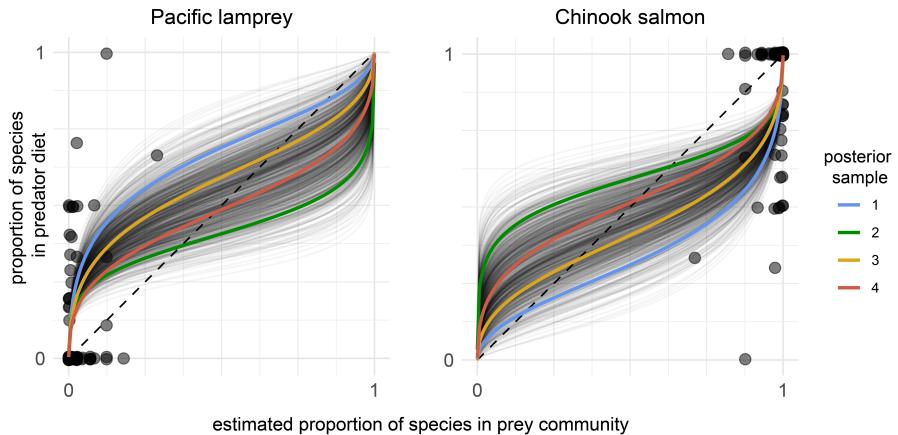


Figure 3: Multi-species functional response, measuring the rate at which California sea lions (CSL) consume prey as a function of the composition of the prey community. **A.** Relationship between 1) the proportion of each fish species in the predator diet, measured with gastro-intestinal analysis of euthanized California sea lions, and 2) proportion of each fish species in the prey community, based on the mean posterior estimate of available prey, L_A and S_A for salmon and lamprey, respectively. The credibility intervals for the estimates of available prey, L_A and S_A , are shown in Figure S3. **B.** Conceptual multi-species functional responses demonstrating how two multi-species functional response curves can have similar local properties in the observed parametric region shown in panel A, yet different global properties due to a large, unobserved parametric region. **C.** Estimated multi-species functional response, where each black line represents a posterior sample describing the predicted relationship between the proportion of each species in the CSL diet and the proportion of each species in the prey community. Four posterior samples are highlighted and are used in Figure 4. The dashed line indicates the 1:1 line, where CSL consume prey in equal proportion to their abundance in the prey community.

107 **3.3 Decision model**

108 We built a decision model to quantify the cost of lamprey-related uncertainty to a decision maker. The
109 Pacific lamprey has both inherent value and spiritual and cultural value to humans, including as a First
110 Food for Columbia River Basin tribes (Close et al., 2002; Columbia River Inter-Tribal Fish Commission,
111 2011). However, for the purposes of this decision problem, we primarily considered the value of Pacific
112 lamprey through its ecological role as a predation offset for salmonids. We therefore framed the decision
113 problem as finding the action, a^* , that maximizes utility, U , where utility is defined as the equilibrium
114 abundance of Chinook salmon returning to spawn in freshwater, \hat{R}_S .

115 In the decision problem, we considered a set of actions, $a \in A$, that represent changes in lamprey produc-
116 tion, α_L . Since the production parameter, α_L , can be understood as the product of adult freshwater survival
117 and intrinsic rate of population growth, an action of increasing α_L could refer to increasing adult lam-
118 prey survival (e.g., improving dam passage) and/or increasing lamprey reproduction (e.g., artificial lamprey
119 propagation).

120 While many uncertainties exist in this system, we considered two sources of parametric uncertainty
121 (Figure 2): 1) uncertainty in the density-dependent California sea lion functional response, F , quantified
122 above and 2) uncertainty in the strength of parasitism, P , or the rate at which salmon ocean survival
123 declines as a function of lamprey abundance. We calculated the utility, $U(a, f, p)$, of each action, a , using
124 the dynamical system model (Equations 1-7) under all expressions of functional response and parasitism
125 uncertainty, F and P .

126 The optimal action, a^* , that maximized utility (i.e., equilibrium abundance of salmon returning to the
127 Columbia River basin) varied across different expressions of functional response and parasitism uncertainty
128 (Figure 4A; Figure S4). The utility associated with the optimal action, $\max_a U(a, f, p)$, also varied across
129 different expressions of functional response and parasitism uncertainty (Figure 4B; Figure S4). In general,
130 expressions of MSFR uncertainty associated with a global preference for lamprey (Figure 3C, blue line)
131 corresponded to higher maximized expected utility, $\max_a E_P[U(a, f, p)]$ (Figure 4A, blue line). Whereas
132 expressions of MSFR uncertainty associated with negative switching (Figure 3C, green line) corresponded to
133 lower maximized expected utility (Figure 4A, green line; Figure S5). Additionally, the bet-hedging strategy,
134 or the action that maximizes utility over all uncertainty ($\max_a E_{F,P}[U(a, f, p)]$), tended to be higher than the
135 action that maximized utility after functional response uncertainty had been resolved ($\max_a E_P[U(a, f, p)]$)
136 (Figure 4A; Figure S5).

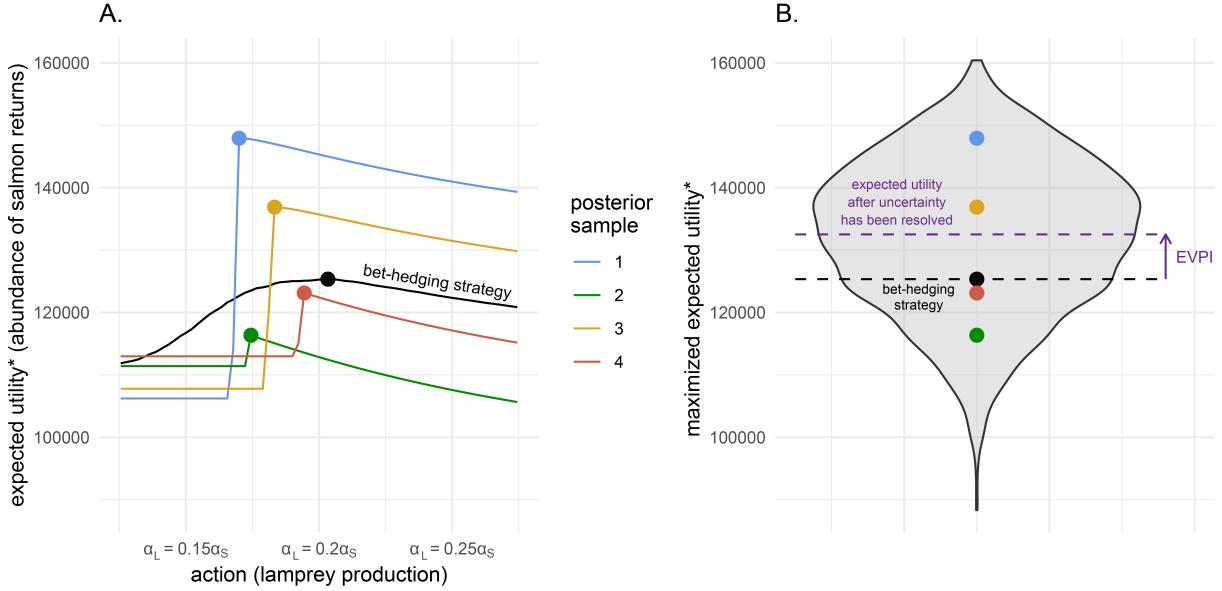


Figure 4: Quantifying the value of reducing lamprey-related uncertainty. **A.** Relationship between the expected utility and action for each multi-species functional response (MSFR) posterior sample highlighted in Figure 3C. Asterisk indicates that the expected utility, $E_P[U(a, f, p)]$, is calculated as the expectation over parasitism uncertainty, P (Figure 2). The actions are the lamprey production, α_L , relative to salmon production, α_S , and can be understood as actions that either increase freshwater lamprey adult survival or the intrinsic rate of lamprey population growth. The points indicate the action that maximizes expected utility (i.e., $\max_a E_P[U(a, f, p)]$) for each expression of functional response uncertainty. The black line indicates the expected utility over both parasitism and functional response uncertainty (i.e., $E_{F,P}[U(a, f, p)]$), and the black point indicates the action that maximizes utility over all uncertainty, or the bet-hedging strategy (i.e., $\max_a E_{F,P}[U(a, f, p)]$). **B.** Violin plot of the maximized expected utility of all posterior samples, calculated as the expectation across parasitism uncertainty (i.e., $\max_a E_P[U(a, f, p)]$). Colored points indicate the maximized expected utility of the selected posterior samples from panel A. The black point indicates the maximized expected utility across both parasitism and functional response uncertainty, or the utility associated with the bet-hedging strategy, $\max_a E_{F,P}[U(a, f, p)]$. The purple dashed line indicates the expected utility after all uncertainty has been resolved, $E_{F,P}[\max_a U(a, f, p)]$. The expected value of functional response and parasitism information (i.e., expected value of perfect information, EVPI) is therefore the difference between $E_{F,P}[\max_a U(a, f, p)]$ and $\max_a E_{F,P}[U(a, f, p)]$.

137 3.4 Cost of lamprey uncertainty to a decision-maker

138 In the context of this decision problem, the value of lamprey information was quantified as the expected im-
 139 provement on the management objective (maximize abundance of Chinook salmon returning to the Columbia
 140 River Basin) if functional response uncertainty, F , and parasitism uncertainty, P , were reduced (Runge et al.,
 141 2011). The utility associated with the bet-hedging strategy ($\max_a E_{F,P}[U(a, f, p)]$) was 125,343 fish, whereas
 142 the expected utility after all uncertainty had been resolved was 132,511 fish (Figure 4B). The expected value
 143 of perfect information, EVPI, was therefore 7167 fish (Figure 4B). Framed another way, the expected increase
 144 in Chinook salmon returning to the Columbia River Basin was 7167 fish, if lamprey uncertainty - generated

145 as an outcome of cultural bias - was not impeding the choice of action.

146 4 Discussion

147 Evaluating the outcomes of conservation actions can be limited by structural uncertainty that arises from
148 cultural bias. An ecological system with multiple interacting species in the Columbia River Basin provides a
149 useful setting for quantifying the extent to which dominant value systems can impede conservation decision-
150 making. Here, management has historically focused on high-value salmon fisheries and recent predation
151 pressure by sea lions, while overlooking the Pacific lamprey. This focus has led to asymmetric measurement
152 error and observation of local, rather than global, properties of the system, reflecting historical bias against
153 the Pacific lamprey by dominant society.

154 By combining uncertainty quantification with decision theory, we have illustrated a method to measure
155 the cost of overlooking this species in decision-making. The Bayesian approach to uncertainty quantification
156 offers a flexible framework for representing uneven data-generating processes, and the Value of Information
157 analysis facilitates systematic exploration of this uncertainty in a decision-making context. By unifying
158 these approaches, we quantify the extent to which uncertainty about Pacific lamprey impedes decision-
159 making about Chinook salmon, which can be understood as the cost of cultural bias, measured in units
160 relevant to a decision maker.

161 4.1 Reconciling unknown unknowns

162 Quantifying the cost of cultural bias to a decision maker through a Value of Information analysis is only
163 possible if a spark brings to light previously ignored sources of uncertainty. In the case of the Pacific lamprey,
164 Native American tribes began championing the importance of the species in the early 1990s, recognizing
165 the declining numbers of lamprey and reflecting on the role of dominant Euro-American societal values in
166 contributing to their decline (Clemens et al., 2017; Close et al., 2002, 2004). There is, however, not a VOI
167 calculus for uncertainty that is not articulated, reflecting the philosophical conundrum of understanding
168 the cost of “unknown unknowns” in scenarios where the truth lies far outside of the articulated hypotheses
169 (Wintle et al., 2010).

170 However, structural uncertainty in ecological modeling is often not random, as science is not neutral
171 to power and uneven knowledge can arise systematically from political-economic structures and processes
172 (Silver et al., 2022). Moving from “unknown unknowns” to quantifying the cost of “known unknowns” can
173 involve interrogating systems of knowledge production through long-established ideas from the fields of en-
174 vironmental justice and science and technology studies. Investigating how environment and social difference

175 are intertwined can provide valuable insight into how uneven distribution of power shapes conservation in-
176 vestment and research (Walker, 2012). Considering knowledge as situated and knowing is a social process can
177 be crucial for reflecting upon the systems of scientific practice (Bloor, 2004; Haraway, 2013). For instance,
178 reflection on the relationship between a perceived ecological role and necropolitics – who should live and who
179 should die – can be useful for interrogating the relationship between human psychology and conservation
180 policy (Chao, 2021). Integrating these ways of thinking into statistical ecology and decision making will be
181 crucial for understanding how legacies of human structures can be present or create absences in ecological
182 model development.

183 **4.2 Implications for adaptive management and structured decision-making**

184 Conservation decision-making is always bias- and value-laden; in fact, decision theory encourages value-based
185 thinking and posits that values should be the driving force for decision-making (Keeney, 1996). Danger, how-
186 ever, comes from a lack of reflection on where values enter the decision-making process. Decision analysis
187 traditionally assumes that facts and values are separable: values are used to formulate the decision context
188 and objectives, and facts are used to determine the consequences of actions (Gregory et al., 2012). Here
189 we have shown, however, that historical values of a dominant society affect the ability to predict the conse-
190 quences of actions, generating a quantifiable impediment to decision-making about salmon and lamprey in
191 the Columbia River Basin.

192 While the inseparability of facts and values may challenge the conceptual foundation of decision analysis
193 and structured decision making, including reflexive and relational thinking in adaptive management cycles
194 represent a productive path forward. Adaptive management (AM) involves acknowledging uncertainty and
195 seeking to reduce it through the process of management; AM can include two learning cycles, a technical
196 learning cycle nested within a larger cycle of learning about the decision structure itself (Williams & Brown,
197 2016). To reduce uncertainty in how systems of power shape knowledge production and impede decision-
198 making, this outer loop of double-loop learning should involve processes by which a decision analyst extends
199 a relational understanding of the world to modelling, a practice known as “Situated Modelling” (Klein et al.,
200 2024). This practice includes reflecting on the broader context in which knowledge is generated, questioning
201 where modeling assumptions come from and what is left out, and broadening perspectives and ways of
202 knowing at the decision-making table.

203 **4.3 Limitations of an utilitarian understanding of information value**

204 In this analysis, we chose to evaluate the cost of lamprey uncertainty with respect to one decision objective -
205 maximize the abundance of Chinook salmon returning to the CRB - among many possible decision objectives.
206 This deliberate choice to frame the value of lamprey through the lens of its ecosystem service for salmon
207 was chosen to represent how a historic, dominant value system that prioritized Pacific salmon can impede
208 decision-making, even if the value system remains unchanged.

209 The cost of cultural bias in decision-making, however, would change with a different decision objective
210 or a different understanding of cost. While we translated signatures of cultural bias reflected in ecological
211 data to a measurement of cost in units relevant to a decision maker (i.e., expected number of salmon),
212 this utilitarian representation reflects a narrow understanding of information value. Cultural bias-derived
213 uncertainty can impede decision-making in other ways, including generating conflict and diminishing trust
214 among decision makers, thereby inhibiting the adaptive governance of the social-ecological system (Folke
215 et al., 2005).

216 **5 Materials and Methods**

217 We first describe a stylized representation of a Chinook salmon and Pacific lamprey dynamical system (Box
218 1). We then quantify uncertainty in estuarine predation using a Bayesian multi-species functional response
219 (MSFR) model using sea lion gastro-intestinal diet data and fish passage data at Bonneville dam. Finally, we
220 build a decision model that accounts for multiple sources of uncertainty in the dynamical system to evaluate
221 management actions with respect to an objective of maximizing Chinook salmon equilibrium abundance.
222 Using a Value of Information (VOI) analysis, we quantify how parametric uncertainty - generated as an
223 outcome of cultural bias - impedes decision-making.

224 **5.1 Multi-species dynamical system**

225 Chinook salmon and Pacific lamprey are anadromous fish, migrating from freshwater rivers to the ocean and
226 back to spawn in or near their natal streams (Hess et al., 2023). While their lifecycles in the freshwater and
227 marine systems extend across many years, we simplify the cycle to occur across one time step from t to $t + 1$.

228 **5.1.1 Estuary predation**

229 The expected number of Pacific lamprey and Chinook salmon consumed by California sea lions (CSL) is
230 described using a multi-species functional response (MSFR) that allows the attack rate to be dependent on

²³¹ prey density (Rosenbaum et al., 2024). Here, \tilde{F}_i represents the expected number of prey i consumed per
²³² predator integrated across one day, a_i represents the density-dependent attack rate of species i , h_k represents
²³³ the handling time for species $k = 1 \dots m$, and E_i represents the abundance of species i entering the estuary.

$$\tilde{F}_i = \frac{a_i E_i}{1 + \sum_{k=1}^m a_k h_k E_k} \quad (1)$$

²³⁴ The density-dependent attack rate, a_i , is a function of coefficient, b_i , and exponent, q . When $q = 0$, the
²³⁵ MSFR follows a Holling type 2 functional response, and when $q < 0$, the MSFR follows a Holling type 3
²³⁶ functional response (Figure S6).

$$a_i = b_i E_i^q \quad (2)$$

²³⁷ The relationship between the abundance of fish returning to freshwater to spawn, R_i , and adults entering
²³⁸ the estuary, E_i , of species $i \in \{L, S\}$ is therefore a function of the expected number of prey, \tilde{F}_i , and the
²³⁹ expected number of CSL days (i.e., daily abundance in estuary \times days), P :

$$R_i = E_i - \tilde{F}_i \times P \quad (3)$$

²⁴⁰ 5.1.2 Freshwater population growth

²⁴¹ The relationship between 1) the abundance of fish returning to the Columbia River Basin to spawn, R_i
²⁴² and 2) the abundance of juveniles/smolt exiting Bonneville dam downstream, J_i , is described with the
²⁴³ Ricker stock-recruit relationship, where α is a production parameter, and K is the smolt or juvenile carrying
²⁴⁴ capacity. The production parameter, α , combines both freshwater mortality and the population intrinsic
²⁴⁵ rate of growth.

²⁴⁶ We use the following growth equations to describe the relationship between the abundance of returning
²⁴⁷ fish, R_i , and abundance of juveniles, J_i , for fish species i :

$$J_i = R_i \times \frac{\alpha_i}{(1 + \beta_i R_i)} \quad (4)$$

$$\beta_i = \frac{\alpha_i}{K_i} \quad (5)$$

²⁴⁹ 5.1.3 Marine mortality

²⁵⁰ In the marine environment, Pacific lamprey and Chinook salmon exhibit a host-parasite relationship (Clemens
²⁵¹ et al., 2017). Salmonid host abundance in the marine environment is a principal factor in predicting Pacific

252 lamprey returns to the Columbia River (Murauskas et al., 2013), and while Chinook salmon are common
 253 lamprey hosts and exhibit wounds from Pacific lamprey bites (Shevlyakov & Parensky, 2010; Weitkamp
 254 et al., 2015), the effect of these bites on their physiological condition are not well understood (Pelenov et al.,
 255 2008).

256 The relationship between the abundance of lamprey juveniles entering the ocean, J_L , and the abundance
 257 of lamprey adults returning to the estuary, E_L , is described by the following equation, where survival increases
 258 as a function of salmon density, J_S , at a rate described by D_L :

$$E_L = J_L \times s^o \times (1 - e^{-D_L \times J_S}) \quad (6)$$

259 The relationship between the abundance of salmon smolts entering the ocean, J_S , and the abundance of
 260 salmon adults returning to the estuary, E_S , is described by the following equation, where survival decreases
 261 as a function of lamprey density, J_L , at a rate scaled by D_S :

$$E_S = J_S \times s^o \times (1 - e^{-D_S / J_L}) \quad (7)$$

262 Here, density-independent ocean survival, s^o , is shared between both species.

263 5.2 Quantifying uncertainty in the multi-species functional response (MSFR)

264 Below we outline the Bayesian model formulation used to estimate the multi-species functional response
 265 (MSFR) parameters with California sea lion gastro-intestinal diet data and fish count data at Bonneville
 266 dam (Tables S3-S6). More information on data sources and model fitting can be found in Supporting
 267 Information.

268 5.2.1 Chinook salmon prey abundance

269 The observed number of Chinook salmon passing through the Bonneville dam fish ladders in time window,
 270 t , S_t^P , is drawn from a Poisson distribution with \widetilde{S}_t^P representing the expected number of salmon passed
 271 (Table S4):

$$S_t^P \sim \text{Poisson}(\widetilde{S}_t^P) \quad (8)$$

272 The number of salmon available for CSL consumption, S_t^A is greater than the number of salmon passing
 273 through the dam, as the dam passage efficiency is less than one. The expected number of salmon passed,
 274 \widetilde{S}_t^P , is therefore drawn from a Binomial distribution with the size as the difference between the number of

275 salmon available for consumption, S_t^A , and the total number of salmon consumed across all euthanized CSL
 276 individuals at time t , $\sum_{j=1}^{O_t} F_{t,j}^S$. Here, O_t is the total number of individuals euthanized at time t , and $F_{t,j}^S$
 277 is the number of Chinook salmon enumerated in the digestive tract of CSL individual, j . The probability is
 278 the salmon passage efficiency at Bonneville dam, p_S , (Frick et al., 2008):

$$\widetilde{S}_t^P \sim \text{Binomial}(S_t^A - \sum_{j=1}^{O_t} F_{t,j}^S, p_S) \quad (9)$$

279 **5.2.2 Pacific lamprey prey abundance**

280 In the years 2017 and 2019 when the lamprey night-time and LPS counts were recorded, the observed number
 281 of lamprey passing through all passage structures (LPS + fish ladders) in time window t , L_t^P , is drawn from
 282 a Poisson distribution with \widetilde{L}_t^P representing the expected number of lamprey passed (Table S4):

$$L_t^P \sim \text{Poisson}(\widetilde{L}_t^P) \quad \text{for } t \in \lambda^E \quad (10)$$

283 where λ^E represents the set of time windows associated with CSL euthanasia in 2017 or 2019.

284 In the years when the lamprey night-time and LPS counts were not recorded, the observed number of
 285 lamprey passing through all passage structures, L_t^P , is drawn from a Binomial distribution, with the size
 286 parameter as the expected number of lamprey passed, \widetilde{L}_t^P , and probability of detection in daytime visual
 287 counts, p_t^D (Table S4):

$$L_t^P \sim \text{Binomial}(\widetilde{L}_t^P, p_t^D) \quad \text{for } t \in \lambda^I \quad (11)$$

288 where λ^I represents the set of time windows associated with CSL euthanasia in 2018 or 2021-2023.

289 The probability of detection in daytime visual counts during the time window t , p_t^D , is drawn from a
 290 Beta distribution:

$$p_t^D \sim \text{Beta}(\alpha^D, \beta^D) \quad \text{for } t \in \lambda^I \quad (12)$$

291 These beta distribution hyperparameters were informed by the passed lamprey recorded via visual count,
 292 C_d^V , and the total recorded passed lamprey across all passage structures and all times of day, C_d^T , for each
 293 monitored three-day interval, d , in 2017 and 2019 (Table S5, Figure S7). C_d^V/C_d^T therefore represents the
 294 fraction of all passed lamprey that were visually counted during the day:

$$C_d^V/C_d^T \sim \text{Beta}(\alpha^D, \beta^D) \quad (13)$$

295 The number of lamprey available for CSL consumption, L_t^A is greater than the number of lamprey passing
 296 through the dam, as the dam passage efficiency is less than one. The expected number of lamprey passed,
 297 \widetilde{L}_t^P , is drawn from a Binomial distribution with the size as the difference between the number of lamprey
 298 available for consumption, L_t^A , and the number of lamprey consumed across all euthanized CSL individuals
 299 at time t , $\sum_{j=1}^{O_t} F_{t,j}^L$. Here, $F_{t,j}^L$ is the number of lamprey enumerated in the digestive tract of CSL individual,
 300 j . The probability is the lamprey passage efficiency at Bonneville dam, p_L , (Moser et al., 2002):

$$\widetilde{L}_t^P \sim \text{Binomial}(L_t^A - \sum_{j=1}^{O_t} F_{t,j}^L, p_L) \quad (14)$$

301 5.2.3 Consumed prey

302 The number of prey consumed by each CSL individual is likely to deviate from the expected number of prey
 303 consumed due to heterogeneity in preference and behavior across CSL individuals. Model process error is
 304 therefore incorporated as Poisson-distributed variation in CSL consumption rates. The observed number of
 305 Chinook salmon and Pacific lamprey consumed by CSL individual j , $F_{t,j}^S$ and $F_{t,j}^L$, respectively, is drawn
 306 from a Poisson distribution with the expected number of prey consumed, \widetilde{F}_t^S and \widetilde{F}_t^L , as the rate parameters,
 307 respectively (Table S6):

$$F_{t,j}^S \sim \text{Poisson}(\widetilde{F}_t^S) \quad (15)$$

308

$$F_{t,j}^L \sim \text{Poisson}(\widetilde{F}_t^L) \quad (16)$$

309 5.2.4 Multi-species functional response (MSFR)

310 The expected number of prey consumed, $\widetilde{F}_{i,t}$, of species i is related to the available number of prey, $A_{i,t} =$
 311 $\{S_t^A, L_t^A\}$, using the MSFR described in Equations 1-2.

$$\widetilde{F}_{i,t} = \frac{a_{i,t} A_{i,t}}{1 + \sum_{k=1}^m a_{k,t} h_k A_{k,t}} \quad (17)$$

$$a_{i,t} = b_i A_{i,t}^q \quad (18)$$

312 5.3 Decision model

313 We then developed a decision model, where we framed the decision problem as finding the action, a^* , that
 314 maximizes utility, U , where utility is defined as the equilibrium abundance of Chinook salmon returning to

315 spawn in freshwater, \hat{R}_S . The set of actions, $a \in A$, under consideration in the decision problem include
316 changes in lamprey production, α_L . While many uncertainties exist in this system, we considered two sources
317 of parametric uncertainty (Figure 2): 1) functional response uncertainty, F (Figure 3) and 2) parasitism
318 uncertainty, P , describing uncertainty in the rate at which salmon ocean survival declines as a function of
319 lamprey abundance.

320 We calculated the utility of each action, a , using the dynamical system model (Equations 1-7) under
321 all combinations of functional response and parasitism uncertainty, F and P . Here, $U(a, f, p)$ is the utility
322 associated with taking action a assuming $f \in F$ and $p \in P$. The set F corresponds to 1000 randomly
323 selected samples from the MSFR model posterior distribution, and the set P corresponds to three values of
324 D_S (Equation 7) with equal prior probability (Figure 2, Table S1). The utility, or the equilibrium salmon
325 return abundance (\hat{R}_S), was calculated through simulation, starting at an arbitrary abundance of salmon and
326 lamprey returns, R_S and R_L , and finding the mean salmon return abundance, \hat{R}_S , after removing transient
327 dynamics.

328 **5.3.1 Value of Information**

329 We then used a Value of Information analysis to calculate the value of lamprey information. In classical
330 decision theory, the expected value of perfect information (EVPI), is the difference between the expected
331 value of an optimal action after new information has been collected and the expected value of an optimal
332 action before new information has been collected:

$$\text{EVPI} = E_{F,P}[\max_a U(a, f, p)] - \max_a E_{F,P}[U(a, f, p)] \quad (19)$$

333 The first term in Equation 19 represents the expected utility once all uncertainty has been resolved,
334 because the optimal action is chosen after perfectly knowing the multi-species functional response relationship
335 and how parasitism strength scales with lamprey density. The second term in Equation 19 is the bet-
336 hedging strategy, or the expected value associated with the action that maximizes utility over all sources of
337 uncertainty. The difference between these two terms, EVPI, is therefore defined as the expected increase in
338 utility if lamprey uncertainty is resolved.

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