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Using Decision Analysis to Balance Angler Utility and Conservation in a Recreational Fishery

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Abstract
Recreational fisheries are often managed to provide satisfying fishing experiences for anglers while conserving wild fish stocks. However, managing recreational fisheries is difficult because fish populations are often infrequently monitored and fishing effort is uncontrolled; moreover, a satisfying fishery may draw many anglers, which may lead to enhanced risk of overfishing. Furthermore, external pressures will also affect fisheries, leading to fishery collapses despite the best intentions of management. Any management decision about regulations and habitat alteration will have effects on angler satisfaction and conservation. Decisions should be made with the intention of achieving fisheries objectives despite the uncertainties that arise from sampling data, ecosystem processes, and external factors, yet they must be defensible to stakeholders and the public. We show herein how decision analysis can be used to evaluate and communicate the relative efficacy of management decisions that are made to achieve fisheries management objectives by using a variety of commonly collected field data. We used a wild kokanee population at risk of overfishing as a case study and evaluated the medium-term effects of fishing regulations and habitat alterations on conservation and angler utility objectives. Using a flexible age-structured model, we determined that these two objectives are often at odds, where management actions leading to high angler utility in this fishery also lead to high conservation risk. Overall, decision analysis helps to communicate these tradeoffs and makes it clear how particular decisions were made. Decision analysis is not new, but it is often underused in recreational fisheries. This work demonstrates how it may streamline decisions, even for infrequently monitored fisheries, and lead to better fisheries overall.

Recreational fisheries on wild fish populations are typically managed with the paired goals of satisfying anglers and ensuring that fish populations are healthy (Powers and Lackey 1976; Radomski et al. 2001; Pereira and Hanson 2003; Cowx et al. 2010). While it is convenient to believe that recreational fisheries are self-regulating (in that anglers leave if catch rates get too low, thereby conserving the stock), this will not be true if anglers are not primarily motivated by catch rates (Post et al. 2002). Research has demonstrated that anglers are actually motivated by several fishery attributes that contribute to their satisfaction (e.g., catch rates, fish size, social interactions), and the importance of each of these attributes varies among anglers (Bryan 1977; Beardmore et al. 2014) and fisheries (Beardmore et al. 2011). This diversity of motivations means that recreational fisheries are not self-regulating; effort may stay high even as abundance declines (Post et al. 2002; van Poorten et al. 2016). Moreover, not all of the attributes that contribute to angler utility and satisfaction are under the control of fishery managers.

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Managing a fishery such that it provides a satisfying fishing experience while conserving the stock requires an integrated understanding of angler expectations so that it is viable to predict angler response to management changes.

The suite of management tools that is available to freshwater fisheries management is relatively broad (Nielsen 1999). They can include manipulating angler efficiency through regulations or manipulating ecosystems through stocking, habitat alteration, nutrient enhancement, and predator control. The responses to these actions of a fish population may be counterintuitive due to density-dependent changes in growth and survival and subsequent changes in size structure. For example, increasing minimum harvest size limits may increase the abundance of spawning individuals and boost total egg production and recruitment (Allen et al. 2013). Alternatively, increasing juvenile survival through habitat improvements may lead to an increase in total biomass but an undesirable shift in size structure to smaller individuals and increased "stunting" (Rinne 1982). Anglers similarly exhibit complex responses to such management changes in the fishery either through direct behavior responses to regulation changes (Aas et al. 2000; Beard et al. 2003) or indirect responses due to changes in catch rates and sizes (Johnson and Carpenter 1994; van Poorten and Post 2005). Uncertainty in the type and magnitude of system response can only truly be considered by using quantitative models.

While there is considerable uncertainty in how a fishery will respond to management actions, external stressors affect the system as well. For example, human population growth continues to exert pressure on natural systems through urbanization (Wang et al. 2001; Seilheimer et al. 2007), changes in land use (Evans et al. 1996), and even increases in fishing capacity (Post et al. 2002). Changes to nutrient loading may occur indirectly due to changes in upstream flow regimes (Prowse et al. 2006) or directly due to agricultural and urban runoff (Blann et al. 2009). How these inputs affect the natural system dynamics on any single waterbody over time is subject to considerable uncertainty and needs to be assessed with a systematic approach to management.

In the face of obvious process and observation error and even changes in underlying productivity, it is easy for a decision maker to become overwhelmed and just rely on past experience and expert judgment (Powers et al. 1975; Powers and Lackey 1976). However, it is important for decision makers to understand and embrace the limited ways that managers can control the system and make decisions that are robust to this uncertainty (Jones and Bence 2009). Decision analysis provides a structured approach to providing management advice (Walters 1986; Peterman and Anderson 1999) by simply evaluating which management actions are robust to uncertainty while providing the best possible outcomes (Robb and Peterman 1998; Harwood 2000; Jones and Bence 2009). Defining the "best possible outcomes" depends on identifying measurable objectives, a key prerequisite to any decision and a necessary part of decision analysis. Decision analysis has been used in a variety of environmental and natural resource contexts, including recreational (Peterson and Evans 2003; Varkey et al. 2016) and commercial fisheries (Punt and Hilborn 1997; Robb and Peterman 1998), forestry (Cohan et al. 1984; Crome et al. 1996), conservation (Harwood 2000; Dreschler and Burgman 2004), and the response of invasive species (Maguire 2004). Decision analysis allows trade-offs between the objectives (e.g., biological and social objectives) that are to be visualized and understood; the end result is a decision that is clear, understandable, and defensible.

We present a framework for deciding which changes to the management or habitat in a recreational fishery are most appropriate by demonstrating the tradeoffs between conservation and use objectives. We develop a model that predicts changes in the size structure and abundance of a fished population by including density-dependent growth and survival. While many population models are concerned with maximizing catch-based outcomes, we take a more nuanced approach and examine how angler utility and resulting fishing effort will change as a result of changes to the population. Finally, the model feeds into a decision analysis, thereby providing managers and decision makers with the tools that are necessary to evaluate the tradeoffs.

METHODS

Study site.— Kawkawa Lake is a 72-ha coastal montane lake that is approximately 150 km from Vancouver, British Columbia (BC). The lake is used by anglers that are fishing for wild kokanee *Oncorhynchus nerka*, Coho Salmon *O. kisutch*, Rainbow Trout *O. mykiss*, and Cutthroat Trout *O. clarkii* as well as by nonangling boaters. Kokanee are the most commonly targeted species of the fishery, primarily because they grow to uncharacteristically large sizes (asymptotic length >400 mm) and because they are abundant. Fishing regulations limit kokanee harvest to four per angler per day with no size restrictions. The large body size of kokanee in this population, which is attractive to anglers, combined with the relatively close proximity to a large metropolitan area (metropolitan Vancouver) may cause stress on the fish population due to high fishing pressure and harvest.

Kawkawa Lake is surrounded on two sides by steep, unstable terrain; the other two sides have residential and recreational development. The kokanee population spawns in four spring-fed streams that flow through the residential community and enter the lake along the eastern end of it. Habitat in all of the streams is affected to varying degrees by residential development including channel realignment, streambed disturbance, sediment inputs, and invasive plant species. All of the buildings in the area were connected to the district sewer system in the 1970s (Kevin Dicken, Director of Operations, District of Hope), but there is concern that now unused septic tanks and/or lawn fertilizer are contributing to nutrient eutrophication in the lake (Michael Willcox, BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development, personal communication).

Data collection and analysis.— The kokanee population and fishery in Kawkawa Lake were monitored in 2016. A fixed-point completed trip creel survey was performed three to four times per week from May to October. The surveys were stratified by time of day (0800 to 1400 hours; 1400 to 2000 hours) and day of the week (i.e., weekday, weekend, or holidays). Angling parties leaving via the single public boat launch were asked how many were in their fishing party, the number of kokanee that were released and retained, and how long they had been fishing. The fork length of the harvested fish was recorded and scales were removed for later age assignment.

Interviews were also used as an opportunity to gain insight into the catch-related fishing utilities that were perceived by anglers. Each angler that was interviewed in the creel survey was asked two sets of questions to bound their level of interest in catch rates and fish size in a trip. Specifically, each angler was asked open-ended questions regarding his or her ideal number of landed kokanee per day of fishing (i.e., that which would maximize their satisfaction) and what catch rate would cause them to be disinterested in fishing on the lake again (i.e., that which would minimize their satisfaction). Similarly, the anglers were asked what size of kokanee would be ideal and what size would make them want to stop fishing the lake. The answers to these questions were used to parameterize the utility functions that were related to angler satisfaction.

Angler utility for both daily harvest and mean size was described by using a logistic function. We assigned a utility of 0.05 to the daily harvest rates and mean sizes that the anglers stated would result in their leaving the fishery unsatisfied. Likewise, the harvest rates and sizes that the anglers stated would result in high satisfaction were assigned a utility of 0.95. We estimated the posterior distribution for the harvest rate at 50% utility ($H_{50[N]}$) and logit transformed the standard deviation in utility for harvest rate ($\sigma_{[N]}$) by fitting the resultant logistic model to all of the coded angler responses regarding harvest rates that were obtained in the creel survey (Table 1). The posterior estimates for harvested fish length mean ($H_{50[L]}$) and standard deviation ($\sigma_{[L]}$) were similarly obtained by fitting the resultant logistic model to the coded angler responses regarding fish size that were obtained in the creel survey (Table 1). The posterior distributions were numerically approximated in JAGS 3.4.0 (Plummer 2003) by using a Markov chain–Monte Carlo simulation. The posterior distributions were calculated from 10,000 iterations after an initial burn-in of 5,000,000 iterations and further thinned to provide a final sample of 10,000 iterations from each of three Markov simulation chains. The simulated parameters were used to define the effort response function and the stated preference utility function that was later used as a fishery objective (see the *Decision analysis* section).

Fishing effort was estimated by using a combination of traffic counters that were installed along the single access road to the boat ramp and independent visual observations of anglers and boat traffic. Two traffic counters were installed in April 2016 and remained in place through the following January. Visual counts of traffic were conducted during the creel survey days at the ramp to count traffic with and without boats and to count boats on the lake that were fishing and those that were not fishing. Methods for estimating fishing effort and the resulting posterior estimate for annual fishing effort are described in van Poorten and Brydle (2018). Briefly, this method estimated daily angler arrivals and departures by fitting to traffic counter data, boat and nonboat traffic observations, and fishing and nonfishing boat counts on the lake that were taken during the creel surveys. The daily angler estimates were summed over the season to provide an estimate of seasonal fishing effort. The posterior estimate for fishing effort (in angler-days per year; AD/year) was multiplied by the mean observed harvest per unit effort from the creel survey to provide an estimate of total annual harvest.

The growth parameters for kokanee were estimated by fitting a two-parameter von Bertalanffy growth model (i.e., L_∞ and K) to the length-at-age data that were collected from the harvested fish that were sampled during the creel survey (Table 1). It was not possible to estimate both parameters without prior information due to the limited age range of the fish in the fishery (mean = 2.9 years, SD = 0.4). Therefore, the model was estimated by using a normally distributed prior probability distribution on the metabolic parameter, K, based on the estimate for kokanee from a nearby lake (van Poorten et al. 2018a), which helped reduce the correlation among the two growth parameters. The posterior distributions for the von Bertalanffy parameters were approximated as above.

A hydroacoustic survey of kokanee in the lake was performed on July 21, 2016, by using a 120-kHz split-beam sounder, set at 2–5 pings/s and towed at ~2 m/s at a depth of 1 m. The echograms for each transect were analyzed at 10-m equal depth layers. Depth-stratified pelagic gill nets were used the following evening to characterize the species and size composition of the fish by depth stratum. Based on this supplemental information, only targets that were sampled from depths between 5 and 15 m were used and

TABLE 1. Bayesian models that were used to estimate the key population parameters from the field data. The prior probability distributions and likelihood functions that were used to calculate the posterior estimates for each parameter of interest are shown.

Variables and models	Prior probability distribution	Likelihood
Angler utility		
$U_{(N\|HPUE)} = \frac{1}{1+\exp\left[\frac{-\left(HPUE-H_{50(H)}\right)}{\sigma_{(H)}}\right]}$	$H_{50(H)} \sim N$ (0, 1,000) $\sigma_{(H)} \sim N$ (0, 1,000) $\tau_u \sim G$ (0.01, 0.01)	$0.05 \sim N\left(U_{low}, \tau_u^{-0.5}\right)$
$U_{(L\|\bar{L})} = \frac{1}{1+\exp\left[\frac{-\left(\bar{L}-H_{50(L)}\right)}{\sigma_{(L)}}\right]}$	$H_{50(L)} \sim N$ (0, 1,000) $\sigma_{(L)} \sim N$ (0, 1,000) $\tau_u \sim G$ (0.01, 0.01)	$0.95 \sim N\left(U_{high}, \tau_u^{-0.5}\right)$
Kokanee growth function		
$\hat{L}_{age=a} = \dot{L}_{\infty}(1 - e^{-Ka})$	$\dot{L}_{\infty} \sim N$ (500, 1,000) $K \sim N$ (0.51, 0.017) $\tau_L \sim G$ (0.01, 0.01)	$L_a \sim N(\hat{L}_a, \tau_L^{-0.5})$
Spawner abundance		
$A_{t,stream=i} = Esc_i \int_{j=0}^{t} \left[\frac{1}{\sigma\sqrt{2\pi}} e^{\frac{\tau_a(j-m_i)^2}{2}}\right]$	$Esc_{stream=i} \sim N(0, 1{,}000)$	$S_{t,i} \sim N(\nu\hat{S}_{t,i}, \tau_S^{-0.5})$
$D_{t,stream=i} = Esc_i \int_{j=0}^{t-s} \left[\frac{1}{\sigma\sqrt{2\pi}} e^{\frac{\tau_a(j-m_i)^2}{2}}\right]$	$m_{stream=i} \sim N(280, 20)$	
$\hat{S}_{t,stream=i} = A_{t,i} - D_{t,i}$	$\nu \sim B$ (1, 1) $\tau_a \sim G$ (0.01, 0.01) $\tau_s \sim G(0.01, 0.01)$	

of these 51% were kokanee. Age 0 kokanee could reliably be distinguished from older age-classes based on target strength, although there was uncertainty about the proportion of small targets that were small kokanee versus invertebrates and air bubbles (D. Johner, BC Ministry of Forests, Lands, Natural Resource Operations, and Rural Development, personal communication). We represented this uncertainty by multiplying the estimated number of small targets (p_{juv}) by a beta-distributed random variable with shape parameters 50 and 5, providing a mean value of 0.91 ± 0.03. This choice of the prior distribution and shape parameters that were used reflects the professional opinion of the hydroacoustic technicians who performed the survey.

Each inlet stream was surveyed weekly from early October to mid-November 2016 to index spawning kokanee. Live spawners were counted in an upstream orientation from the confluence with the lake until the first contiguous 50 m, where no spawners were seen. Spawning kokanee were found in four of the five inlet streams; one of these only had a low number of spawners present on two occasions (21 total), so it was dropped from further analysis. The remaining three streams were used to estimate total spawner abundance by using the statistical escapement model from Hilborn et al. (1999; Table 1). Arrival timing was assumed to be normally distributed; survey life (the length of time that kokanee remained in the stream) was set to 10.2 based on observations in Andrusak et al. (2004). The posterior distributions were approximated as above.

Stable isotope ratios that were measured in particulate organic matter were used to determine whether nutrient enrichment was occurring in the lake. Three replicate water samples were taken on August 1, 2016, at various locations: mid-lake (at 2-, 7-, and 14-m depths), at the outlet, and at the two largest inlet streams (Kopp and Menz). The water samples were filtered in the field and stored in a refrigerated, opaque container until analysis, For the nutrient analysis, $\delta^{15}N$ was measured at the University of British Columbia by using an elemental analyzer that was coupled to a gas chromatograph and reported with respect to air.

Operating model.— The effects of different management actions on both angling utility and population conservation were evaluated by using a density-dependent, age-structured simulation model (Table 2). The model includes parameter estimates that were derived from the survey data in Kawkawa Lake (T2.1) and estimates based on values that have been reported in the literature and the expert judgment of the authors (T2.2). All of the indices, parameters, and variables are described in detail in Table 3. The model was initialized assuming that the fishery is currently at equilibrium; therefore, equilibrium recruitment

($R_{[F]0}$) was set to the estimated age 0 abundance from the hydroacoustic survey (i.e., the number of small hydroacoustic targets multiplied by p_{juv}). Equations T2.3–T2.10 sequentially define the current fished state of the kokanee population in Kawkawa Lake. The von Bertalanffy growth function was used to estimate length at age (T2.3), which in turn was used to predict fecundity at age 3 (T2.4). Capture selectivity was assumed to be a logistic function of length (T2.5). Initial vulnerable abundance at the middle of the fishing season was approximated by estimating the remaining spawner abundance after accounting for half a season of natural mortality and adding back half of the estimated harvest (T2.6) for the same time interval. Estimating abundance at the middle of the fishing season is necessary to estimate the season-wide fishing mortality rate from the total harvest rate more accurately. The initial fishing mortality rate was calculated to include release mortality (T2.7). Unfished survivorship was assumed to be constant over ages (T2.8), and fished survivorship included a parameter that incorporates fishing mortality (T2.9). Initial abundance by age-class (T2.10) was calculated by using estimates of equilibrium fished recruitment and fished survivorship multiplied by a log-normal recruitment deviate (e^{Ω_a}), where Ω_a is normally distributed with a standard deviation of 0.4.

Model initialization was necessary to calculate several of the derived variables. The unfished and fished incidence functions (T2.11 and T2.12, respectively; Walters and Martell 2004) were used to predict unfished recruitment (T2.13) as well as the equilibrium Beverton–Holt recruitment parameters (T2.14 and T2.15). Equations T2.16 through T2.18 calculate the parameters of a food-dependent recruitment function, assuming that the proportion of recruit survival is influenced by variation in food density (z_t), based on van Poorten et al. (2018b). Food density was set relative to that measured in 2016 (i.e., $z_{2016} = 1.0$). Catchability was calculated by dividing the predicted fishing mortality rate by the observed fishing effort (T2.19). Finally, the density-dependence parameter of the annual asymptotic length function was calculated by solving T2.22 for $\beta_{L\infty}$ at initial conditions based on surface area (SA) = 72 ha (T2.20).

With initial population parameters, the operating model was used to make projections of age-structured population dynamics, harvest dynamics, and angler utility over the next 20 years, considering uncertainty in the fitted population parameters and process error. The model evaluated how changes in fishery management controls affect both the population and the fishery. Possible management controls included daily bag limits (BL), minimum length limits (MLL), and changes to the available spawning habitat (HAB) through spawning habitat improvements or exclusions to available spawning habitat. Additionally, the model evaluated how progressive changes in fishing effort capacity (through regional demographic growth) and lake productivity (through changes in land use) affect the system.

Predicting abundance at age proceeded in a similar manner to estimating the initial values; however, proposed controls were included to simulate changes to bag limits on numbers harvested, minimum length limits for harvest, and changes to available spawning habitat. Length at age was predicted from von Bertalanffy growth parameters, where K is assumed to remain constant and $L_{\infty,t}$ varies positively with available food density (T2.23); the parameters for the density-dependent function for predicting asymptotic length (T2.22) were generated assuming that the maximum asymptotic length at current food rates would extend to 1,000 mm. Selectivity to retention based on the minimum length limit was modeled as a logistic approximation to the cumulative normal distribution, thereby accounting for variability in length at age within an age-class (T2.24). Landed catch for each year and age-class were predicted by using the standard catch equation (T2.25). The proportion of angler days resulting in catch in excess of the bag limit was predicted assuming that the daily catch rate is Poisson distributed (T2.26), which was then used to calculate the proportion of captured fish that are legal for harvest. The rates for harvested fish for each year and age-class were predicted by modifying the catch equation by the proportion of fish harvested and assuming that length-based selection to harvest is a function of both the selection to the fishery and the minimum length limit (T2.27). The mean annual length of harvested fish was simply calculated as length-at-age weighted by the relative distribution of captured ages (T2.28). Total fishing mortality on the kokanee population is a function of both harvest and release mortality (T2.29). Abundance in the following year was modeled separately for recruits (age 0) and older fish (ages 1 to 3) that are subjected to fishing mortality. The Beverton–Holt recruitment function (T2.30) positively varies both maximum survival rate at low abundance and asymptotic recruitment based on the simplified prey-dependent recruitment function proposed in van Poorten et al. (2018b). Effective density (the total consumptive pressure on the shared food resource; Walters and Post 1993; Post et al. 1999), which was used in the density-dependent growth function (T2.22), was calculated as the squared sum of lengths of individuals per area (T2.31). Finally, angling utility was a weighted average of the utility that anglers have for both daily harvest and harvested lengths (T2.32). Both utilities were weighted equally, assuming that size and catch rates are of equal importance to anglers. Fishing effort the following year was expressed simply as the utility multiplied by the maximum possible fishing effort ($E_{max,t}$; T2.33). Note that the utility function that was used in this application (T2.32) recognizes that although these two metrics are not necessarily independent, the questions that were

TABLE 2. Fishery operating model for generating age-structured population dynamics, harvest dynamics, and angler utility for the kokanee fishery in Kawkawa Lake.

Equation number	Equation	Conditions
Parameters		
T2.1	$\Theta = \left\{\dot{L}_{\infty}, K, H_{2016}, Sp_{2016}, p_{(r)1}, R_{(F)0}, H_{50}, \sigma H, HL_{50}, \sigma L\right\}$	
T2.2	$\varphi = \left\{\alpha_f, \beta_f, \alpha_s, \beta_s, M_{(r)}, M, E_{2016}, \kappa, p_c, \alpha_{L_\infty}, \mathrm{cv}_1\right\}$	
Initial population		
T2.3	$L_{2016,a} = \dot{L}_{\infty}(1 - e^{-K \cdot a})$	
T2.4	$f_t = \alpha_f L_{2016,a=A}^{\beta_f}$	
T2.5	$sc_{t,a} = \left[1 + \exp\left(-\frac{L_{t,a} - \beta_s}{\alpha_s}\right)\right]^{-1}$	
T2.6	$V_{(F)} = Sp_{2016} e^{0.5M} + 0.5 \cdot H_{2016}$	
T2.7	$F_{2016} = \log_n\left(1 - \frac{H_{2016}}{V_{(F)}}\right)\left[p_{(r)1} + \left(1 - p_{(r)1}\right) M_{(r)}\right]$	
T2.8	$lx_{(U)a} = \begin{cases} 1 \\ lx_{(U)a-1} e^{-M} \end{cases}$	$a = 0.25$ $0.25 < a \le A$
T2.9	$lx_{(F)a} = \begin{cases} 1 \\ lx_{(F)a-1} e^{-M - s_{1,a-1} F_{2016}} \end{cases}$	$a = 0.25$ $0.25 < a \le A$
T2.10	$N_{1,a} = R_{(F)0} lx_{(F)a} e^{\Omega_a}$	
Derived parameters		
T2.11	$\phi_{(U)0} = \sum_{a=0}^{A} lx_{(U)a} f_{t=1}$	
T2.12	$\phi_{(F)0} = \sum_{a=0}^{A} lx_{(F)a} f_{t=1}$	
T2.13	$R_{(U)0} = R_{(F)0} \frac{\phi_{(F)0}}{\phi_{(U)0}} \frac{(\kappa - 1)}{\left[\kappa \frac{\phi_{(F)0}}{\phi_{(U)0}} - 1\right]}$	
T2.14	$\alpha_R = \frac{\kappa}{\phi_{(U)0}}$	
T2.15	$\beta_R = \frac{(\kappa - 1)}{R_{(U)0} \phi_{(U)0}}$	
T2.16	$c_{(1)R} = -\log_e(\alpha_R)(1 - p_c)$	
T2.17	$c_{(2)R} = -\log_e(\alpha_R) p_c z_{t=1}$	
T2.18	$c_{(3)R} = \beta_R z_{t=1}$	
T2.19	$q = \frac{F_{2016}}{E_{2016}}$	
T2.20	$\beta_{L_\infty} = \left(\frac{\alpha_{L_\infty}}{L_{\infty,t=1}} - 1\right) \frac{SA}{\sum\left(R_{(F)0} lx_{(F)a}\right)}$	
State dynamics		
T2.21	$Egg_t = N_{t,a} f_t$	
T2.22	$L_{\infty,t} = \frac{\alpha_{L_\infty} z_{t-1}}{1 + \beta_{L_\infty} L_{t-1}^2}$	

TABLE 2. Continued.

Equation number	Equation	Conditions
T2.23	$L_{t,a} = \begin{cases} L_{\infty,t}[1-\exp(-K\cdot a)] \\ L_{t-1,a-1}\exp(-K) + L_{\infty,t}[1-\exp(-K)] \end{cases}$	$a = 0.25$ $0.25 < a \leq A$
T2.24	$sr_{t,a} = \left\{1+\exp\left[-\frac{1.7(L_{t,a}-\mathrm{MLL})}{L_{t,a}\mathrm{cv}_l}\right]\right\}^{-1}$	
T2.25	$C_{t,a} = N_{t,a}\left[1-\exp\left(-qE_t sc_{t,a}\right)\right]$	
T2.26	$p_{(r)t} = \frac{\sum_{x=1}^{100}\left\{\min(x,BL)\frac{\left[\left(\frac{C_{t,a}}{E_t}\right)^x \exp\left(-\frac{C_{t,a}}{E_t}\right)\right]}{x!}\right\}}{\left(\frac{C_{t,a}}{E_t}\right)}$	
T2.27	$H_{t,a} = \sum_{a=0}^{A}\left\{N_{t,a}p_{(r)t}\left[1-\exp\left(-qE_t sc_{t,a}sr_{t,a}\right)\right]\right\}$	
T2.28	$HL_t = \frac{\sum_{a=0}^{A}\left\{H_{t,a}L_{t,a}\right\}}{\sum_{a=0}^{A}H_{t,a}}$	
T2.29	$F_{t,a} = qE_t sc_{t-1,a}\left[p_{(r)t-1}sr_{t-1,a} + \left(1-p_{(r)t-1}sr_{t-1,a}\right)M_{(r)}\right]$	
T2.30	$N_{t,a} = \begin{cases} \frac{Egg_{t-1}\exp\left(-c_{(1)R}\frac{c_{(2)R}}{z_{t-1}}+\Omega_{t+A-1}\right)}{1+\frac{c_{(3)R}}{z_{t-1}\mathrm{HAB}}Egg_{t-1}} \\ N_{t-1,a-1}e^{-M-F_{t,a}} \end{cases}$	$a = 0.25$ $0.25 < a < A$
T2.31	$L_t^2 = \frac{\sum L_{t,a}N_{t,a}^2}{SA}$	
T2.32	$U_t = \frac{0.5}{1+\exp\left(-\frac{\frac{\sum_{a=0}^{A}H_{t,a}}{E_t}-H_{50(H)}}{\sigma_{(H)}}\right)} + \frac{0.5}{1+\exp\left(-\frac{HL_t-H_{50(L)}}{\sigma_{(L)}}\right)}$	
T2.33	$E_{t+1} = E_{max,t}U_t$	

used to parameterize each function did not suggest an interaction between catch rate and size. Therefore, the two logistic functions were integrated into an overall utility function by taking a weighted average of the two components to be consistent with the overall intent of respondents to the survey.

The deterministic model evaluations were repeated for each value that was sampled from the estimated posterior distributions. The parameters that were based on literature values or expert judgment of the authors were assumed to be normally distributed with a coefficient of variation of 0.1. This allowed the model to represent uncertainty across all of the parameters.

To initialize the population, it is necessary to define the proportion of captured fish that are harvested at fished equilibrium (i.e., the proportion of captured fish that were below the current bag limit of four fish per day; $p_{[r]1}$). This was accomplished for each random combination of parameters by using a simple grid search across values from 0 to 1 by increments of 0.01. Each $p_{(r)1}$ was chosen based on the value that minimized the calculated interannual variation in spawner abundance.

Decision analysis.— We evaluated various management actions in the face of parameter and process uncertainty by using a Bayesian decision analysis framework (Robb and Peterman 1998). Decision analysis determines and communicates the relevant performance of management options across a range of hypotheses about the state of the system (Walters 1986). Each hypothesis is assigned a prior probability that reflects the relative belief in the hypothesis compared with all of the others. Integrating the expected performance of each management option across

TABLE 3. Estimated and fixed parameters that were used in the fishery operating model. Note that the parameters with no range are assigned fixed values in the model. The index values are presented as a range of values. The parameter values are expressed as the estimated mean with standard deviation in parentheses.

Parameter	Value	Description	Source
		Indices	
t	{2016, 2017, … T}	Time step ($T = 2036$)	
a	{0.25, 1.25, … A}	Age-class ($A = 3.25$)	
		Parameters estimated from data	
L_∞	444.4 (11.5)	Initial von Bertalanffy asympotic length	
K	0.5 (0.02)	von Bertalanffy metabolic parameter	
H_{2016}	1,545.3 (65.4)	Harvest in 2016	
Sp_{2016}	2,801.3 (728.3)	Spawner abundance in 2016	
$R_{(F)0}$	19,034.3 (803.5)	Equilibrium recruits (set to 2016 fry estimates)	
$H_{50(N)}$	2.4 (0.25)	Mean number of harvested fish at 50% angler utility	
$\sigma_{(N)}$	0.64 (0.19)	Logistic slope in angler utility for harvested fish numbers	
$H_{50(L)}$	316.7 (6.8)	Mean length of harvested fish at 50% angler utility	
$\sigma_{(L)}$	12.0 (3.9)	Logistic slope in angler utility for harvested fish length	
$p_{(r)1}$	0.36 (0.43)	Initial proportion released	
		Parameters based on literature or expert judgement	
α_f	3.7 10^{-4} (3.7 10^{-5})	Scalar in length–fecundity function	McGurk 2000
β_f	2.5 (0.25)	Power parameter in length–fecundity function	McGurk 2000
M	0.6 (0.06)	Instantaneous natural mortality rate	McGurk 1999
$M_{(r)}$	0.3 (0.03)	Release mortality rate	Bartholomew and Bohnsack 2005
E_{2016}	6,786 (289.9)	Fishing effort in 2016	van Poorten and Brydle 2018
α_S	13.0 (1.30)	Slope parameter in logistic selectivity function	Expert judgement
β_S	310 (31.0)	Length at 50% selectivity to fishing gear	Expert judgement
κ	5.2 (0.52)	Goodyear compensation ratio	Myers et al. 1999
p_c	0.9 (0.04)	Proportion of recruit survival due to prey availability	Expert judgement
α_{L_∞}	1,000 (100.0)	Prey-dependent density-dependent growth parameter	Expert judgement
cv_l	0.1	Coefficient of variation in length at age	Expert judgement
p_{juv}	0.9 (0.04)	Proportion of juvenile target strength range that is kokanee juveniles	Expert judgement

all possible hypotheses multiplied by the prior belief in each hypothesis provides a posterior expected value for that management option, essentially identifying policy options that are robust to uncertainty in the state of nature (Walters and Martell 2004).

Our evaluation followed the six basic steps of decision analysis (modified from Robb and Peterman 1998): (1) identify available management actions; (2) identify management objectives; (3) identify alternative hypotheses regarding the state of nature; (4) assign prior probability to each hypothesis; (5) calculate outcomes for each management action–hypothesis combination; and (6) evaluate the management options. Here, we discuss each of these steps in turn.

First, we identified the available management actions that were possible for Kawkawa Lake. The simplest of these is to impose or adjust regulations on the recreational fishery. These included: daily harvest (bag) limits, which we determined to be four, two, or zero (catch-and-release) fish per day; or minimum length limits on harvestable fish, which were either not imposed or set at 35 cm. Another management action is to directly modify available spawning habitat, reflecting the desire of managers to address urban encroachment and invasive plant species in the streams. Alternately, managers may choose to limit access to spawning habitat to reduce densities and potentially improve growth. Therefore, we included management scenarios where spawning habitat was increased or decreased by 25% or unchanged.

We next identified management objectives for the fishery, which were used to rank the relative efficacy of different management actions in achieving fishery goals. Recreational fishery goals in British Columbia include both maintaining angler satisfaction and conserving the resource (British Columbia Ministry of Environment 2007). Therefore, we defined objectives that are related to angler satisfaction and conservation of the population. We assumed that utility of daily catch rates and size of captured fish could be used to represent overall angler satisfaction, based on observations that satisfaction is routinely based on catch-related attributes of recreational fisheries (Arlinghaus 2006) and a recent meta-analysis of angler preference demonstrating that these two metrics were often important considerations when measuring catch-related utility (Hunt et al. 2019). Angler utility in the operating model was calculated in each time step and each management scenario by using equation T2.32, which was parameterized by using the stated preferences of the anglers that were interviewed in the creel survey (see the *Data collection and analysis* section). Using this metric, we defined our angler objective as that of achieving an angler utility greater than 50%; in other words, our objective is to have a fishery with angler satisfaction that is greater than neutral. Conservation was measured by using the spawning potential ratio (SPR), the expected lifetime egg production per recruit in the fished relative to the unfished state (i.e., $\Phi_{(U)0}$). Walters and Martell (2004) suggest maintaining SPR > 0.3, while Clark (2002) suggests that less resilient species must maintain SPR > 0.4. Therefore, we imposed a conservative objective to maintain SPR > 0.4. Performance indicators are measureable values that are used within the decision analysis to determine the relative success of different management actions in their ability to influence the objectives of the fishery. Therefore the performance indicators that were used for the future projections were the proportion of model runs across all random variables that resulted in angler utility >0.5 and spawning potential ratio >0.4, calculated 20 years after changes to the regulations or spawning habitat availability have been made. When evaluating both objectives together, we recognize that there is likely a trade-off between conservation and recreational use. There are a number of ways to combine multiple objectives (Kiker et al. 2005); we chose to multiply the expected values for each management option across conservation and angler objectives. In doing so, no single goal (recreation or conservation) may be compromised while maximizing the overall objective. Note that the management objective is multiplicative while the angler utility (T2.32) is additive. This implies that while individual anglers chose their fishing activity based on either size or catch rates, management considers that across all anglers both are important and a decline in utility for size or catch rates is detrimental to the overall utility.

There are two primary concerns regarding the state of nature and how it may affect the fish and fishery of Kawkawa Lake. The first is the state of primary productivity in the lake, which may decline over time as nutrients from septic fields dissipate. Therefore, we evaluated situations where in-lake productivity (z_t) varies annually as $z_t \sim N(dz_{t-1}, 0.1)$, where d was used to modify the rate of change in productivity to either increase ($d > 0$), vary randomly ($d = 0$), or decrease ($d < 0$). Another primary concern is the potential for increased fishing effort due to human population growth. We hypothesized that maximum annual fishing effort may increase at the same rate as the regional population growth ($g = 1.7\%$/year over the past 20 years; Statistics Canada 2017) or may grow twice as fast as the regional average, which might reflect an increase in participation rate or a propensity for local residents to be more interested in fishing than is represented by the regional average. Therefore, maximum annual fishing effort is evaluated as (1) $E_{max,t} \sim N(g \cdot E_{max,t-1}, 0.1)$ or (2) $E_{max,t} \sim N(2\,g \cdot E_{max,t-1}, 0.1)$. Each combination of these hypothesized states of nature were given an equal prior probability of being true; therefore, $p(\text{model}_i) = 0.167$ for each of the six modeled combinations of system productivity and fishing effort.

For each management action and state of nature, we calculated the probability of angler utility's dropping below 0.5 and the spawner potential ratio's being below 0.4 across all random draws of the estimated parameter posterior distributions (T2.1) and across all years. We then calculated the expected value (i.e., the weighted average) of each performance indicator for each management action across all states of nature (the hypotheses about productivity and fishing effort). Expected values were used to evaluate the management actions in light of the two fishery objectives. The final multicriteria objective was calculated as the product of expected values under each management action across conservation and angler objectives:

$$U_{MV} = \frac{\sum_{i=1}^{SN} U_{(N|HPUE)i}}{SN} \cdot \frac{\sum_{i=1}^{SN} U_{(L|\bar{L})i}}{SN},$$

where each component on the right represents the expected value of utility for catch rate and fish size across all states of nature $(SN) = 6$. This multiplicative utility function assumes that the angling satisfaction subobjectives for catch size and catch rates are independent.

Lastly, a one-way sensitivity analysis was conducted to evaluate the relative influence that each parameter had on the multicriteria objective across all of the possible management interventions. This was done by systematically setting each parameter to a series of fixed values across the range of that parameter, while all of the other parameters were stochastic within their distribution. The range of objective values that was observed across all of the management actions was reported for each parameter (Conroy and Peterson 2013).

RESULTS

A total of 669 anglers were interviewed over 68 creel survey days in 2016, reporting a total of 2,830 hours of fishing. The anglers that were interviewed reported a mean catch per unit effort of 1.4 kokanee per day and a mean harvest per day of 1.0 kokanee per day. Based on the estimated 2016 fishing effort in van Poorten and Brydle (2018), the total annual harvest was 1,544 (95% quantiles: 1,415, 1,671) kokanee.

Angler opinions on the number of fish that were harvested and their mean size varied widely across individuals. Some anglers admitted that they would be happy to come back to Kawkawa Lake regardless of the fishing experience because of various noncatch related motivations. However, among all anglers, it was possible to estimate a mean utility function for daily harvest and size (Figure 1). These functions predict a 50% utility for daily harvest of 2.4 fish with a mean size of 317 mm (Figure 1). Additionally, while anglers derive at least some utility for a wide range of daily harvest rates, they have a very low utility for small kokanee (Figure 1).

The size of the harvested kokanee ranged from 220–384 mm in length. Fifty fish from the fishery were assessed for age; of these, most (86%) were age 3, and the remainder were ages 2 and 4 (10% and 4%, respectively). Using an informative prior probability distribution for the von Bertalanffy *K* parameter, we calculated posterior predictions of growth parameters for use in the predictive model (Table 2).

The stable isotope analysis supported the hypothesis that nutrient enrichment was occurring at one of the two sampled inlet streams due to anthropogenic sources. The mean $\delta^{15}N$ was significantly higher in Kopp Creek than in any other location that was sampled and 3.4‰ higher than the mean value for the lake (Table 4). This highly elevated $\delta^{15}N$ suggests anthropogenic enrichment, although the influence on overall productivity will require further investigation.

A total of 2,058 spawning kokanee were observed in four of the five inlet streams between October and November 2016. The mean spawning date ranged from October 4–12 for the three streams that were analyzed. The median number of spawners that was estimated for each stream was 21, 699, 420, and 1,681, yielding a total of 2,801 spawners in 2016 (Sp_{2016}; Table 3).

The operating model provided useful baseline estimates of the current state of the fishery. Based on estimated vulnerable biomass (assuming the fishery primarily targets age 3 fish), the current fishing mortality is estimated to be 0.42/year (Figure 2A). Based on the value for fishing effort that was estimated in van Poorten and Brydle (2018), this leads to a catchability of 0.01 ha/angler day (Figure 2B). The current mean utility for the fishery that is derived by anglers was calculated as 0.44 (Figure 2C), which is largely driven by low average harvest rates across all of the anglers but large size of the harvested fish.

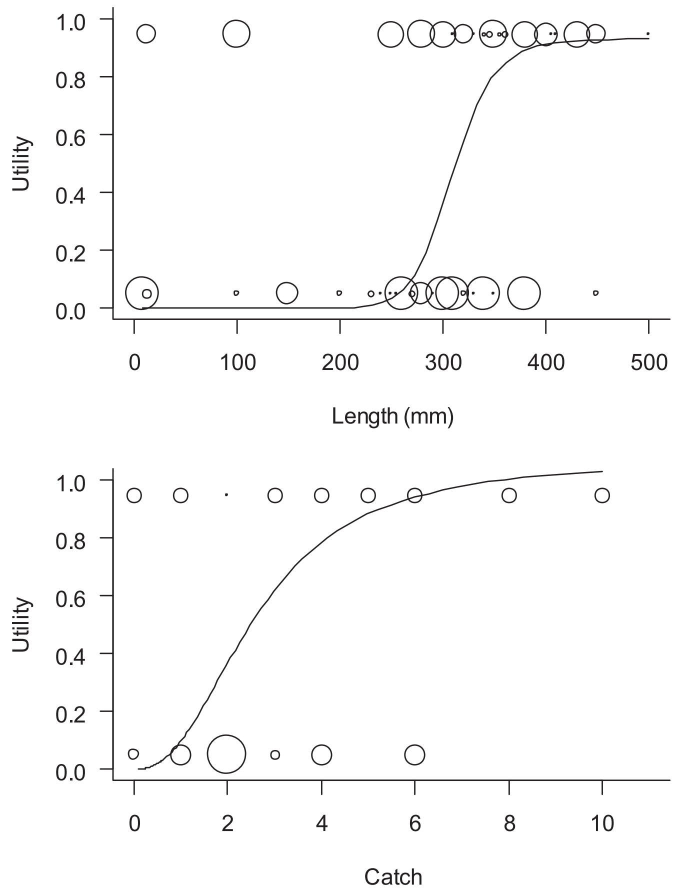

FIGURE 1. Logistic functions that were used to characterize angler utility for length of harvested fish (top panel) and daily catch rate (bottom panel). The dots represent aggregated angler responses to mean fish lengths and daily catch rates that lead to dissatisfaction (utility = 0.05) or complete satisfaction (utility = 0.95). The size of the dots corresponds to the number of responses for a particular length or catch rate. The lines represent the logistic function at the posterior parameter modes.

TABLE 4. Mean ± SE (sample size in parenthesis) δ^{15} values for particulate organic matter in the Kawkawa Lake samples.

	$\delta^{15}N$ (‰)	
Site	Mean	SE
Kopp Creek	5.4	1.0 (2)
Menz Creek	2.0	0.9 (3)
Mid lake	2.1	0.3 (3)
SE shore	2.0	0.1 (3)
Outlet	2.0	0.1 (3)

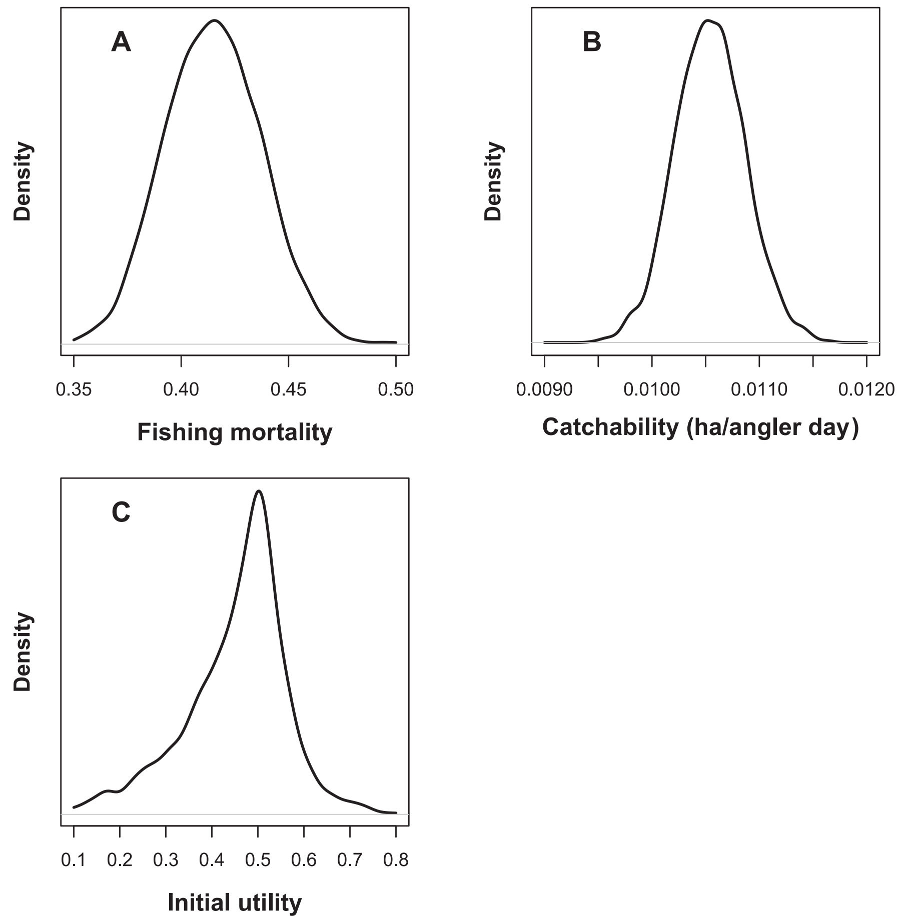

FIGURE 2. Calculated distribution of **(A)** fishing mortality, **(B)** catchability, and **(C)** angler utility for the Kawkawa Lake kokanee fishery in 2016 based on posterior parameter estimates input into the fishery model.

The operating model predicted that under the current management regulations of a daily harvest limit of four fish, if lake productivity maintains at the current level and maximum possible fishing effort tracks historic regional rates of population increase, the spawning stock will progressively decline due to increased fishing mortality (Figure 3). As population abundance declines, the mean length of harvested fish will increase, although marginally. Increases in fishing effort approximately offset increases in recruitment, resulting in stable harvest rates but a decline in spawner abundance by more than 50% (Figure 3). While effort increases due to increases in the number of anglers, utility remains relatively stable due to the very moderate change in the size and number of harvested fish.

If fishing effort increases faster than regional population growth or productivity declines over time, similar patterns will be seen in the fish population and the fishery when managing by using a daily harvest limit of four fish (Figure 3). If productivity declines at an annual rate of 2%, recruitment is impaired somewhat more than growth rate; therefore, the reduction in recruitment causes an overall moderate increase in fish size despite a reduction in prey availability. Spawner abundance in this scenario is approximately unchanged from the constant productivity scenario. If fishing effort increases at twice the regional population growth rate, spawner abundance declines by 75% over 20 years. In this scenario, the daily harvest rate begins to decline as a result of overharvest. If fishing effort increases at twice the regional population growth rate concurrently with declines in productivity, spawner abundance again declines by 75%, harvest rate begins to decline, and the mean size of fish increases to over 400 mm on average.

Optimal Management Action

Decision analysis was used to evaluate the performance of each management intervention across a series of hypotheses about how maximum fishing effort and system productivity may change over a 20-year horizon. If management and fishery productivity remain status quo (i.e., a four-fish bag limit and no other management actions; Table 5) and effort is assumed to increase continually with

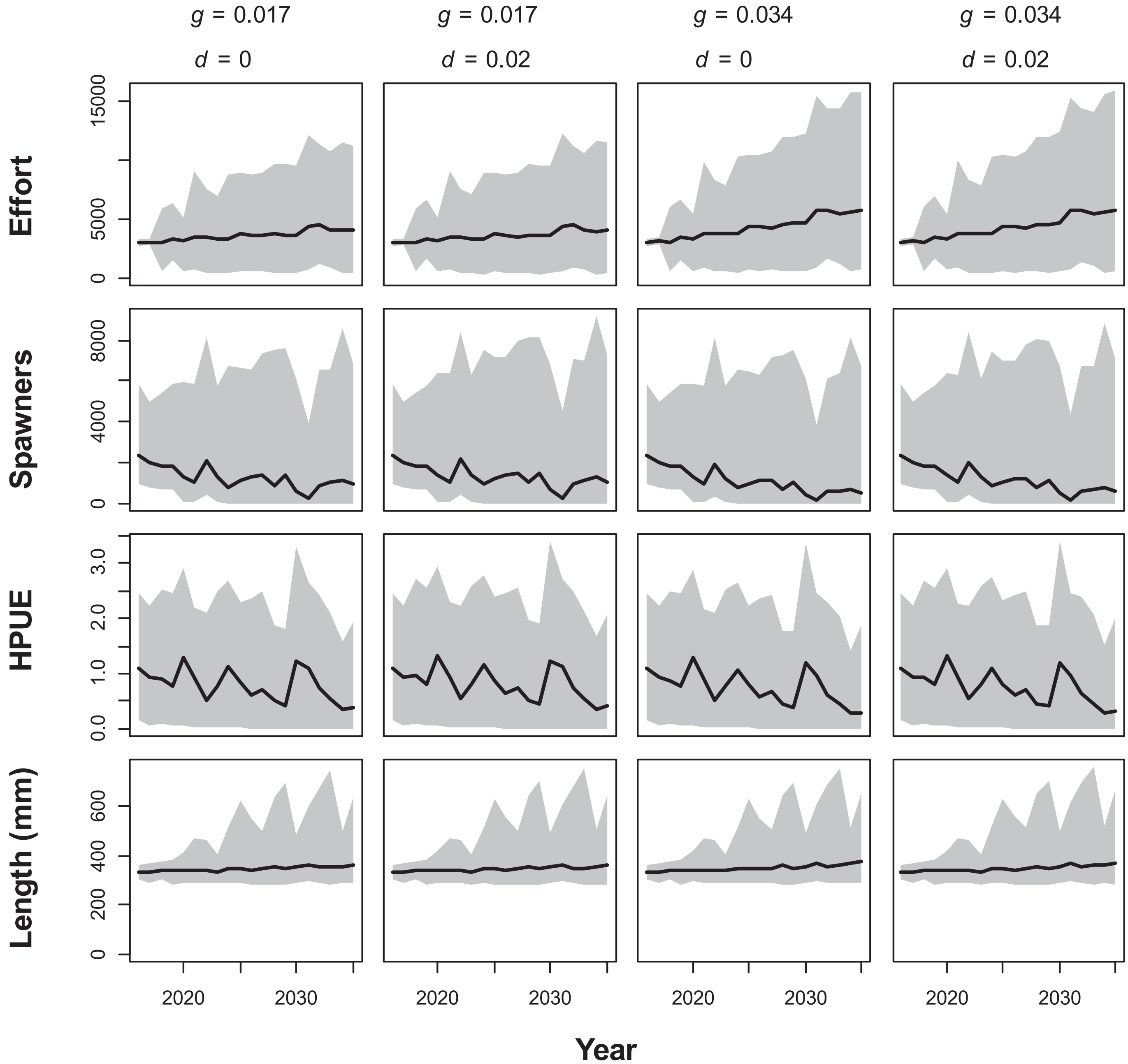

FIGURE 3. Projected time series of fishing effort (top row), spawner abundance (second row), mean daily harvest rate (third row), and mean length of harvested fish (bottom row) under different hypotheses (columns) for the rate of increase in angler capacity (g) and the rate of decrease in fish population productivity (d). The solid line represents the median projection; the gray shaded areas represent 80% quantiles.

regional population growth, marginal improvements in angler utility are predicted. However, angler utility is generally insensitive to changes in productivity and increasing effort; changes in long-term angler utility are most influenced by management actions. Reducing the daily harvest limit to two fish reduces angler utility, as highly skilled anglers are restricted in the number of fish that they can harvest. Catch and release regulations (zero fish may be harvested) universally result in the lowest angler utility under all scenarios. Similarly, size restrictions also lead to low angler utility, as many fish that would normally be harvested must now be returned. Increasing the available spawning habitat uniformly reduces angler utility due to an increase in recruitment, reducing density-dependent growth and the mean size of harvested fish. Conversely, the highest angler utility was predicted when spawning habitat was reduced due to the indirect effects on fish size.

TABLE 5. Probability of exceeding the angler utility threshold (i.e., $U > 0.4$), given different hypotheses regarding future trends in ecosystem productivity and capacity in fishing effort (columns) and management actions taken to achieve the angler satisfaction management goals (rows). The values in bold italics indicate the maximum expected values.

			No change in fishing effort			Increase in fishing effort			
Habitat	Size limit	Catch limit	Decrease in productivity	No change in productivity	Increase in productivity	Decrease in productivity	No change in productivity	Increase in productivity	Expected value
No change	None	4	0.59	0.58	0.57	0.63	0.62	0.62	0.6
	None	2	0.55	0.53	0.52	0.6	0.58	0.57	0.56
	None	0	0.31	0.3	0.29	0.33	0.32	0.31	0.31
	35 cm	4	0.43	0.42	0.4	0.46	0.45	0.43	0.43
	35 cm	2	0.42	0.41	0.4	0.46	0.44	0.42	0.42
Increase	None	4	0.46	0.45	0.44	0.5	0.49	0.47	0.47
	None	2	0.44	0.42	0.4	0.47	0.46	0.44	0.44
	None	0	0.26	0.24	0.23	0.28	0.26	0.25	0.25
	35 cm	4	0.35	0.34	0.33	0.38	0.36	0.35	0.35
	35 cm	2	0.35	0.35	0.32	0.37	0.36	0.35	0.35
Decrease	None	4	***0.78***	***0.78***	***0.78***	***0.83***	***0.82***	***0.82***	***0.8***
	None	2	0.75	0.73	0.72	0.8	0.79	0.77	0.76
	None	0	0.42	0.41	0.4	0.45	0.44	0.42	0.42
	35 cm	4	0.6	0.58	0.57	0.64	0.63	0.61	0.6
	35 cm	2	0.59	0.57	0.55	0.63	0.61	0.6	0.59

TABLE 6. Probability of exceeding the angler conservation threshold (i.e., SPR > 0.4), given different hypotheses regarding future trends in ecosystem productivity and capacity in fishing effort (columns) and management actions taken to achieve the conservation management goals (rows). The values in bold italics indicate the maximum expected values.

			No change in fishing effort			Increase in fishing effort			
Habitat	Size limit	Catch limit	Decrease in productivity	No change in productivity	Increase in productivity	Decrease in productivity	No change in productivity	Increase in productivity	Expected value
No change	None	4	0.69	0.7	0.7	0.5	0.51	0.52	0.6
	None	2	0.73	0.74	0.75	0.53	0.56	0.55	0.64
	None	0	***0.99***	***0.99***	***0.99***	***0.98***	***0.98***	***0.98***	***0.98***
	35 cm	4	0.91	0.91	0.91	0.78	0.79	0.8	0.85
	35 cm	2	0.9	0.9	0.91	0.78	0.78	0.79	0.84
Increase	None	4	0.75	0.75	0.76	0.6	0.61	0.62	0.68
	None	2	0.78	0.79	0.79	0.62	0.64	0.65	0.71
	None	0	***0.98***	***0.98***	***0.98***	***0.98***	***0.97***	***0.98***	***0.98***
	35 cm	4	0.92	0.92	0.92	0.82	0.83	0.83	0.87
	35 cm	2	0.91	0.91	0.91	0.81	0.82	0.83	0.87
Decrease	None	4	0.64	0.64	0.64	0.38	0.39	0.4	0.51
	None	2	0.67	0.68	0.68	0.41	0.42	0.43	0.55
	None	0	***0.98***	***0.98***	***0.98***	***0.97***	***0.97***	***0.97***	***0.98***
	35 cm	4	0.87	0.88	0.88	0.68	0.69	0.7	0.78
	35 cm	2	0.86	0.86	0.86	0.67	0.69	0.7	0.78

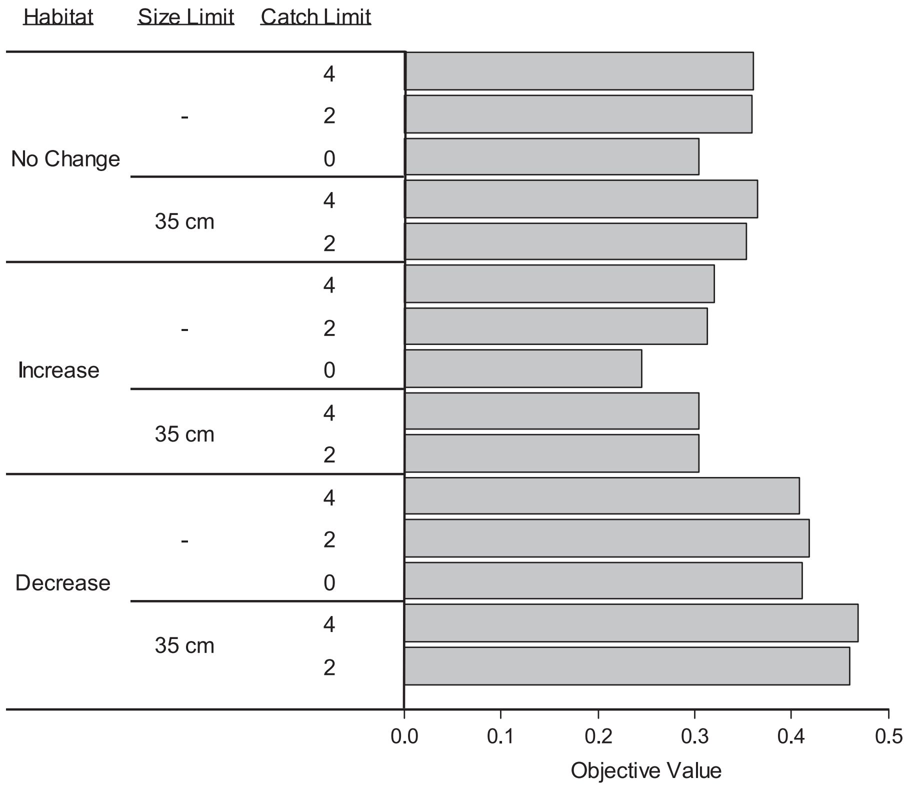

FIGURE 4. Multiattribute objective value for each management action, calculated as the product of the expected value for each management action across utility objectives for conservation and angler use.

Considering the expected value across all states of nature allows us to determine which management actions are robust to uncertainty about how fishing effort or system productivity may change over time. The model predicts that angler utility is highest with four- or two-fish bag limits, and bag limits are preferred to either catch-and-release regulations or size limits. Increasing spawning habitat is strongly discouraged in this context (i.e., maximizing angler utility) and reducing spawning habitat has the best overall outcome.

Evaluating the conservation indicator (the probability of the spawner potential ratio's declining to below 0.4) produced nearly opposite outcomes to evaluating the angler indicator (Table 6). Bag limits were much less effective at meeting conservation objectives than were catch-and-release or size limits. Increasing or retaining available spawning habitat had better conservation outcomes than did reducing current spawning habitat, except when paired with catch-and-release regulations because increased fish size led to increased egg production per fish. Overall, success at meeting the conservation objective was far more sensitive to changes in angler effort. The probability of falling below the conservation threshold decreased significantly if angler effort increased over time except for scenarios where catch-and-release regulations were implemented. Changes in productivity had no effect on the conservation indicator.

The multiplicative multicriteria objective was used to minimize a trade-off between the two objectives. If spawning habitat were to be maintained, limiting harvest by using a four- or two-fish bag limit would produce the highest management outcomes, especially when paired with a conservative minimum length limit (Figure 4). However, if management were willing to reduce spawning habitat, thereby increasing fish size, any fishing regulation will provide reasonable management outcomes. The best overall performance is with a four-fish bag limit and reduced spawning habitat.

The parameters that are related to size had the most influence on the multicriteria objective (Figure 5). Specifically, the median length of fishing selectivity and the slope of the fecundity relationship could each result in over a 20% increase in value or over a 70% decrease in the objective value. Most of the other parameters had a similar range in influence on the objective value.

DISCUSSION

Fisheries management strives to make choices among uncertain actions (Walters and Martell 2004). This

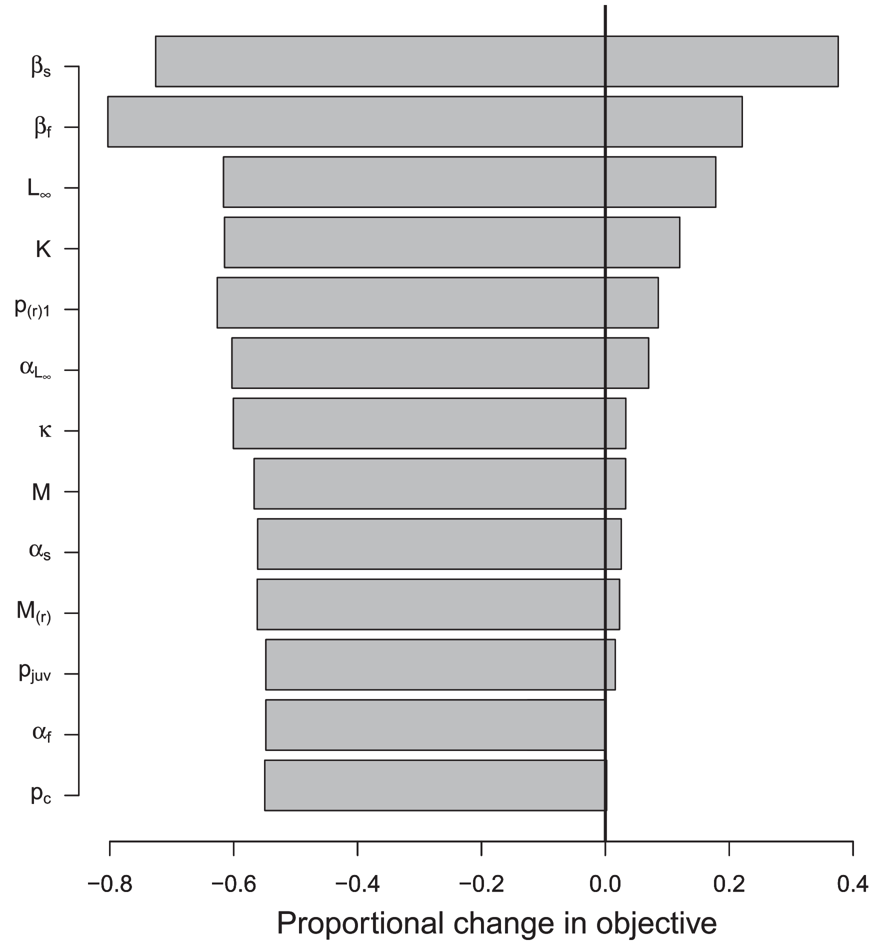

FIGURE 5. Tornado plot showing the proportional change in objective function that is possible across a range of actual values for each parameter.

involves explicitly stating management objectives, admitting which aspects of the system are uncertain, and predicting how each choice might affect the system. Decision analysis captures all aspects of this process by evaluating how the model predictions for different management actions affect management objectives amid uncertainty (Hilborn and Walters 1992; Robb and Peterman 1998). Decision analysis is a routine part of many commercial stock assessments, but it is relatively underused in recreational fisheries management applications (Peterson and Evans 2003; but see examples in Irwin et al. 2008; Jones and Bence 2009). For the Kawkawa Lake case study, decision analysis forced us to recognize the trade-offs that exist in our system, specifically the desire to improve abundance by increasing spawning habitat (a conservation argument) versus the desire to satisfy anglers by allowing harvest. The overall best management option in any decision where multiple attributes are considered within the objective function will depend on how various subobjectives are weighted. Managers can now use these results to make a clearly rationalized decision that can be communicated to stakeholders.

We have presented simplified management objectives, both for social and ecological outcomes, based on the stated preferences of anglers who were already on the lake (we do not know the views of anglers who may already be dissatisfied and not fishing; Lynch et al. 2017) and commonly agreed-upon conservation metrics (e.g., spawner potential ratio). Creating simplified management objectives was necessary, as there are no quantitative objectives for recreational fisheries in British Columbia or for most recreational fisheries generally (Lackey 1998). Our fishing objectives were based on the broad goals that are set out for recreational fisheries management in BC (British Columbia Ministry of Environment 2007), reflecting both ecological and social values. We feel that identifying and quantifying fishery objectives that match management goals is perhaps the most important step in a decision analysis and will help to avoid important pitfalls in the future (Barber and Taylor 1990; Hilborn 2007).

Our method for establishing catch-based angler utility is rudimentary, but it is consistent with the recreational management goals of the fishery (British Columbia Ministry of Environment 2007) and many other fisheries (Radomski et al. 2001; Pereira and Hanson 2003). The data that were used to parameterize our utility functions and the outcomes of these functions are easily interpretable by managers and stakeholders, which is important in any decision context. Although many recreational fisheries are guided by the goals of angler satisfaction and conservation, evaluating the human dimension of recreational fisheries is often lacking in many field-based assessments. We have incorporated empirically derived angler utility functions to quickly represent the heterogeneity of angler perceptions of various catch-related aspects of the fishery. Incorporating angler feedback to determine stated preferences for current and future fishery conditions in the fishery is entirely novel in recreational fisheries, and while we accept that there are many more appropriate methods for assessing angler utility and satisfaction (e.g., discrete choice experiments; Aas et al. 2000) we see this as a reasonable alternative that is easily conducted and interpreted by managers that are employing typical survey techniques that are common to small recreational fisheries.

Our results suggest that maintaining angler utility and satisfied anglers will not necessarily coincide with meeting conservation objectives. This reinforces the point that recreational fisheries often will not achieve a suitable bionomic equilibrium because of the multiple, often contradictory, objectives that are being evaluated by anglers (Hunt et al. 2011). For example, if anglers were only interested in catch rates, it is reasonable to expect that as catch rates decline effort would dissipate, resulting in a sustainable fishery. However, because kokanee anglers at Kawkawa Lake were more interested in fish size and because density-dependent growth results in extreme increases in body size at low density (Post et al. 1999), angler utility is maximized at low densities. Managers must carefully acknowledge the resultant trade-off between angler utility and conservation outcomes. Decision analysis helps to expose these trade-offs and facilitates discussion of these important outcomes.

Our system model incorporates density-dependent growth, which helped to produce some plausible, if somewhat counterintuitive, results. For example, without density-dependent growth, reducing spawning habitat would have merely affected catch rates but not size. This increase in growth results in a higher level of satisfaction with fish size as well as fecundity, thereby buffering the conservation outcome of reduced abundance. Therefore, including density-dependent growth changed the outcomes of our decision analysis, more accurately reflecting the conservation and satisfaction implications of management decisions. These results highlight the importance of including density-dependent processes when considering social-ecological fishery outcomes (Lorenzen 2016).

Monitoring effort is generally spread thinly across waterbodies because recreational fisheries managers are often responsible for hundreds to thousands of directed fisheries on individual waterbodies (Shuter et al. 1998). As such, time series analyses of fisheries data, as is typically available for many commercial stocks, are notably rare among all but the most economically and politically valuable recreational fisheries (De Graaf et al. 2015; Fitzgerald et al. 2018). We did not base our decision analysis on a typical stock assessment model (e.g., virtual population analysis, statistical catch-at-age analysis; Hilborn and Walters 1992) because we did not have a time series of data to fit to. Instead, we took information from a variety of sources to parameterize a plausible description of the Kawkawa Lake fishery. Further, we assumed that the population was at equilibrium prior to the initiation of monitoring, which is never technically true. Although we explicitly considered a slow change in system productivity, we would argue that this does not greatly influence our overall assumption of equilibrium due to the relative dynamic rates of populations and modeled productivity. Similar models that simulate interactions among ecosystem components with very different dynamic rates (e.g., phytoplankton and fish) can be appropriately approximated by setting one component as constant relative to the other, a process called variable speed splitting (Walters and Korman 1999), which we have essentially done here. While our modeling method may have oversimplified or poorly predicted some interactive processes, we feel that this is an appropriate method for leveraging the available data to make better and more informed decisions. As is common in decision analysis applications, we were able to combine information from different sources (Peterman and Anderson 1999) and thereby represent uncertainty in both our model parameters and the underlying states of nature with a fair amount of realism. Further work should consider the sensitivity analysis that was conducted (Figure 5) to prioritize important aspects of the system and model that have a large influence on objective values and decisions. Reducing uncertainty in these variables, particularly the length at 50% selectivity to the fishery and the fecundity relationship, would reduce uncertainty in the overall model predictions.

Recreational fisheries management is about much more than setting fishery regulations. It may involve (among other things) controlling invasive species, adding nutrients to a reservoir, creating spawning habitat, and recovering species at risk (Nielsen 1999). Engaging in any of these activities involves tradeoffs, among either stakeholders or objectives. Our work highlights the need for setting quantitative objectives; creating defensible, quantitative models (even simple ones, provided they address the problem at hand); and admitting uncertainty in both parameters and our presumption of the state of nature. Decision analysis allows a decision maker to clearly view how any suite of management actions will affect objective indicators and how each action compares against all others, improving the odds of creating robust and attractive recreational fisheries.

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