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Addressing Challenges Common to Modern Recreational Fisheries with a Buffet-Style Landscape Management Approach

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ABSTRACT

Recreational fisheries management strives to provide satisfying fishing experiences to heterogeneous anglers while conserving fish stocks of varying productivity. Achieving this balance with one-size-fits-all regulatory strategies is challenging; but complex, waterbody-specific regulations may be onerous to anglers and managers. An alternative strategy is a limited but specifically diverse "buffet" of regulations across a landscape of discrete fisheries to improve outcomes over existing regulation strategies. This approach is tested using a landscape bioeconomic model with density dependent growth and survival feedbacks in fish populations and dynamic angler behavior. Sources of heterogeneity in angler behavior and biological processes are considered to select and apply an optimal suite of fishing regulations. At a regional level, the buffet-style strategy offers improvements over other management strategies by recognizing tradeoffs among the utility and effort patterns of diverse angler types. Furthermore, these benefits are generally maintained even when limited to only five regulations to ease implementation logistics. Additional requirements for management agencies using the buffet strategy are discussed, such as assessing angler heterogeneity and determining which regulations are implemented on which waters. Some of these challenges may be overcome because this approach is imminently compatible with active-adaptive and cooperative management ideas.

KEYWORDS
Angler heterogeneity; buffet management; conservation; fishing motivations; participation; satisfaction

Introduction

Recreational fisheries comprise a dominant use of many fresh and coastal waters throughout the world (Lewin et al., 2006), and provide substantial socio-economic benefits to anglers (Toivonen et al., 2004; Arlinghaus and Cooke, 2009; Ihde et al., 2011) who, through the act of fishing, catching, and harvesting fish, exert mortality on fish populations that can sometimes be unsustainable (Post et al., 2002; Coleman et al., 2004; Arlinghaus and Cooke, 2005). Thus, providing anglers with satisfactory with fishing experiences, without sacrificing the long-term sustainability of the fish populations is the primary aim of institutions charged with governing recreational fisheries (Royce, 1983; Hilborn, 2007; Koehn, 2010).

Fisheries management agencies have traditionally tried to regulate fishing mortality by implementing closed seasons and/or harvest regulations limiting the size and number of fish removed to ensure adequate spawning fish for sustainable recruitment (Cowx, 2002; Pereira and Hansen, 2003; Walters and Martell, 2004). Harvest regulations that maximize long term catch or harvest may be poorly suited for recreational fisheries where angler satisfaction may not be closely tied to aggregate biomass harvested (Malvestuto and Hudgins, 1996; Radomski et al., 2001), and humans fish for leisure (Arlinghaus and Cooke, 2009; Cowx and van Anrooy, 2010). With this in mind, management agencies make decisions with the dual goals of satisfying anglers while still conserving fish populations. Certainly, in low-risk fisheries, increasing attention is paid to satisfying anglers. Angler satisfaction is a social construct derived from expectations and actual fishing experiences that include catch (size, numbers) and non-catch (crowding, esthetics, facilities) related attributes (Arlinghaus, 2006; Hunt et al., 2013a, Beardmore et al., 2015). But angling populations are diverse in how they achieve satisfaction (Holland and Ditton, 1992; Oh and Ditton, 2006), and

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this heterogeneity complicates managing for angler satisfaction (Johnston et al., 2010; Gwinn et al., 2013).

Angler heterogeneity stems from diverse motivations for engaging in and gaining satisfaction from recreational fishing (e.g. Fedler and Ditton, 1994; Massey et al., 2006; Oh and Ditton, 2006). Motivations (e.g. ex ante anticipations of expected outcomes) that stimulate anglers to engage in recreational fishing are notably diverse, including attaining harvest for consumption or sale, social interactions, challenge, time in nature, and trophy opportunities (e.g. Beardmore et al., 2011, 2015; Arlinghaus et al., 2016). Diverse angler motivations relate to the multiple functions by which anglers achieve satisfaction from fishing—i.e. the *ex post* psychological state associated with achieving expectations (Holland and Ditton, 1992; Arlinghaus, 2006; Beardmore et al., 2015). The relative importance of the variety of catch and non-catch motivations and determinants of satisfaction can vary among anglers (Holland and Ditton, 1992; Johnston et al., 2010). The prominence of certain fishing aspects for overall satisfaction are often used to group anglers into "angler types," such as "trophy oriented" and "catch rate oriented" (Johnston et al., 2010; Beardmore et al., 2011; Carruthers et al., 2018). Critically, the existence of multiple angler types implies multiple and potentially competing objectives for managing angler satisfaction, since management actions that most benefit one angler type may have little positive or even a negative effect on the satisfaction derived by another (Aas et al., 2000; Johnston et al., 2010; Ihde et al., 2011). For example, length-based harvest restrictions may promote larger catch size and the satisfaction of trophy-oriented anglers, but the same actions may produce suboptimal outcomes for harvest-oriented anglers (Gwinn et al., 2013). Such scenarios would produce tradeoffs, where improvement in the satisfaction achieved by one angler type in a single water body and temporal period could have the opportunity cost of reduced satisfaction for another type (Johnston et al., 2010; Garcia-Asorey et al., 2011). Thus it is extremely difficult and unlikely to simultaneously satisfy diverse angler types who fish for different reasons, with different expectation and exhibit different behaviors (Johnston et al., 2010).

A related challenge is that heterogeneous angler types will likely behave and impact fisheries in particular patterns (Ward et al., 2013b) that may deplete fish populations. For example, a trophy-oriented angler type targeting larger fish is apt to select particular angling locations, gear, techniques, and harvesting choices (e.g. Arterburn et al., 2002; Hutt and Bettoli, 2007). Such behaviors affect selective fishing mortality, which in turn structures the fish population and thereby provides a feedback to the catch-related aspects of the fishery (Ward et al., 2013a, Hansen et al., 2015b, van Poorten et al., 2016). This means heterogeneous angler behavior can shape the fishing opportunities available to all anglers and may exacerbate tradeoffs among angler types. But it also implies that as the fishery becomes unattractive to one angler type due to declining catch rates, another type may find the fishery increasingly attractive due to, for example, increasing mean size (van Poorten et al., 2016). This process of effort switching between angler types is referred to as "effort sorting" and may act to keep fishing mortality rate high even as fish abundance precipitously declines (Walters and Martell, 2004; Ward et al., 2013a, van Poorten et al., 2016); one of many mechanisms leading to hyperstability (Hilborn and Walters, 1992). Although the concept of angler diversity in motivations and attributes has been well-studied in the human dimensions literature (Bryan, 1977; Chipman and Helfrich, 1988; Fedler and Ditton, 1994; Arlinghaus, 2006; Beardmore et al., 2011), it has been relatively underappreciated among fisheries biologists and managers (Fulton et al., 2011; Hunt et al., 2013b, Ward et al., 2016) and is one potential mechanism for the "invisible collapse" of many recreational fisheries (Post et al., 2002; Post, 2013), which obviously is a threat when managing to conserve fish populations. As such, the mere existence of angler heterogeneity creates the potential for a significant conservation risk for fisheries landscapes (Hunt et al., 2011; van Poorten et al., 2016).

Addressing potentially competing objectives among angler types while preventing overharvest presents a formidable management challenge (Radomski et al., 2001; Hunt et al., 2011), which until recently has been the subject of comparatively few studies assessing alternative management approaches (Johnston et al., 2010, 2013, 2015; Gwinn et al., 2013). These studies demonstrate how it is necessary to consider angler heterogeneity to appropriately select regulation options, but generally do not offer a solution to the tradeoff among angler types. This is understandable because some tradeoffs may not permit easy compromises—i.e. there may be no single regulation that simultaneously maximizes satisfaction of trophy and catch-rate oriented angler types (Knoche and Lupi, 2016). This was recognized by Johnston et al. (2010), who stated "Managers are likely to encounter difficulties in jointly satisfying the interests of the entire angling public." While this is true for any single fishery (i.e. discrete water body), management agencies regulating multiple discrete waters or fishing sites throughout a region often have the option of selecting different regulations for these waters (Cowx, 2002; Parkinson et al., 2004; Post and Parkinson, 2012). Waterbody-specific regulations can and sometimes are implemented to ensure conservation of differently productive and harvested fish populations and/or to provide different types of fishing opportunities (e.g. Shetter and Alexander, 1966; Schill, 1996; Margenau and Petchenik, 2004). While special, waterbody-specific regulations are not rare, research assessing their efficacy is. In one of the few studies considering this issue, Carpenter and Brock (2004) suggested that diversified policies for overall lake management can offer broad advantages over "One-Size-Fits-All" (OSFA) strategies, though the study focused on a broad suite of ecosystem services beyond fishing, and did not explicitly consider many of the socioecological and behavioral feedbacks that are now understood to operate in recreational fisheries (Ward et al., 2016; Arlinghaus et al., 2017). Furthermore, implementing waterbody specific regulations also has challenges (Radomski et al., 2001). Numerous and complex different regulations may frustrate anglers or law enforcement agents, and establishing science-based waterbody-specific regulations can require overwhelming monitoring or research (Lester et al., 2003). What does not exist are studies assessing how diversified angling regulations should be designed to be practically applied to landscapes in a way that specifically satisfies heterogeneous anglers while also sustaining fish populations.

This work seeks to evaluate the expected outcomes of a spatially diversified approach to recreational fisheries management using an integrated bioeconomic landscape model. This approach, which involves effectively offering a buffet of regulation options to meet the diverse motivations of a heterogeneous angling community, is wholly different from previously explored objectives of identifying the best single action to be applied to heterogeneous fisheries (Johnston et al., 2010; Fenichel and Abbott, 2014). The model is used to assess the efficacy of buffet management strategy of setting management regulations for achieving desired outcomes at a regional level. The potential gain in recreational fisheries objectives is evaluated over other management approaches as heterogeneity of fishing opportunities and anglers increases. An additional zoned-approach with a small subset of regulation options (a reduced buffet of options) is tested to see if this might be an appropriate compromise between one-size-fits-all and lake-by-lake management.

Model overview

A bioeconomic landscape simulation model was used to test for the effects of different angling regulation strategies on each independent fish population in a landscape of fisheries (e.g. lakes) and in turn, the aggregate value of the fishing experience. To evaluate and compare the aggregate value achieved across all fisheries and angler types a landscape of fisheries (51 total fish populations) with a variety of unfished density and size structure attributes is simulated. This creates a variety of unique fisheries, which will each change with fishing pressure due to density dependent recruitment compensation and growth. The landscape of fisheries was recreationally fished by a population of anglers equally composed of four types, each uniquely defined by their interest in catch rates, harvest opportunities and size of fish captured, as well as their dissatisfaction in crowding and travel distance to a fishing site (Figure 1). Additionally, each angler type had a different impact on the fishery due to different efficiency (catchability), size-selectivity and discard mortality rate. The model was used to show the implications of ignoring heterogeneity in lake biology across a landscape and heterogeneity in angler preferences and attributes across the population, and go on to illustrate how a diversified buffet approach can better satisfy diverse anglers without impinging on fish population sustainability. The model further demonstrates that similar outcomes can be attained with a limited suite of regulations applied across a landscape to still provide a range of fishing experiences.

Model formulation

The landscape of fish populations (e.g. a lake region) was composed of lakes each containing the same single species of targeted fish. Each fish population (l) had a unique productivity based on unfished recruitment ($R_{0,l}$) and size structure based on unfished asymptotic length ($\bar{L}_{\infty,l}$). Fish populations were distributed among three distance classes from the main angler population center: 50, 150, and 400 km. Unfished equilibrium densities for each population were calculated using life history incidence functions (Botsford, 1981; Walters and Martell, 2004; Table 1). These equilibrium states were used as the starting points for the dynamic model. Parameters used to characterize the state of the model are shown in Table 2.

The model first simulated an unfished state for each lake based on a population-specific unfished recruit density and asymptotic length (Table 1). These

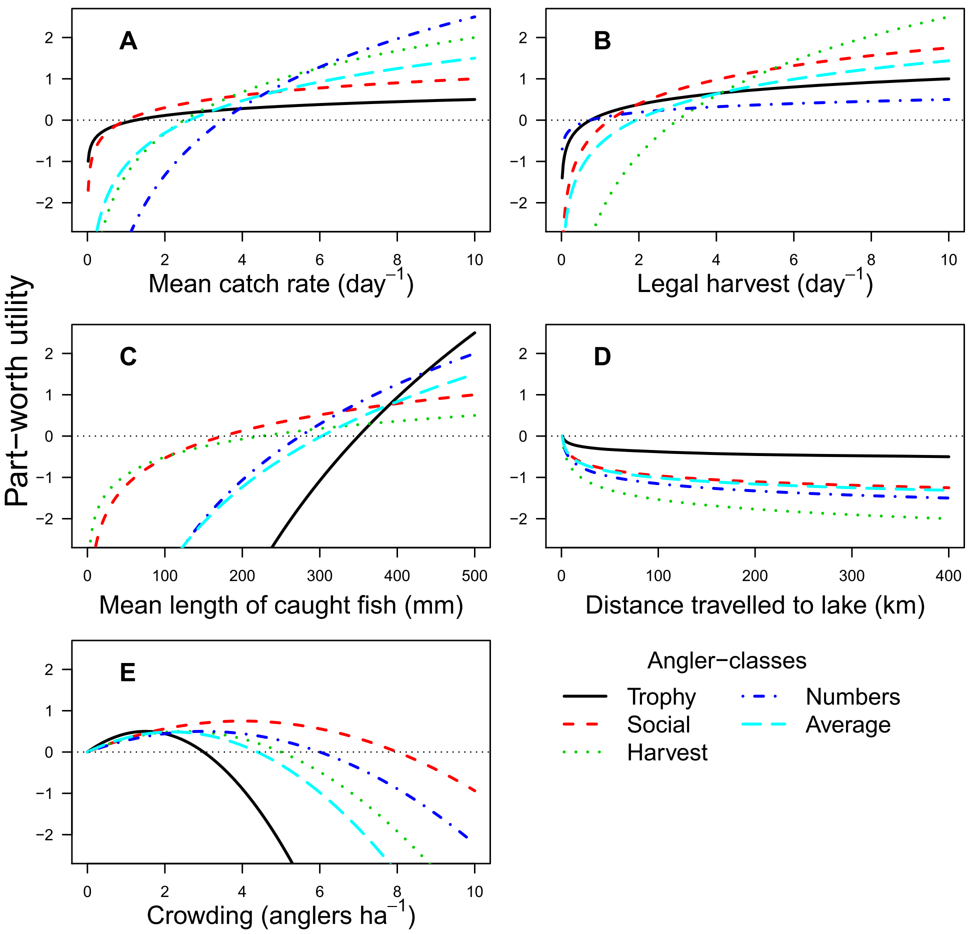

Figure 1. Part-worth utility functions describing the preferences of trophy, harvest, social, and catch angler types to daily legal harvest, daily catch, and mean length of captured fish.

two states (productivity and growth rate) were negatively correlated across populations (T2.2-T2.6). Asymptotic length was used to estimate length- and weight-at-age (T2.7, T2.8) and weight-at-maturity (T2.9). Weight-at-age was then used to estimate age-specific fecundity (T2.10). Survival of recruited fish was assumed constant (T2.11) Based on these variables, it is possible to estimate unfished equilibrium states for eggs-per-recruit (T2.12), egg density (T2.13), numbers-at-age (T2.14) and effective density (calculated as the sum of squared lengths; T2.17; Post et al., 1999; Walters and Post, 1993) for each population. Using a common recruitment compensation ratio (κ) and the population-specific equilibrium eggs per recruit and egg density, it was then possible to calculate parameters for Beverton-Holt recruitment functions for each population (T2.18-T2.19; Walters and Martell, 2004). Finally, parameters for a density-dependent growth function were calculated using lake-specific equilibrium effective density and asymptotic length (T2.20-T2.21; van Poorten and Walters, 2016).

The angling population was made up of four angler types whose total annual fishing effort and the distribution of effort among lakes is based on expected utility gained from fishing each lake. These angler types are designed to be consistent with the theory of recreational specialization (Bryan, 1977), ranging from the casually involved to the specialist angler. As specialization level increases, skills (e.g. catchability, survival upon release) improve, size is of greater importance for targeting and motivation, and harvest is of less importance (influencing release behavior and motivation; Bryan, 1977). Each angler type was named based on the primary motives for fishing: trophy anglers (fishing for large fish); harvest anglers (fishing for the opportunity to harvest many fish per trip); social anglers (fishing with others; not driven by any particular catch-related aspect); and catch anglers (fishing to maximize catch per unit effort, but not necessarily interested in harvest). Angler types had a unique set of part-worth utility functions for catch rates, harvest rates, fish length, travel distance, and crowding (Table 3; Figure 1). All part-worth utilities

Table 1. Initial states of size structure and abundance in each of the fish populations in the recreational fishing model.

Parameters		
T1.1	$\Theta = \left\{\mu_{R_0}, \sigma_{R_0}, \mu_{L\infty}, K, M, \kappa, p_m, w_{egg}, p_{fem}, \beta_{1,c}, \beta_{2,c}\right\}$	
Lake-specific variables		
T1.2	$R_{0,l} = N(\mu_{R_0}, \sigma_{R_0})$	Unfished recruitment
T1.3	$b_{L_\infty} = \frac{-\mu_{L\infty}}{2(\max(R_{0,l}) - \min(R_{0,l}))}$	Slope of mean asymptotic length vs. unfished recruitment
T1.4	$a_{L_\infty} = 0.75\mu_{L\infty} - b_{L_\infty}\max(R_{0,l})$	Intercept of mean asymptotic length vs. unfished recruitment
T1.5	$\hat{L}_{\infty,l} = a_{L_\infty} - b_{L_\infty} R_{0,l}$	Predicted asymptotic length
T1.6	$L_{\infty,l} = N\left(\hat{L}_{\infty,l}, 0.1 \cdot \hat{L}_{\infty,l}\right)$	Asymptotic length
Life history schedules		
T1.7	$\bar{L}_{l,a} = L_{\infty,l}(1 - e^{-K(a)})$	Initial length-at-age
T1.8	$\bar{w}_{l,a} = 1e^{-5}\left(\bar{L}_{l,a}\right)^3$	Initial weight-at-age
T1.9	$\bar{w}_{(m)l} = 1e^{-5}(L_{\infty,l}p_m)^3$	Initial weight-at-50%-maturity
T1.10	$\bar{f}_{l,a} = \left[max\left(0, \bar{w}_{l,a} - \bar{w}_{(m)l,a}\right)/w_{egg}\right]p_{fem}$	Initial fecundity-at-age
T1.11	$\bar{lx}_{l,a} = \begin{cases} 1 & a = 1 \\ e^{-M(a-1)} & a > 1 \end{cases}$	Initial survivorship
Unfished equilibrium states		
T1.12	$\varphi_{(0)l} = \sum_{a=1}^{A} \bar{f}_{l,a} lx_{l,a}$	Unfished eggs per recruit
T1.13	$\bar{Egg}_l = R_{0,l}\varphi_l$	Unfished egg density
T1.14	$\bar{N}_{l,a} = R_{0,l}\bar{lx}_{l,a}$	Unfished density
T1.15	$\bar{sl}_{l,a,c} = \left(1 + e^{-\left(\bar{L}_{l,a} - \beta_{2,c}\right)/\beta_{1,c}}\right)^{-1}$	Initial fishery selectivity to angler type-*c*
T1.16	$\varphi_{(V)l,c} = \sum_{a=1}^{A}\left(\bar{N}_{l,a}\bar{sl}_{l,a,c}\right)$	Initial vulnerable density to angler type-*c*
T1.17	$\bar{L}_{(2)l} = \sum_{a=1}^{A}\left(\bar{N}_{l,a}\bar{L}_{l,a}{}^2\right)$	Initial effective density
Beverton–Holt recruitment parameters		
T1.18	$\alpha_{(1)l} = \frac{\kappa}{\varphi_{(0)l}}$	Maximum recruits per spawner
T1.19	$\alpha_{(2)l} = \frac{\kappa - 1}{\bar{Egg}_l}$	Recruitment density-dependence parameter
Density-dependent growth parameters		
T1.20	$\gamma_{(1),l} = 1.25 \cdot \bar{L}_{\infty,l}$	Maximum asymptotic length
T1.21	$\gamma_{(2),l} = \frac{\left(\frac{\gamma_{(1),l}}{L_{\infty,l}} - 1\right)}{\bar{L}_{(2)l}}$	Growth density-dependence parameter

were non-linear, described using either log-linear or quadratic functions. Shapes and parameters describing utilities and attributes were loosely based on empirical and estimated observations of different angler types in the literature (Ward et al., 2013b, Beardmore et al., 2015; Hunt et al., 2019). Total utility is based on the sum all part-worth utilities (T4.8). Each angler type also had different skills and attributes with respect to fishing. Specifically, catchability, size selectivity, hooking mortality, and probability of retaining a legal sized fish were unique to each angler type (Table 3).

Parameters for the four angler types reflected differential skill, motivation and impacts on fish populations (Table 3). Trophy-oriented anglers were (i) most likely to participate in fishing; (ii) least interested in catch rates; (iii) least interested in harvest; (iv) most interested in large fish size (with part-worth utility increasing nearly linearly with mean fish length); (v) least impacted by travel distance; and (vi) least tolerant of crowding (Figure 1). Trophy anglers also had the highest catchability of all angler types, low release mortality rates, intermediate voluntary release rates and had a selectivity function that targeted large fish (Table 3). Social-oriented anglers were (i) least likely to participate in fishing; (ii) intermediate in their interest in high catch rates but still tolerant of intermediate catch rates; (iii) high in their interest in any opportunity to harvest; (iv) least interested in fish size, but were more tolerant of small sizes than other angler types; (v) intolerant of travel distance; and (vi) most tolerant of crowding (Figure 1). Note that social anglers were described with a greater maximum part-worth utility for crowding, indicating they were less averse to crowding. Social anglers also had the lowest catchability, highest release mortality rate, low voluntary release rates, and had a selectivity function that was least size-selective (Table 3). Harvest-oriented anglers were (i) intermediate in their likelihood to participate in fishing; (ii) highly interested in catch rates and (iii) harvest rates; (iv) generally disinterested in size; (v) most intolerant of travel distance; and (vi) intermediate in their tolerance for crowding (Figure 1). Harvest anglers also have an intermediate catchability, low release mortality rate, harvest every legal fish they catch and have a selectivity function with relatively low size-selectivity (Table 3). Numbers-oriented anglers were (i) most likely to participate in fishing (the same as trophy anglers); (ii) most interested in high catch rates; (iii) relatively uninterested in harvest; (iv) interested in fish size, but less

Table 2. Model indices, variables, and parameter values used in the model with associated descriptions and units.

Symbol	Value	Description	Units
Indices			
l	$\{1, 2, \ldots, n_l\}$	Lake ($L = 51$)	lake
a	$\{1, 2, \ldots, A\}$	Age ($A = 10$)	year
c	$\{1, 2, \ldots, n_c\}$	Angler type ($n_c = 4$)	
Model parameters			
μ_{R_0}	750	Mean unfished recruitment across lakes	recruits
σ_{R_0}	150	Standard deviation in unfished recruitment across lakes	recruits
μ_{L_∞}	400	Mean asymptotic length across lakes	mm
K	0.3	Metabolic rate parameter of von Bertalanffy function	
M	0.3	Instantaneous natural mortality	yr^{-1}
κ	6.84[a]	Compensation ratio in recruitment	
p_m	0.6	Length at maturity (as a proportion of $L_{\infty,l}$)	
w_{egg}	0.1	Weight of a single egg	G
p_{fem}	0.5	Sex ratio	
$\beta_{1,c}$	see Table 3	Length at 50% selectivity for angler type-*c*	mm
$\beta_{2,c}$	see Table 3	Slope of selectivity at $\beta_{1,c}$ for angler type-*c* (logit-scaled)	mm^{-1}
$\alpha_{(x)c}$	see Table 3	Log-linear intercept of part-worth utility functions for component *x* for angler type-*c*	
$\beta_{(x)c}$	see Table 3	log-linear slope of part-worth utility functions for component *x* for angler type-*c*	units of *x*
$U_{(o)c}$	see Table 3	Utility gained from angler type-*c* choosing to fish	
U_n	2	Conditional indirect utility gained by an angler from choosing not to fish on the landscape	
d_l	{50, 150, 400}	Driving distances from population center to lake-*l*	Km
δ	0.8	Persistence of fishing effort	
$p_{(c)}$	{0.25,0.25,0.25,0.25}	Proportion of all anglers belonging to each angler type	
$E_{max,c}$	$500 \cdot p_{(c)} \sum AR_l$	Maximum fishing effort available for angler type-*c*	angler-days
cv	0.07	Variation in length at age	
q_c	see Table 3	Catchability for angler type-*c*	ha/angler-days
d	0.9	Degree of density dependence in catchability	
AR_l	U(10,5000)	Surface area of lake-*l*	Ha
$\bar{p}_{(r)c}$	see Table 3	Probability of retaining legal sized fish for angler type-*c*	
M_d	see Table 3	Hooking mortality for angler angler type-*c*	$fish^{-1}$
Management Controls			
BL_l	{CR,1,2,4, none}	Bag limit	fish/d
ML_l	{none,350,450,550}	Minimum length limit	Mm

[a]Based on mean compensation ratio for freshwater fish in Myers et al. 1999.

motivated by extreme size than trophy anglers; (v) fairly tolerant of travel distance and (vi) crowding (Figure 1). Numbers anglers also had high catchability, low release mortality, highest voluntary release rates and a selectivity function that targeted large fish more than social or harvest anglers (Table 3). In scenarios assuming no heterogeneity among anglers, the mean utility function and fishery impact across all angler types is assumed.

Numerical approximation of equilibrium state

To calculate fishing effort on each site, an initial estimate of total utility (T4.8) is used to distribute effort among lakes based on a multinomial logit utility function (T4.9). Equation T4.9 calculates the probability of fishing any given lake relative to the total utility for that angler type plus a probability of not fishing or fishing elsewhere (U_n). The probability of not fishing in the modeled landscape was set high ($U_n = 2.0$), reflecting an increasing understanding that anglers choose to fish by selecting from a suite of alternative leisure opportunities (e.g. fishing, golfing, camping). This importantly assumes that there is positive utility by choosing not to fish (Ditton and Sutton, 2004; Sutton, 2007). Total fishing effort in each model iteration is distributed among lakes by multiplying the probabilistic distribution of each angler type by the total number of anglers in each angler type (T4.10).

Each iteration begins with calculating density dependent growth as a result of intraspecific competition in the lake (T4.15-T4.16; van Poorten and Walters, 2016). Length at age is then used to calculate selectivity to capture (T4.13) and legal harvest (T4.14) based on the regulated minimum length limit. Expected capture of all fish (T4.18) and legal sized fish (T4.19) based on minimum length limits is calculated using the Baranov equation (Ricker, 1975) distributing catch across angler types based on density dependent catchability for each angler type (T4.17) and natural mortality experienced by fish. The resulting catch per unit effort (T4.20) is used to calculate the expected proportion of total catch that can be harvested within the bag limit assuming realized catch rates among anglers are Poisson distributed (T4.21; Porch and Fox, 1990). Because bag limits result in fish being returned to the population to be caught again, the bag limit sub-model has no closed-form solution. This is accounted for by breaking the fishing season into four time-steps where fish density, total fishing

Table 3. Angler types, their utility for various aspects of the fishery, which drives behavior, and their specific attributes.

Variable	Symbol	Parameter values describing angler types Trophy ($c=1$)	Social ($c=2$)	Harvest ($c=3$)	Catch ($c=4$)
Preference for attributes of the fishing experience[a]					
PWU gained from angler type-*c* choosing to fish	$U_{(0)c}$	0.25	−0.15	0.15	0.25
PWU of daily catch rate for angler type-*c*	$U_{(C)l,c}$	$\alpha_{(C)l,c}=-0.08$ $\beta_{(C)l,c}=0.83$	$\alpha_{(C)l,c}=0.00$ $\beta_{(C)l,c}=1.5$	$\alpha_{(C)l,c}=-1.65$ $\beta_{(C)l,c}=4.15$	$\alpha_{(C)l,c}=-2.98$ $\beta_{(C)l,c}=5.48$
PWU of daily harvest rate for angler type-*c*	$U_{(H)l,c}$	$\alpha_{(H)l,c}=0.11$ $\beta_{(H)l,c}=0.89$	$\alpha_{(H)l,c}=-0.19$ $\beta_{(H)l,c}=1.94$	$\alpha_{(H)l,c}=-1.65$ $\beta_{(H)l,c}=4.15$	$\alpha_{(H)l,c}=0.06$ $\beta_{(H)l,c}=0.44$
PWU of mean length of captured fish for angler type-*c*	$U_{(S)l,c}$	$\alpha_{(S)l,c}=-41.06$ $\beta_{(S)l,c}=16.14$	$\alpha_{(S)l,c}=-6.15$ $\beta_{(S)l,c}=2.74$	$\alpha_{(S)l,c}=-11.74$ $\beta_{(S)l,c}=4.81$	$\alpha_{(S)l,c}=-13.57$ $\beta_{(S)l,c}=5.77$
PWU of distance for angler type-*c*	$U_{(D)l,c}$	$\beta_{(D)l,c}=-0.19$	$\beta_{(D)l,c}=-0.48$	$\beta_{(D)l,c}=-0.77$	$\beta_{(D)l,c}=-0.58$
PWU of crowding fish for angler type-*c*	$U_{(Cr)l,c}$	$\alpha_{(Cr)l,c}=0.67$ $\beta_{(Cr)l,c}=0.22$	$\alpha_{(Cr)l,c}=0.75$ $\beta_{(Cr)l,c}=0.09$	$\alpha_{(Cr)l,c}=0.40$ $\beta_{(Cr)l,c}=0.08$	$\alpha_{(Cr)l,c}=0.33$ $\beta_{(Cr)l,c}=0.06$
Fishing Attributes					
Skill level for angler type-*c*	q_c	0.09	0.03	0.06	0.08
Selectivity for angler type-*c*	$sl_{l,a,c}$	$\beta_{1,c}=10$ $\beta_{2,c}=350$	$\beta_{1,c}=25$ $\beta_{2,c}=250$	$\beta_{1,c}=20$ $\beta_{2,c}=250$	$\beta_{1,c}=20$ $\beta_{2,c}=300$
Probability of releasing legal fish for angler type-*c*	$\bar{p}_{(r)c}$	0.60	0.25	0.00	0.85
Hooking mortality for angler type-*c*	M_d	0.05	0.1	0.05	0.05

[a] See Table 4 for functional forms.

effort and the distribution of effort among lakes are iteratively calculated to account for losses due to release mortality. Using sub-year time-steps allows an accurate approximation of how bag and minimum length limits can affect overall harvest rates. Calculations within each iteration are not shown in Table 4 for clarity of presentation. Finally, harvest, release and natural mortality are removed from the population of fish in each lake based on the total effort from each angler type. Recruitment is calculated at the end of each iteration and each age-class is advanced one.

Predicted utility at the end of each iteration is calculated using T4.8, which updates the predicted distribution of angler types among lakes based on T4.9. Final probability distribution of angler types among lakes is calculated by updating the previous prediction with a degree of relaxation (δ; T4.10). The relaxation parameter prevents undue oscillation of effort among lakes to aid in convergence (Carruthers et al., 2018). Each model simulation was evaluated after the system reached equilibrium.

Management objective

The performance of management strategies was evaluated using a penalized total value, which maximizes recreational benefit until conservation risk is compromised. The conservation metric used was spawner potential ratio (SPR; Walters and Martell, 2004), which is the ratio of egg production per recruit under exploitation relative to the unexploited state. An SPR < 0.3 (Walters and Martell, 2004) is generally considered an early indication of recruitment overfishing (although (Clark, 2002) suggests 0.4 for sensitive and/or long-lived species). A penalty was calculated for each population l, calculated as

$$P_l = \frac{(min(SPR_l, 0.3) - 0.3)^2}{0.3}, \tag{1}$$

which increases from zero each time the population exceeds the conservation threshold of SPR $= 0.3$. The penalty for each lake was applied to the utility of each angler type for that lake. Penalized value for an angler type is simply the sum of penalized utility across lakes:

$$V_{(p)t,c} = \sum_{l=1}^{L} \left(U_{l,t,c}(1 - P_l)\right). \tag{2}$$

This formulation means landscape value increases with the sum of lake-specific utilities across the landscape, but utility for any lake will decline to zero as

Table 4. Dynamics of the recreational fishing bioeconomic model.

Parameters		
T4.1	$\omega = \left\{ \begin{array}{c} \alpha_{(C)c}, \alpha_{(H)c}, \alpha_{(S)c}, \alpha_{(D)c}, \alpha_{(Cr)c}, \beta_{(C)c}, \beta_{(H)c}, \beta_{(S)c}, \beta_{(D)c}, \beta_{(Cr)c}, U_{(o)c}, U_n, d_l, \delta, E_{max,c} \\ \beta_{1,c}, \beta_{2,c}, cv, q_c, d, K, \ M, AR_l, \bar{p}_{(r)c}, M_d, p_{fem}, w_{egg} \end{array} \right\}$	
Management controls		
T4.2	$\{\mathrm{BL}_l, \mathrm{ML}_l\}$	
Angler utility		
T4.3	$U_{(C)l,t,c} = \alpha_{(C)c} + \beta_{(C)c} log_{10}\left(\frac{C_{l,c}}{E_{l,c}}\right)$	Part-worth utility for catch rates for angler type-*c* on each lake *l* in year *t*
T4.4	$U_{(H)l,t,c} = \alpha_{(H)c} + \beta_{(H)c} log_{10}\left(\frac{H_{l,c}}{E_{l,c}}\right)$	Part worth utility for harvest rates for angler type-*c* on each lake *l* in year *t*
T4.5	$U_{(S)l,t,c} = \alpha_{(S)c} + \beta_{(S)c} log_{10}\left(\frac{sl_{l,a}N_{l,a}L_{l,a}}{\sum_a sl_{l,t}N_{l,a}}\right)$	Part worth utility for mean length of fish captured for angler type-*c* on each lake *l* in year *t*
T4.6	$U_{(D)l,c} = \beta_{(D)c} log_{10}(d_l)$	Part worth utility for distance for angler type-*c* on each lake *l*
T4.7	$U_{(Cr)l,t,c} = \alpha_{(Cr)c} + \beta_{(Cr)c}\left(\frac{\sum_c E_{(tot)c}}{365}\right)^2$	Part worth utility for crowding for angler type-*c* on each lake *l* in year *t*
T4.8	$U_{l,t,c} = U_{(0)c} + U_{(C)l,c} + U_{(H)l,c} + U_{(S)l,c} + U_{(D)l,c} + U_{(Cr)l,c}$	Conditional indirect utility of angler type-*c* for fishing in year *t*.
Angler effort dynamics		
T4.9	$\hat{p}_{l,c} = \frac{\exp(U_{l,c})}{\left(\exp(U_n) + \sum_{l=1}^{L} \exp(U_{l,c})\right)}$	Probability of angler type-*c* choosing to fish at lake *l*
T4.10	$p_{l,c,i} = \hat{p}_{l,c}(1-\delta) + p_{l,c,i-1}\delta$	Realized probability of angler type-*c* choosing to fish at lake *l*
T4.11	$E_{l,c} = E_{max,c} p_{l,c,i}$	Effort on each lake by angler type-*c*
Fishing catchability and selectivity		
T4.12	$sl_{l,a,c} = \left(1 + e^{-\left(L_{l,a} - \beta_{2,c}\right)/\beta_{1,c}}\right)^{-1}$	Size-based selectivity to capture
T4.13	$sl_{(H)l,a} = \left(1 + e^{-1.7(L_{l,a} - \mathrm{ML}_l)/(L_{\infty,l} cv)}\right)^{-1}$	Size-based selectivity to harvest based on minimum length limit (ML_l)
T4.14	$q_{l,c} = q_c\left(\frac{\sum_{a=1}^{A} N_{l,a} sl_a}{\varphi_{(V)l,c}}\right)^{d-1}$	Density-dependent catchability
Fish population dynamics		
T4.15	$L_{\infty,l} = \frac{\gamma_{(1)l}}{1 + \gamma_{(2)l} L_{(2)l}}$	Asymptotic length
T4.16	$L_{l,a} = \begin{cases} L_{\infty,l}(1 - e^{-K}) & a = 1 \\ L_{\infty,l} + (L_{l,a-1} - L_{\infty,l})e^{-K} & a > 1 \end{cases}$	Length-at-age
T4.17	$Z_{l,a} = M + \sum_c q_{l,c} E_{l,c}$	Total instantaneous fishing mortality rate
T4.18	$C_{l,c,a} = \frac{N_{l,a} sl_{l,a} q_{l,c} E_{l,c} AR_l}{Z_{l,a}}\left(1 - e^{-Z_{l,a}}\right)$	Total catch
T4.19	$C_{(Leg)l,c,a} = C_{l,c,a} sl_{(H)l,a}$	Total legal catch
T4.20	$CPUE_{(Leg)l,c,a} = \frac{C_{(Leg)l,c,a}}{E_{l,c}}$	Legal catch per effort
T4.21	$p_{(ret)l,c,a} = \frac{\sum_{x=1}^{100}\left[\min(x, \mathrm{BL}_l)\left(\frac{CPUE_{l,c,a}{}^{x} e^{-CPUE_{l,c,a}}}{x!}\right)\right]}{CPUE_{(Leg)l,c,a}}\bar{p}_{(r)c}$	Exploitation rate due to retention given bag limit
T4.22	$H_{l,c,a} = p_{(ret)l,c,a} C_{(Leg)l,c,a}$	Total legal harvest
T4.23	$HM_{l,c,a} = H_{l,c,a} + M_d\left[\left(1 - p_{(ret)l,c,a}\right)C_{(Leg)l,c,a} + \left(1 - sl_{(H)l,a}\right)C_{l,c,a}\right]$	Total harvest and release mortality
T4.24	$f_{l,t} = max\left(0, \bar{w}_{l,a} - \bar{w}_{(m)l,a}\right)/w_{egg} p_{fem}$	Size-based fecundity
T4.25	$Egg_l = \sum_{a=1}^{A}(f_{l,a} N_{l,a})$	Egg density
T4.26	$N_{l,a} = \begin{cases} \dfrac{Egg_l \alpha_{(1)l}}{1 + Egg_l \alpha_{(2)l}} & a = 1 \\ \left(N_{l,a-1} - \dfrac{\sum_c HM_{l,c,a}}{AR_l}\right)e^{-M} & a > 1 \end{cases}$	Fish density

SPR for that population declines below 0.3. Multiplying the utility and conservation objectives effectively scales them to produce a single objective value for each angler type. Total landscape value of the fishery in year-t is given as the geometric mean of penalized values across angler types multiplied by the total fishing effort that year

$$V_{(p)t} = \prod_{c}^{n_c}\left(\sqrt{V_{(p)t,c} N_c}\right) \cdot \sum_{l=1}^{L}\sum_{c}^{n_c} E_{l,t,c}. \tag{3}$$

Taking the geometric mean of value across angler types ensures realized values of each types are traded off, promoting equity among angler types during optimization. Multiplying the geometric mean of value by total effort promotes strategies that increase angler participation.

Simulations

Fishing regulations were used as the primary control over fisheries across the landscape. Fisheries managers typically assign regulations from a few discrete choices rather than tightly linking regulations to biology (e.g. assigning a standard minimum length harvest limit rather than one relative to maximum length or size at maturity; van Poorten et al., 2013). Therefore, the regulation options considered were a combination of bag limits (0, 1, 2, 4, no limit) or minimum length harvest limits (no limit, 300 mm, 400 mm, 500 mm). These discrete options led to 17 regulation combinations (since a zero fish bag limit, or catch-and-release, does not interact with length limits) ranging from very liberal (unlimited bag limit; no minimum length) to very conservative (catch-and-release).

The landscape model was used to evaluate how different management strategies perform under a combination of scenarios representing variation in fish biology across lakes and angler heterogeneity. There were four management strategies evaluated. The first is a one-size-fits-all (OSFA) strategy, which is evaluated as the single best combination of bag and length limits to apply to all fish populations. The second is a biologically optimal strategy, which sets regulations based on the maximum length of fish in a lake. Biological regulations take advantage of the natural size-density gradient across populations to provide a variety of fishing experiences. Lakes within the top 25th percentile of unfished asymptotic lengths ($L_{\infty,l}$) were assigned a 500 mm length limit to promote large fish; lakes within the second 25th percentile of $L_{\infty,l}$ were assigned a 2-fish bag limit and 400 mm length limit to provide some harvest of larger fish; lakes within the third 25th percentile of $L_{\infty,l}$ were assigned no regulations to provide harvest opportunities in naturally high density lakes; and populations within the lower 25th percentile of $L_{\infty,l}$ were assigned catch-and-release regulations to preserve the naturally high density (and small body size) of fish. The third management strategy is a socially optimal strategy, which is evaluated as the best combination of bag and length limits if all anglers were of a single angler type. These four regulations (one for every angler type) are then applied randomly to lakes based on the proportional make-up of anglers. The final management strategy is the buffet of regulation combinations, evaluated using a simulated annealing algorithm, which allows optimization across discrete parameter combinations (such as bag and length limit options). The algorithm iteratively changes management combinations on each lake and evaluates the overall performance metric (total landscape value) at equilibrium until the best combination of regulations on each lake across the landscape is found. Regulations are optimized using the simulated annealing optimization algorithm within the rgenoud package (Mebane and Sekhon, 2011) in the R statistical programing language (R Core Development Team, 2016).

Managers are unlikely to use a wide variety of regulation combinations when choosing how to manage a fishery. Except in special circumstances, it is most likely that they favor a small subset of regulation combinations, likely those that provide a wide variety of harvest opportunities and safeguards against overfishing. This strategy also promotes regulation simplification, which is preferable to anglers (Lester et al., 2003). To reflect this, a fifth management strategy was considered, which was identical to the buffet management strategy above, but with only five extreme regulation combinations considered by the optimization algorithm. These regulation combinations ranged from catch-and-release to unregulated. As with the buffet strategy, the exact regulation applied to each lake was found using a simulated annealing optimization. This strategy is referred to as a reduced buffet management strategy.

Performance of the five management strategies was evaluated assuming three levels of social-ecological complexity, each representing a different hypothesis of variation in the system. The first level was an idealized system with all fish populations identical and all anglers of a single angler type. Fish population parameters were determined by setting all unfished recruits and asymptotic lengths to the mean value (e.g. $R_{0,l} = \mu_{R_0}$ and $L_{\infty,l} = \hat{L}_{\infty,l}$). Angler parameters were determined by setting all utility and attribute parameters to the mean value across angler types. The second level of complexity represented all anglers as a single angler type but each fish population was unique. The final level of complexity is the most realistic where there are four angler types, each with unique preferences and attributes, and a fully heterogenous fishery landscape where each fish population has a distinct size structure and abundance.

Sensitivity analyses were conducted to determine how sensitive the model is to parameter specification and how sensitive the system is to regulation choices. Model sensitivity was evaluated using elasticity, which is evaluated as the proportional change in landscape value with a ±10% change in a parameter. Elasticity was evaluated under one-size-fits-all catch-and-release regulations. Sensitivity of the system to misspecification of regulations was evaluated as the proportional change in landscape value between the optimal diversified buffet strategy and value calculated when 2–50 (in increments of 2) lakes are incorrectly assigned regulations. Random regulation misspecification for a random lake was repeated 100 times to demonstrate the range of possible changes in landscape value.

Results

The total landscape value of the recreational fishery under a single one-size-fits-all regulation was evaluated under three scenarios: (1) all fish populations are equivalent and no angler heterogeneity; (2) all fish populations are unique but no angler heterogeneity; and (3) all fish populations are unique and anglers are of four angler types. The single regulation for each of these scenarios that maximized penalized value was used as the one-size-fits-all strategy for later simulations. Under the simplest scenario, a one-fish bag limit combined with a 400 mm length limit ("one-over 400 mm regulation") provides the best landscape value (Figure 2; top row). It is largely unnecessary to protect smaller fish in this scenario using a minimum length limit because all lakes have the same size structure and anglers do not particularly target fish with large body sizes. The 500 mm length limit provided nearly the same landscape value as catch-and-release because few fish were large enough to exceed the minimum length limit. Bag limits alone or with low minimum length limits were not enough to protect against conservation concerns due to the potential to overfish some populations (Figure 2; top-right panel); the reduced value of these regulations was a reflection of conservation concerns and reduced catch rates, despite an increased opportunity for harvest and moderate increase in fish size due to density-dependent growth. When fish populations are unique but anglers are homogeneous in their multi-attribute utility functions and impacts, a one-over 400 mm regulation was once again the preferred regulation, which maintains catch rates over a wide range of fish population size structures and protects against overfishing, yet still

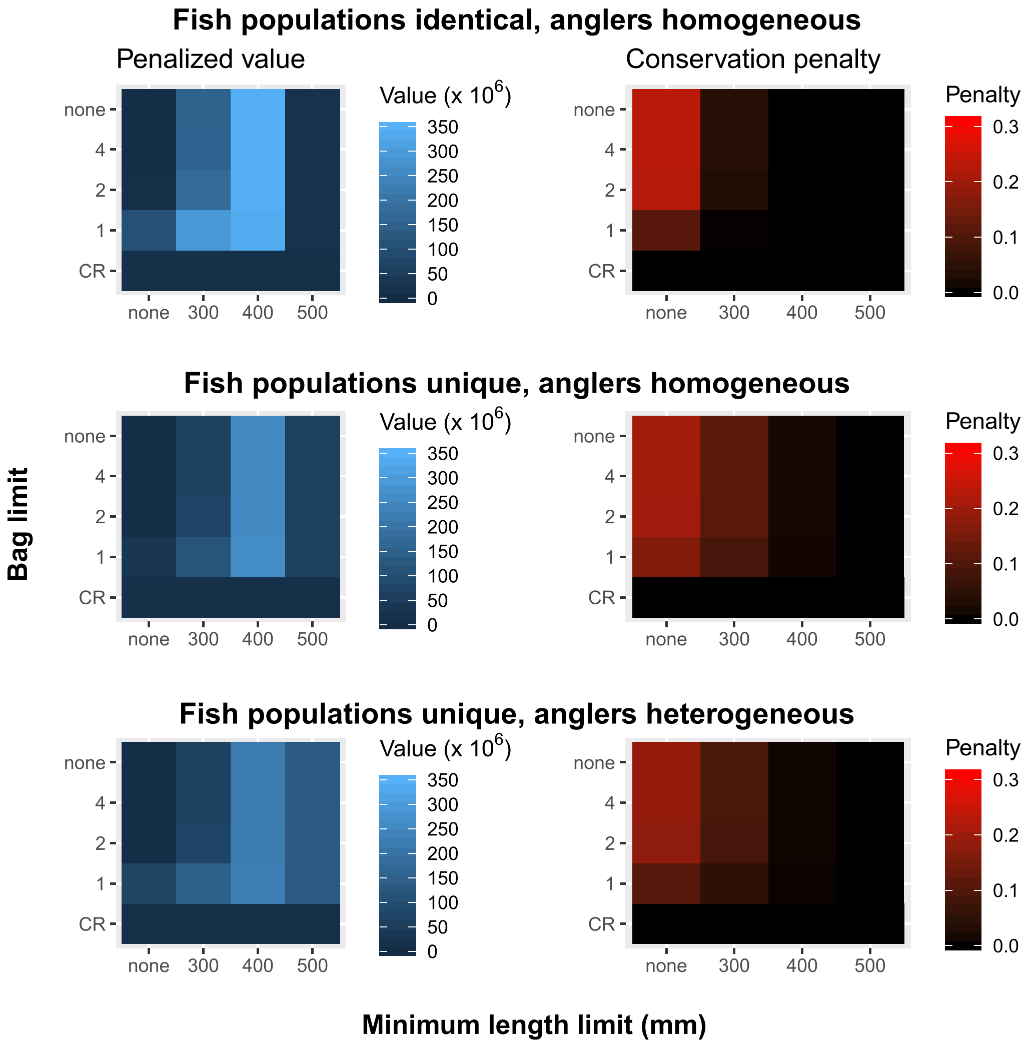

Figure 2. Penalized landscape value (left column) and conservation penalty applied to landscape value (right column) under combinations of bag limits (catch-and-release; 1, 2, or 4 daily harvest limit; no limit) and minimum length limit (no limit; 300, 400, or 500 mm minimum length limit). Panel rows refer to the complexity of the system. Top row: all fish populations are identical and all anglers are homogeneous; middle row: each fish population is unique and all anglers are homogeneous; bottom row: each fish population is unique and anglers belong to one of four homogeneous angler types.

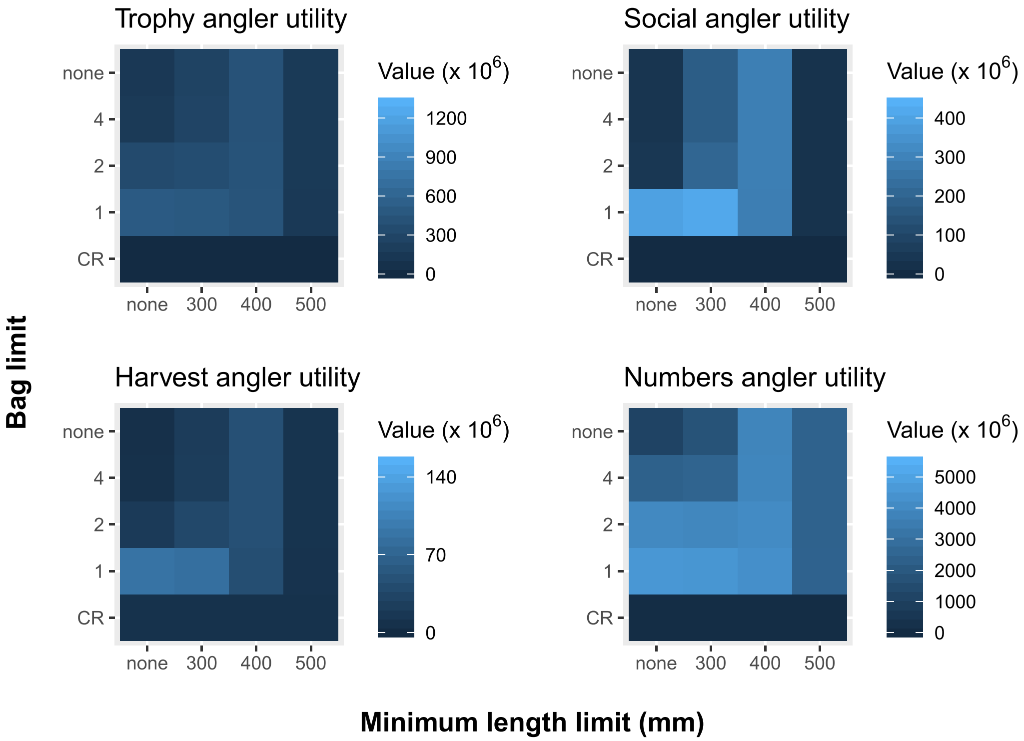

Figure 3. Penalized landscape value under combinations of bag limits (catch-and-release; 1, 2, or 4 daily harvest limit; no limit) and minimum length limit (no limit; 300, 400, or 500 mm minimum length limit). Each panel depicts a situation where all anglers are homogeneous and utility functions are that of either the trophy (top left), social (top right), harvest (bottom left), or catch (bottom right) angler type. Note scales differ among panels.

provides harvest opportunities (Figure 2; middle-left panel). Note the 500 mm minimum length limit provides much greater value in this scenario because the variation in size structure among fish populations means there are more opportunities to harvest large fish across the landscape. In this scenario anything less than a 400 mm minimum length limit can cause overfishing, resulting in a conservation penalty (Figure 2; middle-right panel). When fish populations are unique and anglers are heterogeneous the best single regulation to set on all lakes is again a one-over 400 regulation, which provides harvest opportunities for harvest-oriented anglers yet still effectively protects against overharvest (Figure 2; bottom row). Again, the 500 mm minimum length limit provides greater value still because there is now variation in utility for large fish among anglers in this scenario. Note that the exact combination of regulations that result in the maximum landscape value is entirely dependent on the parameterization used in the simulation model. Different parameter combinations may lead to changes in the relative value achieved across regulation combinations.

Four social regulations were identified by determining which single regulation would provide the greatest value if all anglers were of one of the four angler types (Figure 3). Based on the parameterization of anglers and the fishery landscape, the highest penalized landscape value was obtained with a one-fish bag limit for trophy, harvest, and numbers-oriented angler types, respectively. Social anglers prefer a one-over 300 mm regulation. The absolute landscape value achieved with these regulations varied substantially: numbers-oriented anglers had a penalized value nearly ten times that of any other angler type.

When fish populations were identical and anglers were of a single, average angler type, there was no improvement in value when providing lake-specific regulations over the one-size-fits-all (OSFA) strategy, determined to be the one-over 400 mm regulation (Figure 4; top left panel). The buffet strategy also applied the one-over 400 mm regulation to all lakes since all anglers uniformly preferred the same fishing experience. The reduced buffet strategy did not include a one-over 400 mm regulation, so optimal value was much lower; most lakes had a one-over 500 mm regulation or a one-fish bag limit. The proportion of the maximum possible effort exerted under the OSFA and buffet strategies was approximately equivalent (Figure 4; top center panel), and both resulted in similarly high spawner potential ratio (SPR) across populations and management strategies

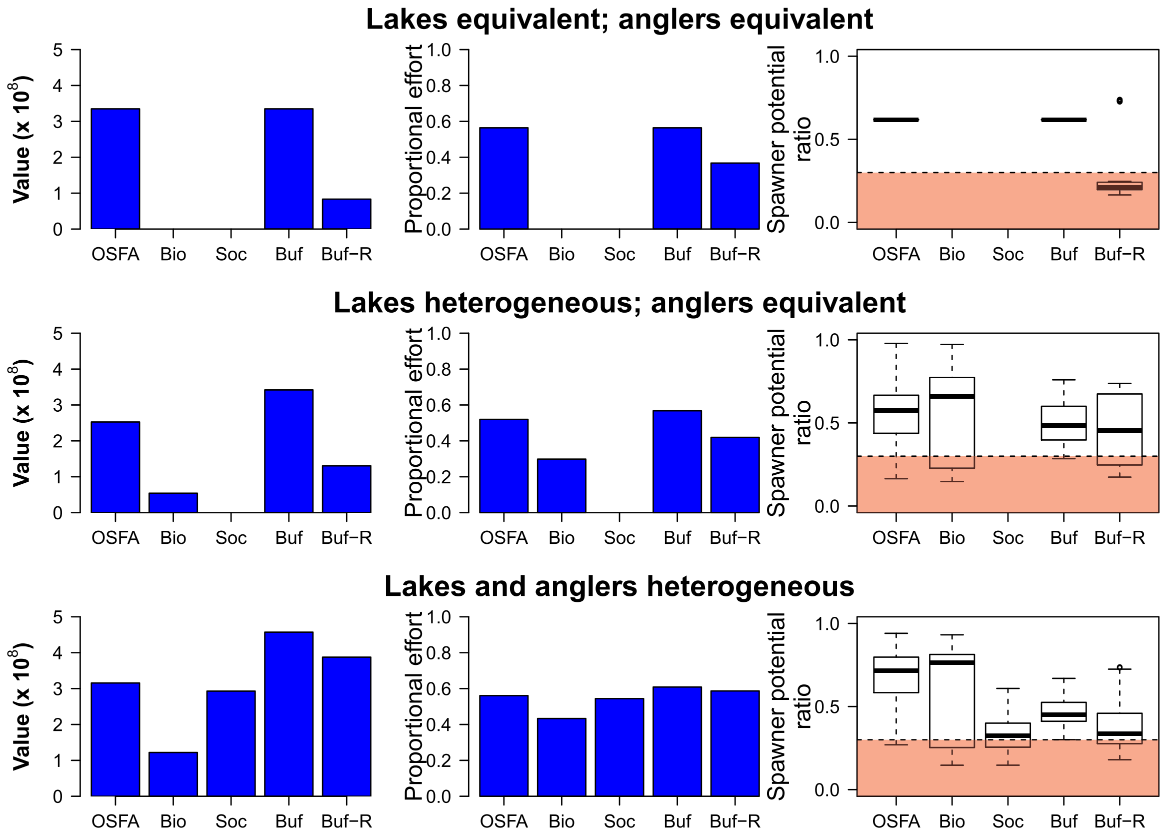

Figure 4. Landscape-level performance of five management strategies: one-size-fits-all (OSFA), biologically-based (Bio), socially-based (Soc), buffet (Buf), and reduced buffet (Buf-R) strategies. Top row of panels represents a situation where all fish populations are identical and all anglers are homogeneous; middle row represents a situation where each fish population is unique and all anglers are homogeneous; bottom row represents a situation where each fish population is unique and anglers belong to one of four homogeneous angler types. Left column shows relative penalized landscape value under each management strategy; center column shows the total proportion of possible fishing effort under each management strategy; right column shows the distribution of spawner potential ratio across lakes under each management strategy.

(Figure 4; top right panel). The reduced buffet option had lower effort and a high proportion of lakes below the conservation threshold. Biological and social strategies for setting regulations were not considered in this context because all lakes and anglers were identical. In a scenario where fish populations were each unique but anglers were homogeneous, the biological strategy had much lower value than the OSFA strategies, suggesting the choice of regulations applied to lakes in the biological strategy may not have led to high satisfaction (Figure 4; center left panel). The buffet strategy had much higher value than any other strategy. Again, because the reduced buffet strategy did not include the optimal OSFA strategy, it still had lower value than under then OSFA strategy. Proportional effort reflected patterns in value, with the buffet strategy resulting in the highest effort (Figure 4; center panel). The OSFA strategy resulted in only one lake below the conservation threshold; other strategies, particularly the biological and reduced buffet strategies, resulted in several populations below the conservation threshold (SPR < 0.3; Figure 4; center-right panel).

In the realistic scenario where fish populations were each different and the angling population was made up of four unique angler types, there was a marked difference in performance across fishery regulation strategies (Figure 4; bottom row). The buffet strategy resulted in a penalized value 45% greater than the OSFA strategy, and greater still than the biological and social strategies (Figure 4; bottom-left panel). Value achieved under the reduced buffet strategy was 22% greater than that achieved with the OSFA strategy, but less than under the buffet strategy. Proportional fishing effort was also highest under the buffet strategy, but the relative improvement over other strategies was low (Figure 4; bottom-center panel). The buffet strategies had the best overall conservation outcome, with no populations falling below the 0.3 SPR threshold (Figure 4; bottom-right panel).

The complexity of the social-ecological system where fish populations are unique and the angling population is heterogeneous means aggregate decisions by anglers on whether and where to fish are driven by the many site-specific variables offered by each fishing opportunity. Across all management strategies evaluated, the trophy angler type experienced the highest mean utility across fish populations of any angler type (Figure 5). This is largely a function of the type of landscape created and the high fishing effort, which reduced densities on many lakes, increasing mean body length of fish. The OSFA management strategy produced extremely low utility for harvest anglers because there was limited harvest opportunities offered across the landscape. Biological and social strategies affected each angler type differently. For example, harvest-oriented anglers had improved utility and effort under the social strategy, but trophy and numbers-oriented anglers had much lower utility and effort than under the OSFA strategy. The buffet strategy resulted in slight reductions in mean value for trophy- and numbers-oriented anglers, but improved landscape value by increasing the value of fishing opportunities for social and harvest-oriented anglers. The ability for the buffet strategies to provide relatively high utility opportunities for all angler types resulted in higher multiplicative utility for the fishery as a whole.

Several patterns emerge when examining where regulations applied to fish populations across the realistic landscape under the reduced buffet strategy (Figure 6). Angling pressure had a noticeable effect on density-dependent parameters (recruit density and asymptotic length) in fished (Figure 6; lower panels) versus unfished populations (Figure 6; upper panels). Most lakes, regardless of their proximity to the population center, were often regulated with a 1-fish bag limit. This regulation often protects against overharvest, yet still provides a diversity of fish size-number combinations. Populations with the largest fish were invariably regulated with one-over 500 mm regulations, which protects against removal of the largest fish. Some populations located close to, and at an intermediate distance from the population center, and with a high maximum size and high density, were occasionally regulated with a 500 mm minimum length limit, which also preserves the largest fish, but permits greater harvest opportunity. The pattern of exploitation and regulations also seems to shift the size-structure of populations. Most lakes are lower abundance than the unfished state, but this results in a larger size-structure, which favors a general desire for larger fish among all angler types. As noted above, this resulted in some populations dropping below the conservation threshold of SPR = 0.3, exposing a tradeoff between angler satisfaction and conservation.

Sensitivity of the model was evaluated by calculating elasticity to changes in parameters associated with each angler type and biology of fish populations separately. Penalized landscape value was relatively inelastic to utilities anglers derive from some aspects of fishing, namely the logistic inflection parameter for

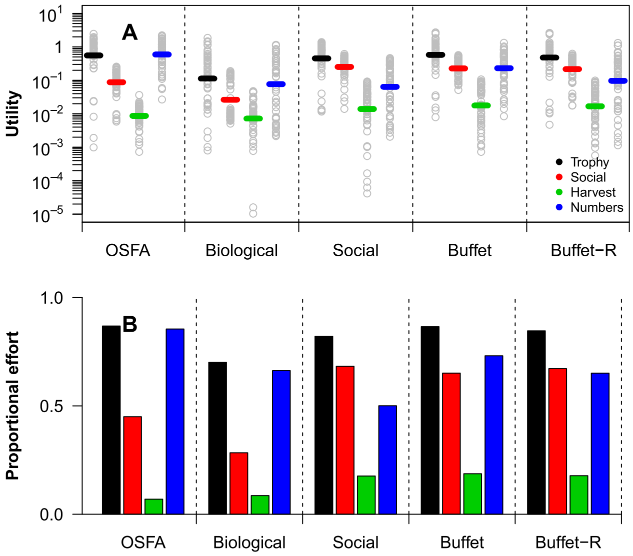

Figure 5. Angler type-level performance when each fish population is unique and anglers belong to one of four homogeneous angler types of five management strategies: one-size-fits-all (OSFA), biologically-based, socially-based, buffet, and reduced buffet (Buffet-R) strategies. Top panel shows the utility experienced by each angler type at each lake (open circles); colored bars represent the mean utility experienced by an angler type across all fish populations. Bottom panel shows the proportion of possible fishing effort exerted across the landscape by each angler type under each management strategy.

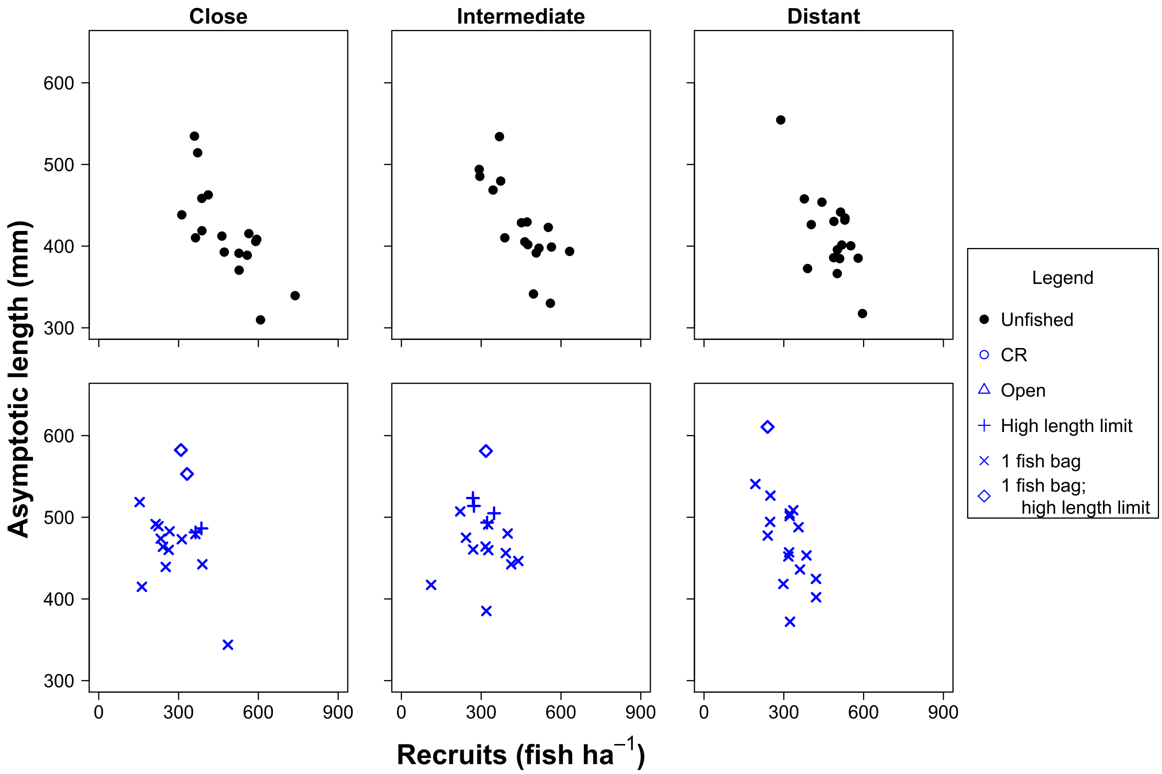

Figure 6. Top row: relative population-level asymptotic lengths and recruits under unfished conditions for populations close, intermediate and distant from the angler population source. Bottom row: relative population-level asymptotic lengths and recruits under equilibrium fished conditions for the same populations when a reduced buffet management strategy is employed on the landscape. Symbols in the bottom panels represent fishing tactics employed on each population under the reduced buffet management strategy.

mean daily harvest, catch and crowding (Figure 7A). Conversely, angler types with high logistic inflection parameters for any trait, especially fish length and distance to lakes, were most sensitive to those traits (i.e. angler types with high logistic inflection parameters were more elastic to those parameters). The model did have high and asymmetric elasticity to catchability with increases in catchability generally resulting in large reductions in landscape value. The model was inelastic to the selectivity and retention rate parameters. The model was sensitive to discard mortality imposed by each angler type, with increases in discard mortality often resulting in reductions in value (Figure 7A). Elasticity of the model to biological parameters revealed a general sensitivity to productivity parameters (R_0, L_∞, K, M), but insensitivity to others.

The relative change in landscape value when regulations are incorrectly applied was evaluated to determine how sensitive the system is to regulations and the relative importance of correctly identifying appropriate regulations. Figure 8 shows the distribution of landscape values calculated over 100 simulations when between two and 50 lakes had incorrect regulation

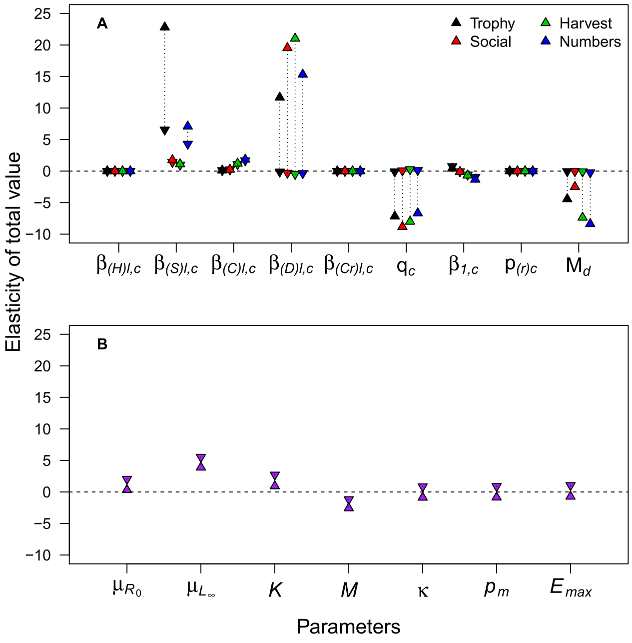

Figure 7. Elasticity of model landscape value relative to one-size-fits-all catch and release regulations. Panel A shows elasticity of social (length at 50% utility) and fishery parameters; panel B shows elasticity of ecological parameters. Up and down pointing parameters depict elasticity when specified parameters are increased or decreased by 10%, respectively.

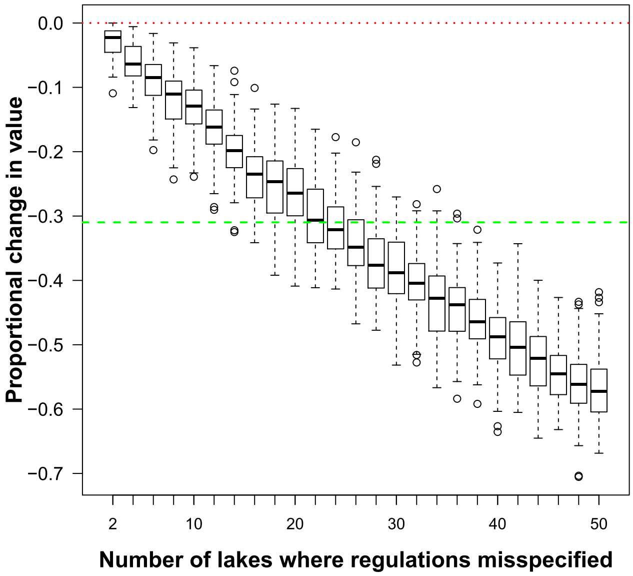

Figure 8. Proportional change in landscape value when regulations on two or more lakes are misspecified relative to the optimal set of regulations across lakes. Dotted horizontal line represents landscape value when all lakes are regulated in a way that results in optimal landscape value; dashed horizontal line represents landscape value achieved under the best one-size-fits-all (400 mm minimum length limit) regulations.

assignments relative to the optimal landscape value. Sensitivity is obviously influenced by which lakes are misspecified and which regulation was applied, with even two incorrectly regulated populations resulting in value ranging from being unchanged to over 10% lower than optimal. In the simulated landscape, only when more than 50% of lakes are incorrectly assigned regulations, did the median value decline to what would be achieved with a one-size-fits-all strategy.

Discussion

Overview of direct implications for fisheries management

This work demonstrates how spatially explicit, purposefully diversified buffet-style management strategies may offer broad improvements for diverse recreational fisheries. At a regional scale, buffet-style strategies outperformed optimally designed OSFA and other management strategies in terms of greater overall and more even (across angler types) utility and effort, generally without inducing substantial fishery overharvest. This means buffet style strategies can potentially simultaneously address the common recreational fisheries management objectives of satisfying anglers and conserving fish populations (Hilborn, 2007; Cowx et al., 2010). Since these objectives often have been traditionally thought to conflict and create tradeoffs (Cheung and Sumaila, 2008; Garcia-Asorey et al., 2011; Thebaud et al., 2014; Camp et al., 2017), these results should be particularly relevant to management agencies concerned with socioeconomic-conservation tradeoffs. Notably, the buffet-style approach has flexibility to be adapted to a diverse suite of multiple, potentially conflicting management objectives, but this will be easier if these multiple objectives are explicitly recognized.

Buffet-style strategies may be attractive to recreational fisheries management agencies for several secondary reasons. First, the buffet style strategies proved robust to imperfect implementation—i.e. applying a less-than-ideal regulation to any particular waterbody. Imperfect implementation of a full buffet style management strategy can occur if waterbody-specific fish populations and region-specific angler types are not thoroughly understood, which is likely in many areas (Radomski et al., 2001; Lester et al., 2003; Carpenter and Brock, 2004; Hansen et al., 2015a). Furthermore, improvements over optimal OSFA or other strategies are still possible under the reduced-buffet strategies. The simplicity of the reduced buffet strategy should make it attractive to agencies seeking to diversify angling experiences (Carpenter and Brock, 2004; Cooke et al., 2016) without implementing too many waterbody-specific regulations that may confuse anglers and law enforcement or prevent systematic learning (Lester et al., 2003; Hansen et al., 2015a). Finally, by supporting more even distributions of effort and utility across different types of anglers, buffet-style strategies may diminish dissatisfaction or disenfranchisement of angling groups, a prominent concern to managers and decision makers (Pope, 1983; Arlinghaus, 2005, 2007; Hilborn, 2007). More even effort across angler types may also facilitate recruiting and retaining a diversity of angling participants to sustain socio-ecological angling systems (Wightman et al., 2008; Aas and Arlinghaus, 2009), which is like to be especially important in the context of angler demographic shifts (Arlinghaus et al., 2015).

Mechanisms driving success of buffet-style strategies in recreational fisheries

Differences between buffet-style and alternative management strategies were partly due to how each addresses angler heterogeneity. The importance of heterogeneity has been established (Beardmore et al., 2013; Johnston et al., 2013), but past studies have largely addressed heterogeneity and resultant tradeoffs by searching for the single best compromise regulation (Johnston et al., 2010; Gwinn et al., 2013). These approaches, similar to the OSFA results of this study, will almost always be less-than-optimal for any single angler type because they are a compromise across all angler types. Buffet-style strategies avoid this by implementing regulations to purposefully vary fishing experiences that match motivations of all angler types. At a regional scale, this allows for increased utility over all types of angler, as well as a greater diversity of types of anglers achieving high degrees of utility, compared to even an optimal OSFA strategy. The concept of doing different things in different places is exceedingly simple and not new to natural resource management—indeed some management agencies implicitly apply this logic when implementing, for example, gear-specific regulations to provide different angling opportunities. However, diversified approaches rarely have been studied in recreational fisheries (Lester et al., 2003; Carpenter and Brock, 2004), and this likely hampers broader and more strategic implementation of such approaches. This work shows it seems to work particularly well in recreational fisheries because of the feedbacks by which collective angler behaviors sculpt angling experiences.

The diversity of fishing experiences created by buffet-style management promotes synergies with socio-ecological feedbacks common to recreational fisheries systems with diverse anglers (Hunt et al., 2013a, Ward et al., 2016; Arlinghaus et al., 2017). Heterogeneous angler types characterized by corresponding behaviors (e.g. catch and release) exert patterned influences on fish population dynamics, which allows anglers to further mold fishing opportunities (Johnston et al., 2010; Camp et al., 2015; Ward et al., 2016). In an OSFA strategy, identical regulations likely encourage multiple angler types to essentially shape a given fishery in potentially opposite ways. For example, the effects of catch-rate-oriented anglers releasing most of their catch might be largely undone if trophy-oriented anglers increase harvest of smaller fish to promote trophy growing conditions. As these competing feedbacks play out across landscapes, fish populations that may have initially been biologically diverse should become more homogenized (Cox et al., 2002; Camp et al., 2015), and result in lower diversity of angling opportunities. Despite these interactions, some sorting will occur across the landscape due to the effect on driving distance, where more distant populations have lower fishing mortality and concurrent changes in population structure (Parkinson et al., 2004; Askey et al., 2013; Wilson et al., 2016). Conversely, the purposefully diversified regulations of a buffet-style management strategy should better sustain diverse fishing opportunities by encouraging anglers to “self-sort” towards locations best suited to their desires. For example, implementing trophy regulations on any given water served to redirect harvest-oriented anglers from those waters and to others, better allowing trophy anglers to mold a larger size structure of the fish population. The key of buffet-style management is that these potentially competing fishery uses are spatially separated, similar to how Marine Spatial Planning or Coastal Zone Management (e.g. Tiller et al., 2012) functions. This lets each objective be maximized within a region, creating better options for different types of anglers and leading to greater fishing effort.

Buffet-style management in the context of previous studies

The buffet style management strategy described here builds off of a small number of previous studies as well as some established concepts in recreational fisheries management. Management agencies have long-recognized that different anglers have different preferences, and certainly some recreational fishery regulations are designed to promote different fishing experiences or to address biological differences in fish populations. For example, stream salmonid fisheries have a long history of being regulated with a subset of waters reserved for catch and release only, or special gear (e.g. fly fishing), while others allow more general gear and/or harvest (Gigliotti and Peyton, 1993; Aas et al., 2000). Such regulations are intended to promote a variety of opportunities for diverse anglers (Engstrom-Heg, 1981; Carpenter and Brock, 2004), as well as to protect more vulnerable fish populations (Post et al., 2003). While there is abundant literature describing angler diversity and preferences for diverse elements of the recreational fishery experience (Fisher, 1997; Wild et al., 1998; Oh and Ditton, 2006), and while the concept of using regulations to promote such diversity is likely familiar to many agencies (Radomski et al., 2001), very little literature exists describing how this ought to be accomplished (Carpenter and Brock, 2004). One-size-fits-all strategies are likely to leave diverse anglers dissatisfied (Carpenter and Brock, 2004), and risk overfishing, especially of easily accessible waters (Post et al., 2002; Hunt et al., 2011). But myriad, waterbody-specific regulations cannot be practically supported by scientific sampling (Shuter et al., 1998), while causing substantial confusion to anglers and law enforcement alike (Lester et al., 2003). What this work does is to introduce buffet-style strategies, especially reduced-buffet options, as a practical compromise between OSFA and overly complex strategies. Specifically, buffet-style management goes beyond randomly providing diverse opportunities to match angler motivations (e.g. the "social" strategy evaluated) to suggest quantitatively evaluating how to use regulations to improve angler utility and conservation outcomes, either through simulation or adaptive management. Equally importantly, this work provides a framework where none existed for agencies to design and implement strategies that serve diverse anglers.

This idea of spatially separating potentially competing uses has been sparsely invoked for recreational fisheries (Aas et al., 2000) but is not new to natural resource management. Buffet-style strategies largely borrows principles from marine spatial planning on zoning research (Crowder and Norse, 2008; Halpern et al., 2008). For example, a common application of marine spatial planning is siting marine protected areas and those intended for specific fisheries to minimize conflict and support multiple objectives (Walters et al., 2007; Agardy et al., 2011). Spatial separation is also common in inland waters, where zoning may separate, for example, swimming or diving areas from pleasure boating or fishing, from other industry such and energy generation (Rees et al., 2010; Christie et al., 2014). The application of these zoning and spatial planning principles has long been recognized in wildlife management to provide diverse opportunities to stakeholders hunting at different times of year or with varying weapons (Hendee, 1974; McCorquodale, 1997), as well as to sustain vulnerable populations of game and non-game species (e.g. Bodmer et al., 1994; Bennett et al., 2007). Similarly, spatially explicit strategies based on suitability mapping and land use planning (McHarg, 1969) have long been used to address conflict in outdoor recreation, such as results from competing uses like forestry, hiking, and wildlife conservation (Franklin, 1994; Harris et al., 1995; Kliskey, 2000). These principles have become commonplace in terrestrial and ocean management, while their application to recreational and especially inland fisheries has lagged, despite the seemingly high degree of compatibility with this sector.

Integration with other management approaches

Buffet style strategies compliment one of the most commonly invoked management approaches, adaptive management (Walters, 1986; Walters, 2007). A persistent challenge to learning from deliberate adaptive management experiments of recreational fisheries has been lack of replication of experimental treatments (Walters, 1998; Lester et al., 2003; Hansen et al., 2015a). This occurs when most waters receive individually-designed regulations (no replication; Lester et al., 2003), as well as when all waters receive the same or very similar regulations (no treatment separation; Hutchings et al., 1997; Walters, 1997). In contrast, substantial replication would be possible under reduced buffet strategies that implement a small number of diverse regulations. This could allow for learning about fish population and human behavioral responses to regulations, such as better understanding how anglers select fishing sites, or what types of opportunities are most desired for different types of anglers. This information can help refine buffet style strategies in the future to suit human and resource needs, to adjust to unpredictable but certain environmental changes or perturbations, or to help agencies more proactively understand and incorporate stakeholders in decision making (Carpenter et al., 2017).

Buffet-style management strategies are also imminently compatible with an increasing emphasis on incorporating stakeholders in the fisheries management process itself through collaborative or co-management (Jentoft, 1989; Pomeroy and Berkes, 1997; Granek et al., 2008; Pinkerton, 2011), and related place-based approaches (Young et al., 2007). Co-management promotes stakeholder investment in management that can further socio-ecological resilience

(Ostrom, 1990; Berkes, 2009), and is generally considered most effective when implemented at more local scales where stakeholders are well-connected to the resource (Cheng and Daniels, 2003; Gutierrez et al., 2011; Edwards and Stephenson, 2013). The flexibility and diversity of buffet-style strategies allows for, and would probably benefit from, agencies seeking greater local stakeholder input and involvement with recreational fisheries regulations. Potential examples could span a continuum of stakeholder inclusion, from involvement in assigning agency-determined regulations to specific waters, to stakeholders helping to define the suite of regulations to be applied. At a time when many recreational fisheries governance agencies are recognizing the need for greater stakeholder participations in the management process (Granek et al., 2008), buffet-style strategies may serve as a valuable tool to facilitate this in a flexible and progressive manner.

Assumptions, caveats, and limitations

One assumption central to this work and previous studies (e.g. Johnston et al., 2010) is the explicit formulation of a quantitative management objective. For this specific study, a management objective must be specified to select optimal OSFA strategies and to assign regulations to waterbodies under buffet-style management. Past studies have addressed the ambiguity of recreational fisheries management objectives differently. Johnston et al. (2010) compared how sociological objectives and overfishing risk trade off; Fenichel and Abbott (2014) used a suite of economic objectives. Here, a single, multi-attribute objective function (Kiker et al., 2005) was used as a simple representation of what is often considered important by management agencies: angler utility that leads to satisfaction, and risk of overfishing (Larkin, 1977). Clearly these are not the only aspects that could be considered, and does not include license sales, political expediency, or other less-often-stipulated attributes that are likely important to management agencies (Lackey, 1979; Hilborn, 2007). While otherwise-formulated objectives might result in different OSFA optimal regulations (with respect to length and bag limits), there is no reason to expect them to alter meaningfully the pattern of comparison between OSFA and buffet-style strategies. Notwithstanding, this does highlight the importance of future research better describing objectives of a recreational fisheries (Barber and Taylor, 1990).

Another set of assumptions affecting the results presented involve the complexity of the socioecological system represented, which could affect the efficacy of buffet-style strategies. This study assumed a regional recreational fishery system with a single population center, many discrete waters, and a single-species fishery. Many regions, however, have multi-species fisheries that can compete, such as between introduced and native species fisheries (e.g. Churchill et al., 2002; Carey et al., 2011), or between native species that ecologically interact (Rowe, 2007; Hansen et al., 2015b, 2017). Additional research is required, but buffet-style strategies may still function in multi-species fisheries if ecological interactions among species are not wholly mutually exclusive. Additional complexities would emerge with recreational use coexists with subsistence or commercial pressure; these situations would require careful thought and experimentation. A greater challenge is posed by landscapes with sparse and indivisible waters (e.g. reservoirs, rivers with migrating fish populations, marine systems). Landscapes with few, large waters lacking natural spatial "boundaries" should impede creating discrete angling opportunities. Indeed, these boundary issues are considered some of the most challenging for marine spatial planning approaches (Walters, 2000; Young et al., 2007; Kellner et al., 2007). Similarly, buffet style strategies should become unnecessary with increasing angler homogeneity, since in these cases OSFA strategies will perform as well as buffet style strategies, without the added cost of additional regulations (Johnston et al., 2010; Gwinn et al., 2013).

Buffet-style management strategies can create additional challenges to recreational fisheries management. Buffet-style management will require initial research to identify a suite of diverse potential regulations to implement across a region, especially given the model sensitivity to regulations considered. Selecting regulations types requires understanding angler characteristics and preferences, as well as biological attributes of fish populations. Assessing both is subject to observation and process error that may complicate assessments. For example, fish populations may not be at equilibrium when surveyed owing to past histories of harvest altering size structure and abundance (Barnett et al., 2017). Or, different angler types may be statistically assigned to the same group based on their utility to certain catch and non-catch attributes if using a latent class choice model, while they in fact have very different fishing behavior and targeting (Morey et al., 2006; Ward et al., 2013b). Such challenges, however, will exist whenever managers seek to consider human and biological information to support regulatory decision making, and are not exclusive to buffet-style strategies. This reinforces the need to make changes within an adaptive management cycle.

Future directions

There are many options for future expansion of the ideas and applications of buffet-style management strategies described here. While this study focused on fisheries harvest regulations specifically—i.e. length and bag limits—these are but a small component of the total management options available. Other actions such as stock enhancement (Lorenzen, 2008; Camp et al., 2013), habitat restoration (Bolding et al., 2004; Seaman, 2007; Poplar-Jeffers et al., 2009), fishing site facilities, or access improvements (Hunt, 2005; Salz and Loomis, 2005) may all have substantial effects on anglers and the utility they achieve (Hunt, 2005). These actions could easily be used in conjunction with length and bag regulations to create even more separation or diversity of fishing experiences, if desired. For example, regular stock enhancement of catchable-size fish might be employed in a limited number of discrete water bodies to which liberal harvest regulations would be applied (i.e. put-and-take fisheries or urban fisheries), or site facilities and access might be augmented in waters intended to appeal to more social or less specialized anglers. The expected benefit of such actions would not only be increased realized utility for the angler types towards which the action were directed (e.g. harvest oriented or social anglers) but likely also greater utility of other groups (e.g. catch-rate or trophy oriented, more specialized anglers) benefiting from the lesser congestion at other sites (Cox et al., 2003; Hunt, 2005; Salz and Loomis, 2005). Such additional management actions may also be useful for expanding buffet-style management to more readily achieve management objectives broader than sustainable satisfaction of anglers, but that are nonetheless related to recreational fisheries, such as the ecological conservation of rare non-targeted species or imperiled habitats (Pikitch et al., 2004; Lewin et al., 2006; Granek et al., 2008). For example, a combination of stock enhancement and harvest regulations could be used to "draw" anglers away from other waters more sensitive owing to their habitat or presence of endangered species (Martin and Pope, 2011; Carpenter et al., 2017). Specific details and ideally case studies exploring how buffet-style strategies can address these other objectives and management options, potentially in conjunction with adaptive management or co-management principles, is likely a verdant area for future research.

Conclusion

In concert, the buffet-style, spatially diversified management strategies described here offer promise for recreational fisheries management. While many management agencies currently provide intentionally diverse fisheries through a combination of stocking strategies, regulations, and amenities, buffet-style management goes further, where management actions on each lake are quantitatively considered, either through simulation or adaptive management, and have the potential to further improve angler utility while minimizing conservation risk. Such strategies can offer improvement over one-size-fits-all strategies by increasing the overall utility experienced by the angling population with minimal conservation concern to fish population. This is expected to promote greater satisfaction (to which utility is related) of current anglers, but should also decrease the proportions of anglers poorly served by existing one-size-fits-all strategies and thus minimize dissatisfaction. Both these are important for agencies interested in recruiting and retaining greater or more diverse participation in recreational fisheries, while sustaining ecological function of fisheries. Simultaneously, buffet style strategies promote simplification of the (likely common) situation in which hundreds of different regulations are applied to individual waters (Lester et al., 2003), which places a high cost on supporting science and enforcement. The theoretical benefits are possible specifically because buffet style strategies account for open access angler dynamics as well as multiple, potentially competing objectives of diverse stakeholders. Realizing the theoretic benefits of buffet style strategies will have challenges, especially related to assessing angler preferences and non-stationarity of fish populations or social norms that may influence fisheries (e.g. pervasive catch-and-release: Gilbert and Sass, 2016; Sass et al., 2018; Shaw et al., 2019). These challenges also offer opportunities to pair buffet style strategies with adaptive management ideals for learning about potentially changing social-ecological systems, and for explicitly incorporating anglers in regulatory decision making per cooperative management principles. Buffet style strategies are certainly not a panacea, but they may prove a useful compromise for agencies seeking to sustain recreational fisheries, while encouraging systemic learning and cooperative governance of resources valuable to many users, including but not limited to, anglers.

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