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Defining a Safe Operating Space for inland recreational fisheries

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Abstract

The Safe Operating Space (SOS) of a recreational fishery is the multidimensional region defined by levels of harvest, angler effort, habitat, predation and other factors in which the fishery is sustainable into the future. SOS boundaries exhibit trade-offs such that decreases in harvest can compensate to some degree for losses of habitat, increases in predation and increasing value of fishing time to anglers. Conversely, high levels of harvest can be sustained if habitat is intact, predation is low, and value of fishing effort is moderate. The SOS approach recognizes limits in several dimensions: at overly high levels of harvest, habitat loss, predation, or value of fishing effort, the stock falls to a low equilibrium biomass. Recreational fisheries managers can influence harvest and perhaps predation, but they must cope with trends that are beyond their control such as changes in climate, loss of aquatic habitat or social factors that affect the value of fishing effort for anglers. The SOS illustrates opportunities to manage harvest or predation to maintain quality fisheries in the presence of trends in climate, social preferences or other factors that are not manageable.

KEYWORDS
habitat, predation, rational expectations, recreational fishery, resilience, sustainability

1 | INTRODUCTION

Recreational fishing is a globally significant social–ecological process. In all developed nations, recreational fisheries are the predominant use of wild inland fish stocks (Arlinghaus, Cooke, & Potts, 2013). Similarly, recreational use of coastal marine fisheries is substantial (Coleman, Figueira, Ueland, & Crowder, 2004). The economic value of marine recreational fisheries is greater than that of all other recreational uses of the world's oceans (Cisneros-Montemayor & Sumaila, 2010). Globally, recreational fisheries expenditures exceed $190B per annum (World Bank, 2012). For the USA alone, inland recreational fisheries expenditures were $27.7B in 2011 (U.S. Department of Interior, 2011). Thus, recreational fishing is a major driver of fish stock dynamics, as well as one of the most important ways that people interact with nature.

Inland recreational fisheries are changing in response to fisher preferences as well as climate, land use, habitat modifications, inputs of nutrients and other chemicals, biotic invasions, harvest and other large-scale drivers (Arlinghaus, Tillner, & Bork, 2015; Carpenter, Stanley, & Vander Zanden, 2011). Multiple drivers and feedbacks lead to complex interactions that may affect both fishes and fishers (Hansen, Gaeta, Hansen, & Carpenter, 2015; Hunt et al., 2016). Therefore, management of inland recreational fisheries in the face of global change also requires recognition that fishes and fishers are components of complex, multifaceted ecological and human interactions (Beard et al., 2011; Schindler & Hilborn, 2015). Unfortunately, fisheries managers can influence fish biomass and harvest using only a limited set of tools, such as harvest regulations, stocking or by limiting access, yet have little or no influence over factors that may strongly affect a given fishery, such as social and macroeconomic trends, climate or fish habitat (Hunt et al., 2016).

Although some responses of ecosystems to global change are gradual, many ecosystem responses are abrupt and long-lasting. An ecosystem may show little response to a driver until a threshold is reached, yet once the threshold is passed, recovery can be frustratingly difficult, slow and expensive (Carpenter, 2003; Scheffer, Carpenter, Foley, Folke, & Walker, 2001). Moreover, living resources are often managed close to thresholds due to social or economic pressures (Brock & Carpenter, 2007; Ludwig, Brock, & Carpenter, 2005). Thresholds themselves depend on multiple interacting factors. For example, some inland walleye (*Sander vitreus*, Percidae) stocks of the western Great Lakes region are now collapsing in the same management regime under which they once thrived (Hansen, Carpenter, Gaeta, Hennessy, & Vander Zanden, 2015). Empirical models show a sharp transition between walleye and warm-water largemouth bass (*Micropterus salmoides*, Centrarchidae) dominance as growing degree days (5°C base) exceed a threshold (Hansen, Read, Hansen, & Winslow, 2017). Current trends suggest that walleye stocks are crossing a threshold, perhaps in response to drought, expansion of other fish species, changes in shoreline habitat, overharvest or other factors (Rypel, Lyons, Griffin, & Simonson, 2016; Tsehaye, Roth, & Sass, 2016).

Responses to changing climate, habitat or other factors are not well integrated into theory or practices for managing recreational inland fisheries at present (Lynch et al., 2016). Yet, the effects of changing drivers must now be considered in any conceptual framework for recreational fisheries (Paukert et al., 2016). Here, we employ the concept of "Safe Operating Space" or SOS (Scheffer et al., 2015; Steffen et al., 2015) for recreational fisheries in a changing environment. The SOS framework emphasizes maintaining a resource within acceptable boundaries that are affected by the interplay of multiple environmental stressors operating at different scales (Figure 1a). For example, adaptation to climate change is possible when local factors can be managed to maintain resources within acceptable levels to offset the potentially adverse effects of climate change (Scheffer et al., 2015) (Figure 1b). As applied to recreational fisheries, the SOS addresses local or regional factors that could be managed to cope with uncontrollable aspects of environmental change.

This article develops the concept of a Safe Operating Space (SOS) for inland recreational fisheries. We introduce a social–ecological model (Schluter et al., 2012) to illustrate the effects of key ecological and human choice processes on the SOS. Graphics derived from the model show potential effects of fishing effort, catchability as affected by fisher preferences and regulations, alternative activities available to fishers, predation and habitat on the SOS.

2 | MODEL FOR THE SAFE OPERATING SPACE OF A FISHERY

2.1 | Definition of the Safe Operating Space

In Earth System Science, the SOS is a multivariate region where humanity's waste emissions and resource use can sustain human well-being at levels deemed acceptable by most people (Steffen et al.,

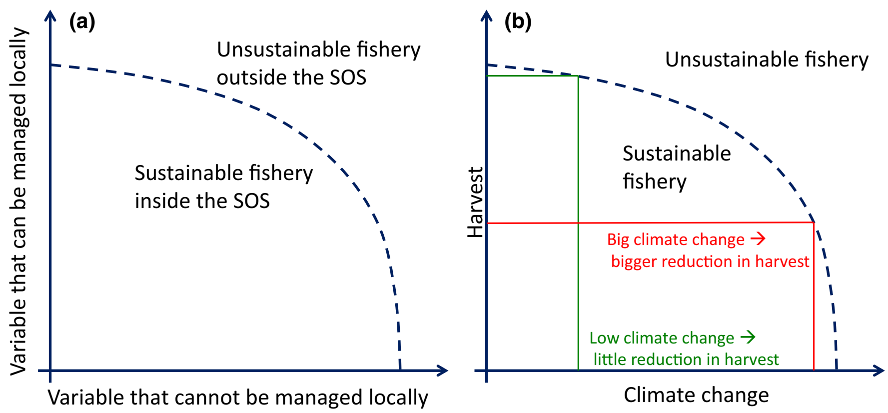

FIGURE 1 Safe Operating Space (SOS) for a recreational fishery. (a) Boundary of the SOS (dashed line) depends on variables that cannot be managed locally (e.g. climate change or macroeconomic trends that affect how fishers allocate time) and variables that are susceptible to action by local managers (e.g. harvest). (b) Hypothetical example of the effects of harvest and climate change on the SOS. If climate change is small, there is little effect on the maximum harvest for the SOS (green lines). If climate change is large, the maximum harvest within the SOS is lower (red lines)

2015). Now scientists are grappling with the problem of downscaling SOS to more local scales that allocate Earth's resources and capacity to process waste in a just and fair manner (Dearing et al., 2014; Häyhä, Lucas, van Vuuren, Cornell, & Hoff, 2016). At the scale of regional natural resource use, it seems possible to manage local variables such as habitat or harvest to offset adverse effects of climate change (Scheffer et al., 2015). For example, warming water temperatures can increase the risk of cyanobacterial blooms in lakes, but reducing nutrient loading by local management actions can offset this risk (Green et al., 2017). Still, there is a lack of concrete examples of SOS for regional resources. Our goal was to develop a framework for SOS of inland regional recreational fisheries that could in principle be integrated with observed data and the concerns of managers and the public.

A minimal representation of a recreational fishery considers biomass growth of the focal species as affected by habitat quality, predation on that focal species and harvest as affected by human behaviour (Figure 2a). In Figure 2a, the green curve is biomass growth in the absence of harvest. At moderate harvest (blue straight line), there are three equilibria; low and high stable points marked by solid circles, and an unstable point marked by an open circle. If harvest increases to a critical level (red line), a critical transition occurs. If harvest exceeds this critical transition, the upper stable equilibrium disappears and the biomass falls to the lower stable equilibrium. Even if harvest remains constant, a critical transition could be caused by a decrease in population growth that pushes the green curve downward. Such a decrease in growth could occur due to loss of habitat, increase in predation by other fish species, or other ecological factors.

We define the SOS of the moderate harvest rate as the difference in slope between the critical and moderate harvest lines (units time^{-1}) (Figure 2a). We focus on this definition because managers of recreational fisheries have tools for managing harvest. Management should aim for a SOS magnitude >0, to provide a cushion against random events that might push the fishery to the lower equilibrium.

Under this definition, the SOS can also be visualized on a plot of equilibrium biomass vs. harvest rate (time^{-1}) (Figure 2b). Each point on the solid green lines of Figure 2b is a stable equilibrium, and each point on the dashed green line is unstable. The critical harvest level occurs at the point where the stable and unstable equilibria meet. At this point, a slight increase in harvest rate causes a single low-biomass equilibrium, whereas a slight decrease in harvest rate leads to three equilibria of which two are stable, one at high biomass and one at low biomass. For any harvest rate less than the critical harvest rate, the size of the SOS is the distance between the current and critical harvest rates.

The goal of SOS management is to maintain the stock in the multidimensional space of harvest, habitat, predation and other factors where it is sustainable. The SOS is precautionary, in the sense that it maintains a safe distance from thresholds of collapse within this space. The SOS differs from maximum sustained yield (MSY) in three ways: no optimal target for exploitation is sought, multiple factors that affect fish production are considered, and management attempts to maintain a safe distance from thresholds. It should be noted that some authors interpret MSY as a limit that should not be exceeded (Mace, 2001). Nonetheless MSY has not traditionally considered factors other than harvest.

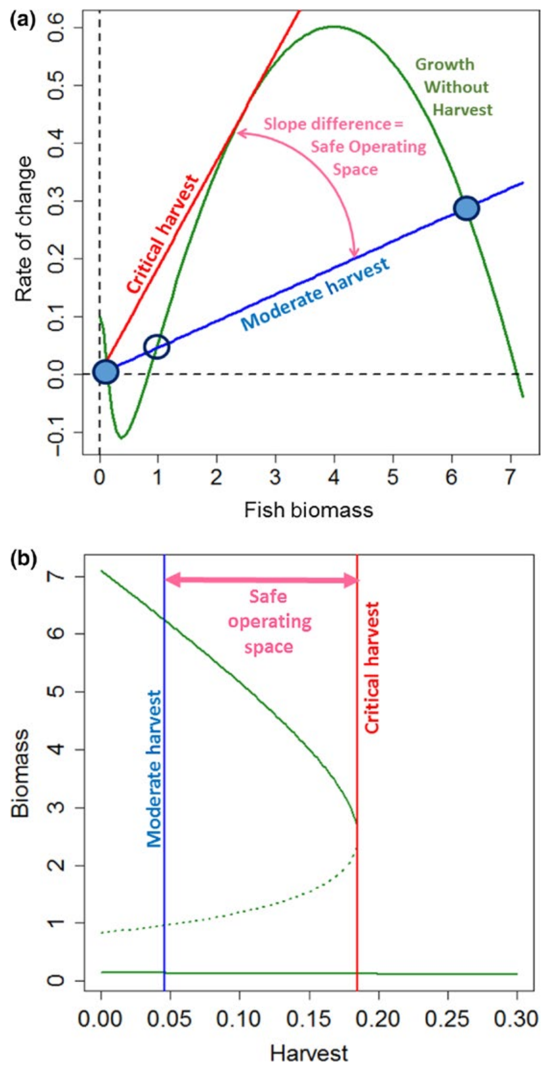

FIGURE 2 The Safe Operating Space (SOS) is the difference between the critical harvest rate and the actual harvest for a given set of conditions. (a) SOS in relation to rates of biomass growth and harvest. Growth of fish biomass in the absence of harvest (green line) with moderate (blue line) and critical (red line) harvest scenarios. On the moderate harvest line, solid circles denote stable equilibria and the open circle is an unstable equilibrium. In the critical harvest line, the only stable equilibrium has low biomass (closed blue circle). The SOS for the moderate harvest is the difference in slope between the critical harvest line and the moderate harvest line. *X*-axis units are biomass, and *y*-axis units are biomass time^{-1}. (b) Bifurcation diagram showing the SOS on axes of equilibrium biomass vs. harvest rate (time^{-1}). Solid lines are stable equilibria, and dashed line is unstable equilibria. The SOS is the difference between critical and moderate harvest rates, as in panel a

2.2 | Model of fish biomass dynamics

To further illustrate the SOS, we employed a classical model of fish biomass with well-understood dynamics (May, 1977; Steele & Henderson, 1984)

$$\frac{dx}{dt} = f(x) = I + rx\left(1 - \frac{x}{K}\right) - \frac{px^2}{h^2 + x^2} - Hx \qquad (1)$$

where x = fish biomass, I = stocking rate (which could be zero), r = growth rate, K = maximum potential biomass (or carrying capacity), p = predation rate, h = value of x where predation is half-maximum, and H = harvest. In Equation (1), biomass growth is logistic and predation follows a sigmoid functional response (May, 1977).

With low-moderate harvest, there is a high positive equilibrium. With excessive harvest, the high positive equilibrium vanishes and the biomass collapses to the low positive equilibrium. The critical point where this occurs is the point where the harvest line is tangent to the net growth curve (Figure 2). Computationally, this critical point is found by solving the two equations $f(x) = 0$ and $df(x)/dx = 0$ for x and H. These solutions are defined as the critical values x_{crit} and H_{crit}.

To evaluate effects of harvesting both predator and prey, we analyse a two-species case where both the focal species x and its predator y are subject to harvest by fishers. In the two-species case,

$$\frac{dx}{dt} = f_x(x,y) = I + r_x x\left(1 - \frac{x}{K_x}\right) - \frac{pyx^2}{h^2 + x^2} - H_x x$$
$$\frac{dy}{dt} = f_y(x,y) = r_y y\left(1 - \frac{y}{K_y}\right) + \frac{cpyx^2}{h^2 + x^2} - H_y y \qquad (1a)$$

Parameters for growth r, carrying capacity K and harvest H are subscripted by species, and c is the proportion of consumed biomass that is added to predator biomass. We use Equation (1a) to study the effects of harvesting the predator on the critical transition point for collapse of x to its low equilibrium. This critical point is found by solving simultaneously the four equations $f_x = 0$, $f_y = 0$, $df_x/dx = 0$ and $df_y/dx = 0$ for x_{crit}, y_{crit} and $H_{x,crit}$ given a particular harvest rate H_y for the predator.

2.3 | Fisher expectations, effort and harvest

Policymakers have long recognized that fishers' expectations have a central role in outcomes of recreational fisheries management (Gale, 1987). Thus, in recreational fisheries, it is appropriate to consider fishers' expectations as a key driver of effort (Fenichel, Abbott, & Huang, 2013; Stoeven, 2014). The amount of time that a person spends fishing depends on the relative value that the individual attaches to fishing vs. alternative activities such as earning a living or pursuing other leisure activities.

The time budget of a representative fisher is as follows:

$$\tau_F + \tau_O = T \qquad (2)$$

where τ is time spent in an activity, T is total time available, and subscripts F and O denote fishing or other activity, respectively. Harvest rate coefficient depends on the number of fishers and the time they spend fishing:

$$H = qN\tau_F \qquad (3)$$

where q is a catchability coefficient, defined as the proportion of stock removed per unit effort, and N is the number of fishers.

From the standpoint of an individual fisher, utility obtained from fishing and other activities is

$$U = (vq\tau_F x)^a + V(T - \tau_F) \qquad (4)$$

The first term on the right is utility from harvest, represented by a Cobb–Douglas production function with exponent a, $0 < a < 1$ (Carpenter & Brock, 2004). The multiplier v ($v \geq 1$) represents the augmented value of fishing beyond value due to harvest, accounting for the fact that some caught fish will not be harvested yet still provide enjoyment to the fisher. The parameter V is the value per unit time of alternative activities. Time spent in alternative activities $T-\tau_F$ is obtained by rearranging Equation (2). For example, V could be the rate of pay for time spent working expressed in the same units as the enjoyment obtained from fishing. Alternatively, V could be the enjoyment obtained from some other non-fishing recreational activity. Expression (4) can easily be expanded to accommodate more than two activities (Carpenter & Brock, 2004), but fishing and not fishing are sufficient for our purposes here.

2.4 | Optimal effort

We assume that fishers base their effort on their beliefs about their prospects for enjoying fishing time vs. other ways their time could be spent. The utility that is maximized with respect to τ_F is

$$U_{private} = \left[vq\tau_F x(\tau_E)\right]^a + V(T - \tau_F) \qquad (5)$$

Here, τ_E is the expected effort by other fishers. A representative fisher believes that there are a large number of other fishers, their activity determines fish biomass $x(\tau_E)$, and an individual fisher has negligible effect on $x(\tau_E)$. $x(\tau_E)$ is the largest stable equilibrium of Equation (1) with Equation (3) inserted for H and with τ_E substituted for τ_F:

$$\frac{dx}{dt} = f(x) = I + rx\left(1 - \frac{x}{K}\right) - \frac{px^2}{h^2 + x^2} - qN\tau_E x \qquad (6)$$

This process (given a value of τ_E, maximize Equation [6] at equilibrium with respect to τ_F) computes a rational expectations community value of τ, $\widehat{\tau}$, as a function of τ_E:

$$\widehat{\tau} = g(\tau_E) \qquad (7)$$

We call a fixed point of Equation (7) a rational point expectations equilibrium. Under regularity conditions, the recursion Equation (7) converges to the optimal value for the time spent fishing under rational expectations, τ_R, at the rational expectations equilibrium corresponding to a fixed point of Equation (7)

$$\tau_R = g(\tau_R) \qquad (8)$$

There may be more than one positive fixed point of Equation (7). However, in the examples presented here, there is only one fixed point of Equation (7).

2.5 | Computation

Given a set of parameter values including the four factors that we studied with respect to the SOS (catchability, value of non-fishing activity, habitat and predation), the pseudocode for finding the SOS is as follows: (i) calculate effort (Equations 5–8); (ii) calculate the equilibria of Equation (1) with Equation (3) inserted for H; (iii-a) if the high-biomass stable equilibrium does not exist, set the SOS to zero and stop; (iii-b) if the high-biomass stable equilibrium exists, calculate the critical H, set the SOS equal to the critical H minus the optimal H, and stop. All computations reported here were performed in the base package of R 3.3.2 (R Development Team, 2012) using programs written by SRC. The calculation of the SOS uses the R base package functions optimize(), optim(), polyroot() and uniroot(). The rootSolve{} package was used to find critical transition points of Equation (1a) (Soetart & Herman, 2009). The fields{} package was used for graphics (Nychka, Furrer, Paige, & Sain, 2015).

The SOS exists for parameter values that give high biomass at low-to-moderate levels of effort, habitat loss and predation. We used a representative set of parameters to illustrate the SOS. The qualitative result—that the SOS looks like a trade-off curve—does not depend on the particular values of parameters, as long as the parameters give positive growth of the fish stock for low harvest. A sample program to calculate the SOS is available from GitHub (https://github.com/SRCarpen/SOS_Rec_Fishery/; updated 9 December 2016) for readers who wish to experiment with alternative parameter values. Except when otherwise specified by figure axes, parameter values for simulations reported here were $I = 0.1$, $r = r_x = 0.5$, $p = 0.5$, $h = 0.2$, $K = K_x = 8$, $r_y = 0.25$, $K_y = 2$, $c = 0.1$, $\tau0 = 1$, $v = 1.5$, $q = 0.2$, $a = 0.5$, $V = 0.5$ and $N = 1$.

3 | RESULTS

Habitat loss and catchability interact to affect the SOS (Figure 3). The size of the SOS decreases as habitat loss and catchability increase (Figure 3a). Precautionary management would aim for a SOS magnitude >0, to buffer against random events that might push the fishery out of the SOS. To allow for this buffer, we present an arbitrary boundary at a small positive value of SOS = 0.02 year^{-1}, meaning that

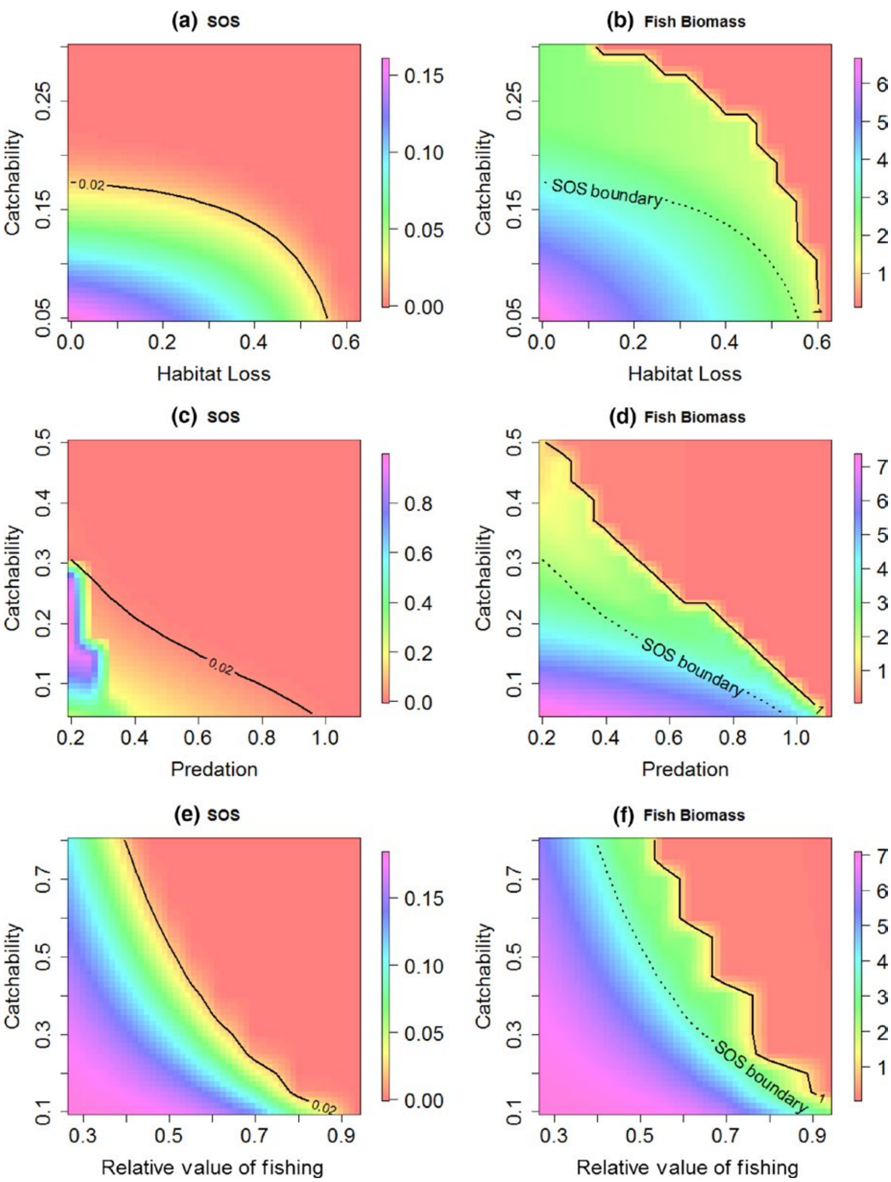

FIGURE 3 Surfaces of Safe Operating Space (left column, SOS, year^{-1}) and fish biomass (right column) as determined by catchability (q y-axes) and three other factors (x axes): habitat loss (top row), predation (middle row) and value of fishing (bottom row). SOS = 0.02 is plotted as the boundary of the SOS. On the biomass surfaces (right column), the SOS boundary and the isopleth for biomass of 1 are plotted for reference. (a) SOS and (b) fish biomass on axes of habitat loss (proportion of nominal K) and catchability (q). (c) SOS and (d) fish biomass on axes of predation coefficient (p) and catchability (q). (e) SOS (year^{-1}) and (f) equilibrium fish biomass on axes of the relative value of fishing to a representative angler ($v/(v + V)$) and catchability (q)

an increase of 2% in the proportion of biomass that is harvested will collapse the stock to the low-biomass equilibrium. Outside the black curve at SOS = 0.02, further increases in catchability or habitat loss cause the SOS to decline to zero, meaning that the high-biomass state no longer exists. Fish biomass is moderate at the SOS boundary and gradually declines as catchability and habitat loss increase beyond the boundary (Figure 3b). Although biomass is declining at the SOS, the disappearance of the high-biomass alternate state may not be detectable from biomass measurements alone.

Predation and catchability also affect the SOS (Figure 3). As predation increases, catchability must be adjusted downward to stay within the SOS (Figure 3c). Fish biomass is moderate at the SOS boundary and declines beyond the boundary as the high-biomass state disappears (Figure 3d). Nonetheless, changes in biomass alone do not provide a strong indication of the disappearance of the high-biomass alternate state.

Because predation has a strong effect on the SOS for a prey species, it is reasonable to think that harvest of a predator will modify the SOS of that species. Results from the two-species model illustrate this effect (Figure 4). If the harvest of the prey species is low (H_x = 0.015), the equilibrium biomass of the prey species increases with harvest of the predator H_y (blue line in Figure 4a). Harvest of the predator allows the prey to persist at lower biomass, so the biomass of the prey at the critical harvest rate (SOS = 0) is lower for high harvest rates of the predator (red line in Figure 4b). Thus, harvest of the predator facilitates the persistence of the prey by reducing the biomass level at which the critical threshold is crossed. The critical harvest level of the prey species is increased by harvesting the predator (Figure 4b), leading to the increase in the SOS seen in Figure 4. In general, harvest of the predator expands the SOS of the prey.

The value that fishers attach to fishing as a recreational activity also affects the SOS (Figure 3e,f). As the relative value of fishing increases, fishers spend more time fishing and the catchability must be lower to remain within the SOS (Figure 3e). If the relative value of fishing is very low, the catchability can be quite high and still the fishery remains within the SOS. In this scenario, the fishery is declining due to loss of participation by fishers. Near the SOS boundary, biomass is moderate, and it declines as the relative value of fishing or catchability increases (Figure 3f). However, biomass changes near the SOS boundary do not provide a strong signal that changes in catchability or relative value of fishing could destabilize the fishery.

4 | DISCUSSION

The SOS of inland recreational fisheries—the range of conditions that maintains fish biomass and potential harvest at relatively high levels—depends on multiple factors including habitat, predation, fishing effort and catchability. For graphical clarity, we plotted the SOS in two dimensions (Figure 3), as curves of the catchability vs. loss of habitat, increasing predation or increasing value of fishing (which increases effort). These curves illustrate compensatory interactions. To remain in the SOS, harvest must be adjusted downward as habitat loss, predation or fishing effort increase. Unlike the maximum sustainable yield which seeks a single optimum harvest level, the SOS is a region within which all combinations of harvest, habitat, predation and catchability are sustainable.

Fish biomass is moderate near the edge of the SOS and can remain so even after the SOS boundary has been crossed. Although biomass is declining at the SOS, the disappearance of the high-biomass alternate state may not be detectable from biomass measurements alone. Thus, biomass is a poor predictor of collapse because it may mask depensatory dynamics in juvenile production or changing ecological conditions. Because exploitation reduces adult biomass, collapse could occur through reduced survivorship of juveniles (i.e., depensation) (Ricker, 1963; Liermann & Hilborn, 1997), cultivation/depensation

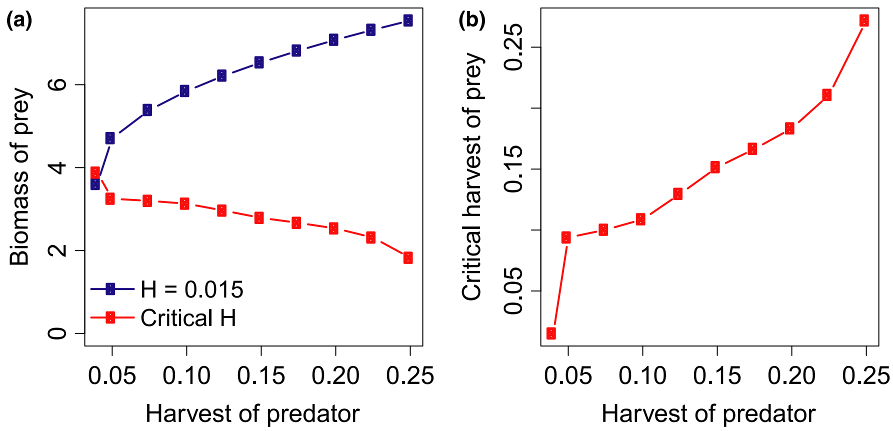

FIGURE 4 Outcomes when prey and predator are subject to harvest, computed with the two-species model. (a) Biomass of the prey species vs. harvest of predator (H_y, year^{-1}). The blue curve is biomass of the prey at a low harvest rate for prey (H_x = 0.015). The red curve is biomass of the prey at the critical value of H_x. As the harvest of the predator decreases, the biomass of the prey species at its critical harvest level approaches the biomass at the low harvest level. Thus, if the harvest of the predator is too low, even a small amount of harvesting of prey will cross the critical threshold and collapse the prey species. (b) The critical harvest (H_x, year^{-1}) of the prey species vs. harvest (H_y, year^{-1}) of the predator. The critical harvest proportion for the prey and therefore the Safe Operating Space for the prey increase as the harvest of the predator increases

effects (Walters & Kitchell, 2001) and/or unfavourable ecological conditions. Such abrupt changes in recreational fisheries have been observed by Post et al. (2002) and predicted by Ricker (1963) and Hansen et al. (2017).

Near the SOS boundary, small increases in catchability, relative value of fishing, habitat loss or predation could trigger an abrupt transition to a low-biomass state. Recreational fisheries may experience losses of habitat, increases in predation or changes in fishers' values that are beyond the control of local management and decrease the size of the SOS. In such cases, reductions in catchability (q) can increase the size of the SOS and maintain high-biomass fisheries in the face of global environmental change. This capacity has limits; extreme losses of habitat or increases in predation will cross the SOS boundary even if harvest is zero, and large reductions in harvest may cause fishers to exit the fishery. Additionally, in some cases, it may be possible to manage habitat or predation to increase the size of the SOS.

4.1 | Habitat

Fish habitat is influenced by climate, hydrology, riparian land use and other environmental factors. Climate change potentially affects fish populations through several mechanisms, and more than 30 case-studies of fish responses to climate change have already been documented in North America (Lynch et al., 2016). Many cool and coldwater fishes require specific oxygen and thermal conditions that are altered by warming or excess nutrient inputs (Fang et al., 2012; Hansen et al., 2017; Jacobson, Stefan, & Pereira, 2010). Structural habitat such as fallen trees and macrophyte beds may decline over time with significant adverse effects on fish stocks (Sass et al., 2006). In whole-lake experiments, removal of fallen trees led to major changes in the fish community, while addition of fallen trees caused more modest responses (Gaeta, Sass, & Carpenter, 2014; Sass, Carpenter, Gaeta, Kitchell, & Ahrenstorff, 2012; Sass et al., 2006). Suitable habitat is critical for fisheries resilience and the size of the SOS, but it is not clear that artificial habitat improvement projects can compensate for losses of natural habitat (Sass, Rypel, & Stafford, 2017).

4.2 | Stocking

Stocking may prevent the biomass from dropping to zero, but unless harvest is curtailed, predation reduced, or habitat improved, the fishery will remain outside of the SOS. Many recreational fisheries rely partially or fully on stocking to maintain fish biomass at acceptable levels. While stocking is often popular with the public, the efficacy of stocking as a long-term means to restoring fisheries is frequently unknown and sometimes questioned (Sass et al., 2017). On the other hand, if stocking increases the relative value of fishing, then stocking could be used as means of directing effort to sustain regional multisite fisheries (Mee et al., 2016). Stocking will continue to be used to maintain put-and-take fisheries, rehabilitate fisheries after mass mortality events, or in biomanipulations to improve water quality (Sass et al., 2017).

4.3 | Predation

Because many recreational fisheries are managed for multiple species (Hansen, Sass, et al., 2015), predator–prey interactions and competition among harvested species will likely influence the size of the SOS (Walters, Christensen, Martell, & Kitchell, 2005). Predators can substantially alter the behaviour, size-structure and density of prey species (Tonn, Paszkowski, & Holopainen, 1992), which may indirectly affect other predators. Predation upon a focal species reduces the size of the SOS for that species. Harvest of the predator releases predation pressure and increases the size of the SOS for the focal species. As such, increased harvest (and reduced biomass) of the predator allows greater SOS of the prey species. These outcomes are intuitive for the simple food chain considered here. In most situations, management of food web interactions is more complex (Kitchell, 1992; Walters & Martell, 2004). The response of the SOS for a particular species to food web management is an important topic for further research. Nonetheless, our analysis shows that reductions of harvest can compensate for effects of predation to some extent.

4.4 | Managing effort and harvest

In the context of this SOS model, recreational fisheries managers may seek to control harvest by indirectly altering catchability, the relative value of fishing vs. alternative activities or fisher expectations. Output controls such as length and bag limits are a common way of attempting to reduce harvest (Cook, Goeman, Radomski, Younk, & Jacobson, 2001; Isermann & Paukert, 2010) and can be sufficiently restrictive to actually reduce harvest on a per-fisher basis. Daily bag limits are often too liberal to effectively reduce harvest (Cook et al., 2001; Mosel, Isermann, & Hansen, 2015), and stricter regulations may be necessary to remain within the SOS. Length and bag limits do not provide direct control of fisher effort, but can influence site choice (Beard, Cox, & Carpenter, 2003; Cox & Walters, 2002; Johnston, Arlinghaus, Stelfox, & Post, 2011). Because of their influence on effort dynamics and noncompliance (Sullivan, 2002), several previous studies have suggested size and length limits may not be effective for improving fishing and conserving stocks at a regional scale (Post, Persson, Parkinson, & Kooten, 2008).

While direct controls on fishing effort (input controls) are commonly used in managing commercial or mixed fisheries in North America, they are rarely implemented for strictly recreational fisheries (Cox & Walters, 2002). Specifically, limited-entry approaches, where the number of fishers is controlled via a permit system, are rarely used for regulating harvest in recreational fisheries, but may be necessary to protect stocks or improve fishery quality, especially near urban centres (Post et al., 2008). Seasonal closures to fishing or harvest offer a hybrid control of sorts, by eliminating effort during defined temporal periods when q may be or is perceived to be relatively high. Alternatively, reserves or sanctuaries protected from fishing may influence the number of fish harvested by individual fishers (Holey et al., 1995; Sztramko, 1985). Regulation of angler effort also depends on whether the fishery is harvest-oriented or predominantly catch-and-release (Fayram, 2003; Gaeta, Beardmore, Latzka, Provencher, & Carpenter, 2013; Rypel et al., 2016). Harvest-oriented fisheries may require greater reductions in angler effort to remain within the SOS compared with catch-and-release fisheries.

Managers can alter non-harvest values of fishing by making fishing more or less attractive relative to fishers' other options. Boat ramps or shore-based fishing piers can be built or easements obtained to improve public access and thereby increase the enjoyment of fishing (*v*). Targeted advertising campaigns can be designed to increase interest in participation (Arlinghaus et al., 2015). In contrast, taxes can be placed on fishing supply and equipment purchases thereby decreasing the value of fishing (*v*). We suggest that decisions to alter fishing licence and permit fees be considered carefully, as declines in sales and participation have cascading effects on local and regional economies, especially where fishing represents an important source of tourism-based revenue (Ditton, Holland, & Anderson, 2002). Furthermore, declining participation in fishing and other outdoor activities has been a concern over the last decade (Arlinghaus, 2006; Dann, Alvarado, Palmer, Schroeder, & Stephens, 2008; Martin, Pracheil, DeBoer, Wilde, & Pope, 2012).

Fishers' expectations can be managed to influence effort. Changes in harvest regulations or stocking regimes can affect fisher expectations even before sufficient time has elapsed for these actions to have altered population status. Beard et al. (2003) showed that bag limits affected fisher effort for walleye in Wisconsin. Implementation of catch-and-release only regulations has resulted in reduced effort (Johnston et al., 2011; Haglund, Isermann, & Sass, 2016). Similarly, several previous studies noted changes in fisher effort that were attributed to changes in stocking rate (Askey, Parkinson, & Post, 2013) or multiple factors including stocking, regulation changes, and publicity (Johnson & Staggs, 1992).

4.5 | Implications for management and research

Although the SOS concept is built upon familiar elements of fisheries research and management, implementation of the SOS would require a shift in research and monitoring priorities. To date, most research and regulation address effects of single factors. The SOS involves interacting factors. New research is needed to understand systematically the interactive effects on fish stocks of harvest, habitat, predation, angler behaviour and other factors. As climate trends alter habitat and social trends alter angler activities, multifactor knowledge will be essential to maintain an SOS for inland recreational fisheries.

In addition, research should address potential thresholds for long-lasting declines in a fishery. Such thresholds may be evident in gradient studies that compare responses among large numbers of lakes (Hansen et al., 2017; Post et al., 2008). In lake-rich regions of the world, experimental management of relatively few lakes can be an effective tool for probing thresholds (Carpenter, 2003). By deliberately creating management regimes that vary among lakes across a landscape, managers can learn to adapt their practices to changing climate, social factors or other drivers of inland recreational fisheries (Hansen, Gaeta, et al., 2015).

Monitoring should be designed to determine how far the stock is from boundaries of the SOS. This assessment requires managers to identify thresholds of concern and appropriate indicators (Biggs, Ferreira, Ronaldson, & Grant-Biggs, 2011). For example, autumn recruitment surveys may be more effective than adult population estimates for assessing risk to natural reproduction of walleye (Hansen, Carpenter, et al., 2015). Theory and whole-ecosystem experiments are showing that distance to a threshold can be inferred from changes in statistical variability over space or time (Carpenter, Cole, et al., 2011, Cline et al., 2014; Pace et al., 2017). Monitoring programs could be reorganized to use these emerging tools.

The SOS concept has at least three practical applications. (i) Fisheries can be classified as inside or outside the SOS, and unsustainable fisheries that could be managed into the SOS can be identified. (ii) Appropriate management actions for maintaining the SOS, or restoring a fishery to its SOS, can be analysed. (iii) The SOS concept provides a framework for communicating and understanding the interactions of multiple factors that affect a fishery.

Challenges of managing the SOS for recreational fisheries include the complexities of managing an interconnected social–ecological system. The SOS depends on utility from harvest as well as non-harvest factors that increase enjoyment of fishing, consistent with studies of why people go fishing (Arlinghaus et al., 2013; Hunt, 2005). The non-harvest benefits of fishing can incentivize fishers to maintain relatively high effort even as fish biomass declines. Empirical studies show that fishers, especially the most highly skilled individuals, may continue to fish even when stocks and harvests are declining (Hunt, Arlinghaus, Lester, & Kushneriuk, 2011). This behaviour stabilizes catch rates even as stocks decline (hyperstability) and can lead to regional overfishing (Post, 2013). The SOS boundary provides a guardrail for management by including aspects of fisher behaviour that stabilize catch rates as biomass and catch decline.

The SOS concept can be extended to more complex situations, including multispecies food webs, landscapes with diverse aquatic habitats, or heterogeneous populations of fishers. Such work is needed to further evaluate the concept and apply it to a wide range of situations encountered in recreational fisheries management. The SOS concept highlights the core interactions and trade-offs among harvest, effort, habitat and predation that affect the potential for success of many inland recreational fisheries. These dimensions offer multiple options for maintaining the SOS, depending on which variables are amenable to management in a particular situation. These options complement emerging ideas about adapting recreational fisheries to trends in climate or land use that are beyond the control of local managers (Paukert et al., 2016). Moreover, the SOS concept is likely generalizable to other fields of renewable natural resource management, such as forest and wildlife management. Thus, in a time of great concern about global environmental change (Bain et al., 2016), the SOS concept provides a path, albeit it is a challenging one, for maintaining the resilience and sustainability of natural resources (Scheffer et al., 2015).

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REFERENCES

Arlinghaus, R. (2006). Understanding recreational angling participation in Germany: Preparing for demographic change. *Human Dimensions of Wildlife*, *11*, 229–240.

Arlinghaus, R., Cooke, S. J., & Potts, W. (2013). Towards resilient recreational fisheries on a global scale through improved understanding of fish and fisher behaviour. *Fisheries Management and Ecology*, *20*, 91–98.

Arlinghaus, R., Tillner, R., & Bork, M. (2015). Explaining participation rates in recreational fishing across industrialised countries. *Fisheries Management and Ecology*, *22*, 45–55.

Askey, P. J., Parkinson, E. A., & Post, J. R. (2013). Linking fish and angler dynamics to assess stocking strategies for hatchery-dependent, open-access recreational fisheries. *North American Journal of Fisheries Management*, *33*, 557–568.

Bain, P. G., Milfont, T. L., Kashima, Y., Bilewicz, M., Doron, G., Gararsdottir, R. B., … Saviolidis, N. M. (2016). Co-benefits of addressing climate change can motivate action around the world. *Nature Climate Change*, *6*, 154–157.

Beard, T. D., Arlinghaus, R., Cooke, S. J., McIntyre, P. B., De Silva, S., Bartley, D., & Cowx, I. G. (2011). Ecosystem approach to inland fisheries: Research needs and implementation strategies. *Biology Letters*, *7*, 481–483.

Beard, T. D., Cox, S. P., & Carpenter, S. R. (2003). Impacts of daily bag limit reductions on angler effort in Wisconsin Walleye Lakes. *North American Journal of Fisheries Management*, *23*, 1283–1293.

Biggs, H., Ferreira, S., Ronaldson, S. F., & Grant-Biggs, R. (2011). Taking stock after a decade: Does the 'thresholds of potential concern' concept need a socio-ecological revamp? *Koedoe*, *53*, 60–68.

Brock, W. A., & Carpenter, S. R. (2007). Panaceas and diversification of environmental policy. *Proceedings of the National Academy of Sciences of the United States of America*, *104*, 15206–15211.

Carpenter, S. R. (2003). *Regime shifts in lake ecosystems: Pattern and variation*. Oldendorf/Luhe, Germany: Ecology Institute.

Carpenter, S. R., & Brock, W. A. (2004). Spatial complexity, resilience and policy diversity: Fishing on lake-rich landscapes. *Ecology and Society*, *9*. Retrieved from http://www.ecologyandsociety.org/vol9/iss1/art8

Carpenter, S. R., Cole, J. J., Pace, M. L., Batt, R., Brock, W. A., Cline, T., … Weidel, B. (2011). Early warnings of regime shifts: A whole-ecosystem experiment. *Science*, *332*, 1079–1082.

Carpenter, S. R., Stanley, E. H., & Vander Zanden, M. J. (2011). State of the world's freshwater ecosystems: Physical, chemical, and biological changes. *Annual Review of Environment and Resources*, *36*, 75–99.

Cisneros-Montemayor, A. M., & Sumaila, U. R. (2010). A global estimate of benefits from ecosystem-based marine recreation: Potential impacts and implications for management. *Journal of Bioeconomics*, *12*, 245–268.

Cline, T. J., Seekell, D. A., Carpenter, S. R., Pace, M. L., Hodgson, J. R., Kitchell, J. F., & Weidel, B. C. (2014). Early warnings of regime shifts: Evaluation of spatial indicators from a whole-ecosystem experiment. *Ecosphere*, *5*, 1–13.

Coleman, F. C., Figueira, W. F., Ueland, J. S., & Crowder, L. B. (2004). The impact of United States recreational fisheries on marine fish populations. *Science*, *305*, 1958–1960.

Cook, M. F., Goeman, T. J., Radomski, P. J., Younk, J. A., & Jacobson, P. C. (2001). Creel limits in Minnesota: A proposal for change. *Fisheries*, *26*, 19–26.

Cox, S., & Walters, C. J. (2002). Maintaining quality in recreational fisheries: How success breeds failure in management of open-access sport fisheries. In T. J. Pitcher, & C. E. Hollingworth (Eds.), *Recreational fisheries: Ecological, economic, and social evaluation* (pp. 107–119). Oxford: Blackwell.

Dann, S.L., Alvarado, A., Palmer, D., Schroeder, B., & Stephens, M. (2008). *Angler participation, recruitment, and retention in Michigan, 1995–2004: Using data-mining techniques for customer-relations management*. Fisheries Research Report, Ann Arbor, MI, USA.

Dearing, J. A., Wang, R., Zhang, K., Dyke, J. G., Haberl, H., Hossain, M. S., … Poppy, G. M. (2014). Safe and just operating spaces for regional social-ecological systems. *Global Environmental Change*, *28*, 227–238.

Ditton, R. B., Holland, S. M., & Anderson, D. K. (2002). Recreational fishing as tourism. *Fisheries*, *27*, 17–24.

Fang, X., Jiang, L., Jacobson, P. C., Stefan, H. G., Alam, S. R., & Pereira, D. L. (2012). Identifying Cisco Refuge Lakes in Minnesota under future climate scenarios. *Transactions of the American Fisheries Society*, *141*, 1608–1621.

Fayram, A. H. (2003). A comparison of regulatory and voluntary release of muskellunge and walleyes in Northern Wisconsin. *North American Journal of Fisheries Management*, *23*, 619–624.

Fenichel, E. P., Abbott, J. K., & Huang, B. (2013). Modelling angler behaviour as a part of the management system: Synthesizing a multi-disciplinary literature. *Fish and Fisheries*, *14*, 137–157.

Gaeta, J. W., Beardmore, B., Latzka, A. W., Provencher, B., & Carpenter, S. R. (2013). Catch-and-release rates of sport fishes in Northern Wisconsin from an angler diary survey. *North American Journal of Fisheries Management*, *33*, 606–614.

Gaeta, J. W., Sass, G. G., & Carpenter, S. R. (2014). Drought-driven lake level decline: Effects on coarse woody habitat and fishes. *Canadian Journal of Fisheries and Aquatic Sciences*, *71*, 315–325.

Gale, R. P. (1987). Resource miracles and rising expectations: A challenge to fishery managers. *Fisheries*, *12*, 8–13.

Green, A. J., Alcorlo, P., Peeters, E. T. H. M., Morris, E. P., Espinar, L., Bravo-Utrera, A., … cheffer, M. (2017). Creating a safe operating space for wetlands in a changing climate. *Frontiers in Ecology and the Environment*, *15*, 99–107.

Haglund, J. M., Isermann, D. A., & Sass, G. G. (2016). Walleye Population and Fishery Responses after Elimination of Legal Harvest on Escanaba Lake, Wisconsin. *North American Journal of Fisheries Management*, *36*, 1315–1324.

Hansen, G. J. A., Carpenter, S. R., Gaeta, J. W., Hennessy, J. M., & Vander Zanden, M. J. (2015). Predicting walleye recruitment as a tool for prioritizing management actions. *Canadian Journal of Fisheries and Aquatic Sciences*, *72*, 661–672.

Hansen, G. J. A., Gaeta, J. W., Hansen, J. F., & Carpenter, S. R. (2015). Learning to manage and managing to learn: Sustaining freshwater recreational fisheries in a changing environment. *Fisheries*, *40*, 56–64.

Hansen, G. J. A., Read, J. S., Hansen, J. F., & Winslow, L. A. (2017). Projected shifts in fish species dominance in Wisconsin lakes under climate change. *Global Change Biology*, *23*, 1463–1476.

Hansen, J. F., Sass, G. G., Gaeta, J. W., Hansen, G. J. A., Isermann, D. A., Lyons, J., & Vander Zanden, M. J. (2015). Largemouth bass management in Wisconsin: Intraspecific and interspecific implications of abundance increases. *American Fisheries Society Symposium*, *82*, 193–206.

Häyhä, T., Lucas, P. L., van Vuuren, D. P., Cornell, S. E., & Hoff, H. (2016). From planetary boundaries to national fair shares of the global safe operating space—How can the scales be bridged? *Global Environmental Change*, *40*, 60–72.

Holey, M. E., Rybicki, R. W., Eck, G. W., Brown, E. H., Marsden, J. E., Lavis, D. S., … Horrall, R. M. (1995). Progress toward lake trout restoration in Lake Michigan. *Journal of Great Lakes Research*, *21*, 128–151.

Hunt, L. M. (2005). Recreational fishing site choice models: Insights and future opportunities. *Human Dimensions of Wildlife*, *10*, 153–172.

Hunt, L. M., Arlinghaus, R., Lester, N., & Kushneriuk, R. (2011). The effects of regional angling effort, angler behavior, and harvesting efficiency on landscape patterns of overfishing. *Ecological Applications*, *21*, 2555–2575.

Hunt, L. M., Fenichel, E. P., Fulton, D. C., Mendelsohn, R., Smith, J. W., Tunney, T. D., … Whitney, J. E. (2016). Identifying alternate pathways for climate change to impact inland recreational fishers. *Fisheries*, *41*, 362–372.

Isermann, D. A., & Paukert, C. P. (2010). Regulating harvest. In W. A. Hubert, & M. C. Quist (Eds.), *Inland fisheries management in North America* (3rd ed.; pp. 185–212). Bethesda, MD: American Fisheries Society.

Jacobson, P. C., Stefan, H. G., & Pereira, D. L. (2010). Coldwater fish oxythermal habitat in Minnesota lakes: Influence of total phosphorus, July air temperature, and relative depth. *Canadian Journal of Fisheries and Aquatic Sciences*, *67*, 2002–2013.

Johnson, B. M., & Staggs, M. D. (1992). The fishery. In J. F. Kitchell (Ed.), *Food web management: A case study of Lake Mendota* (pp. 353–375). New York, NY: Springer.

Johnston, F. D., Arlinghaus, R., Stelfox, J., & Post, J. R. (2011). Decline in angler use despite increased catch rates: Anglers' response to the implementation of a total catch-and-release regulation. *Fisheries Research*, *110*, 189–197.

Kitchell, J. F. (1992). *Food web management: A case study of Lake Mendota*. New York, NY: Springer.

Liermann, M., & Hilborn, R. (1997). Depensation in fish stocks: A hierarchic Bayesian meta-analysis. *Canadian Journal of Fisheries and Aquatic Sciences*, *54*, 1976–1984.

Ludwig, D., Brock, W. A., & Carpenter, S. R. (2005). Uncertainty in discount models and environmental accounting. *Ecology and Society*, *10*. Retrieved from http://www.ecologyandsociety.org/vol10/iss2/art13/

Lynch, A. J., Myers, B. J. E., Chu, C., Eby, L. A., Falke, J. A., Kovach, R. P., … Whitney, J. E. (2016). Climate change effects on North American inland fish populations and assemblages. *Fisheries*, *41*, 346–361.

Mace, P. M. (2001). A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management. *Fish and Fisheries*, *2*, 2–32.

Martin, D. R., Pracheil, B. M., DeBoer, J. A., Wilde, G. R., & Pope, K. L. (2012). Using the internet to understand angler behavior in the information age. *Fisheries*, *37*, 458–463.

May, R. M. (1977). Thresholds and breakpoints in ecosystems with a multiplicity of stable states. *Nature*, *269*, 471–477.

Mee, J. A., Post, J. R., Ward, H., Wilson, K. L., Newton, E., & Cantin, A. (2016). Interaction of ecological and angler processes: Experimental stocking in an open access, spatially structured fishery. *Ecological Applications*, *26*, 1693–1707.

Mosel, K. J., Isermann, D. A., & Hansen, J. F. (2015). Evaluation of daily creel and minimum length limits for black Crappie and yellow Perch in Wisconsin. *North American Journal of Fisheries Management*, *35*, 1–13.

Nychka, D., Furrer, R., Paige, J., & Sain, S. (2015). *fields: Tools for spatial data*. R package version 8.4-1 edn. Retrieved from http://www.image.ucar.edu/fields

Pace, M. L., Batt, R. D., Buelo, C. D., Carpenter, S. R., Cole, J. J., Kurtzweil, J. T., & Wilkinson, G. M. (2017). Reversal of a cyanobacterial bloom in response to early warnings. *Proceedings of the National Academy of Sciences of the United States of America*, *114*, 352–357.

Paukert, C. P., Glazer, B. A., Hansen, G. J. A., et al. (2016). Adapting inland fisheries management to a changing climate. *Fisheries*, *41*, 374–384.

Post, J. R. (2013). Resilient recreational fisheries or prone to collapse? A decade of research on the science and management of recreational fisheries. *Fisheries Management and Ecology*, *20*, 99–110.

Post, J. R., Persson, L., Parkinson, E. A., & Kooten, T. V. (2008). Angler numerical response across landscapes and the collapse of freshwater fisheries. *Ecological Applications*, *18*, 1038–1049.

Post, J. R., Sullivan, M., Cox, S., Lester, N. P., Walters, C. J., Parkinson, E. A., … Shuter, B. J. (2002). Canada's recreational fisheries: The invisible collapse? *Fisheries*, *27*, 6–17.

R Development Team (2012). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Ricker, W. E. (1963). Big effects from small causes: Two examples from fish population dynamics. *Journal of the Fisheries Research Board of Canada*, *20*, 257–264.

Rypel, A. L., Lyons, J., Griffin, J. D. T., & Simonson, T. D. (2016). Seventy-year retrospective on size-structure changes in the recreational fisheries of Wisconsin. *Fisheries*, *41*, 230–243.

Sass, G. G., Carpenter, S. R., Gaeta, J. W., Kitchell, J. F., & Ahrenstorff, T. D. (2012). Whole-lake addition of coarse woody habitat: Response of fish populations. *Aquatic Sciences*, *74*, 255–266.

Sass, G. G., Kitchell, J. F., Carpenter, S. R., Hrabik, T. R., Marburg, A. E., & Turner, M. G. (2006). Fish community and food web responses to a whole-lake removal of coarse woody habitat. *Fisheries*, *31*, 321–330.

Sass, G. G., Rypel, A. L., & Stafford, J. D. (2017). Inland fisheries habitat management: Lessons learned from wildlife ecology and a proposal for change. *Fisheries*, *42*, 197–209.

Scheffer, M., Barrett, S., Carpenter, S. R., Folke, C., Green, A. J., Holmgren, M., … Walker, B. (2015). Creating a safe operating space for iconic ecosystems. *Science*, *347*, 1317–1319.

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, *413*, 591–596.

Schindler, D. E., & Hilborn, R. (2015). Prediction, precaution, and policy under global change. *Science*, *347*, 953–954.

Schluter, M., McAllister, R. R. J., Arlinghaus, R., Bunnefeld, N., Eisenack, K., HÖLker, F., … StÖVen, M. (2012). New horizons for managing the environment: A review of coupled social-ecological systems modeling. *Natural Resource Modeling*, *25*, 219–272.

Soetart, K., & Herman, P. M. J. (2009). *A practical guide to ecological modelling using r as a simulation platform*. Berlin: Springer.

Steele, J. H., & Henderson, E. W. (1984). Modeling long-term fluctuations in fish stocks. *Science*, *224*, 985–987.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., … Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*, 736.

Stoeven, M. T. (2014). Enjoying catch and fishing effort: The effort effect in recreational fisheries. *Environmental and Resource Economics*, *57*, 393–404.

Sullivan, M. G. (2002). Illegal angling harvest of walleyes protected by length limits in Alberta. *North American Journal of Fisheries Management*, *22*, 1053–1063.

Sztramko, L. K. (1985). Effects of a sanctuary on the smallmouth bass fishery of Long Point Bay, Lake Erie. *North American Journal of Fisheries Management*, *5*, 233–241.

Tonn, W. M., Paszkowski, C. A., & Holopainen, I. J. (1992). Piscivory and recruitment: Mechanisms structuring prey populations in small lakes. *Ecology*, *73*, 951–958.

Tsehaye, I., Roth, B. M., & Sass, G. G. (2016). Exploring optimal walleye exploitation rates for northern Wisconsin Ceded Territory lakes using a hierarchical Bayesian age-structured model. *Canadian Journal of Fisheries and Aquatic Sciences*, *73*, 1413–1433.

U.S. Department of Interior, U. S. F. A. W. S., U.S. Department of Commerce, & U.S. Census Bureau (2011). *National survey of fishing, hunting, and wildlife-associated recreation*.

Walters, C. J., Christensen, V., Martell, S. J., & Kitchell, J. F. (2005). Possible ecosystem impacts of applying MSY policies from single-species assessment. *ICES Journal of Marine Science: Journal du Conseil*, *62*, 558–568.

Walters, C. J., & Kitchell, J. F. (2001). Cultivation/depensation effects on juvenile survival and recruitment: Implications for the theory of fishing. *Canadian Journal of Fisheries and Aquatic Sciences*, *58*, 39–50.
Walters, C. J., & Martell, S. J. D. (2004). *Fisheries ecology and management*. Princeton, NJ: Princeton University Press.
World Bank. (2012). *Hidden harvest: The global contribution of capture fisheries*. Report No. 66469-Washington, DC:GLB.

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