Interactions between species are often overlooked in natural resource management in order to simplify complex management problems. However, as human influences on ecosystems continue to grow, so does the need to move from single species management to ecosystem-based management. Ecosystem-based management takes a holistic approach to managing natural resources that includes the interactions of humans within social-ecological systems. Ecosystem-based management can be difficult to implement due to the complex nature of social-ecological systems, where ecosystem services and desired states are integrated within larger systems ranging across governance boundaries from local to international. Although ecosystem-based management implementation may be difficult, it is nevertheless warranted. Aquatic social-ecological systems, including fisheries, provide excellent examples to explore the difficulties of implementing ecosystem-based management. Counterintuitive responses by fish populations to management have shown that in many cases a linear, single-species focused view of these systems can lead managers to make decisions that, in hindsight, are ineffective or even detrimental to these systems (Walters et al. 2000; Hansen et al. 2015; Sass and Shaw 2020).

Consideration of the ecological interactions between species can help managers avoid detrimental, and often unexpected, outcomes (Pine et al. 2009). Instead, managers can leverage these interactions to creatively influence systems to meet their goals. In aquatic communities, species may be simultaneously in competition with each other and interacting with human use of the system. For example, human-induced climate change can result in altered ice cover regimes, thereby altering species interactions between Arctic char (*Salvelinus alpinus*) and brown trout (*Salmo trutta*), likely resulting in decreased Arctic char biomass and systems dominated by brown trout (Helland et al., 2011). Overfishing has interacted with climate change and interspecific interactions to cause dramatic shifts in dominant species on coastal ecosystems around the world (Jackson et al. 2001). As these interactions are unexpected in light of traditional, single-species management, a central theme of these incorrect predictions was the failure to consider interactions between multiple species and life stages (Walters et al. 2000).

These complex intra- and inter-specific interactions in aquatic systems can result in positive feedback loops that allow a stable state to reinforce itself such that efforts by managers to change the stable state may have no or unintended effects. Walters and Kitchell (2001) described how positive feedback loops can create two stable states in a food web consisting of a top predator and a forage species through cultivation-depensation effects. Under low exploitation, the top predator species is abundant and able to cultivate conditions to increase survival of its juveniles by preying on the predators of its juveniles, namely the forage species. Alternatively, the forage species may dominate when exploitation of the top predator is high (as is the case in many fisheries), allowing the forage species to cultivate conditions for itself through predation on juveniles of the top predator. When top predator abundance declines enough, recruitment of new juveniles may be compromised through density-independent elevated mortality rates (in contrast to the commonly assumed density-dependent compensatory recruitment and elevated survivorship) (Liermann and Hilborn 1997; 2001; Carpenter 2003; Hilborn et al. 2014; Sass et al. ?). If the forage species has established itself as the dominant species, simply increasing the survival of adult predators (even through fishery closure) may have no effect, or possibly a negative effect if the associated increase in juvenile production further increases foraging opportunities for the forage species and leads to further increases in their biomass with the increased prey availability. Regime shifts driven by overfishing are one example of the persistence of these new stable states where fish populations are unable to recover even when the fishery is closed for decades (Hutchings 2000).

In fisheries, it is common to focus applied research on a single focal species, even when this species is embedded in a larger community where harvest of multiple species takes place (Hansen et al. 2015). The tradeoffs between competing management goals for several co-occurring species are often not considered; however, some notable exceptions do exist (Essington et al. 2015, Oken et al. 2016, others?). Essington et al. (2015) used competing objectives for a predator fishery (Atlantic cod, *Gadus morhua*) and a forage species fishery (Atlantic herring, *Clupea harengus*) to show how ecological interactions between the two and the market price of each species can be combined to determine the appropriate level of mortality for each species given specific management goals (maximizing combined profit of both species at equilibrium). In contrast to commercial fisheries where users aim to maximize profit, recreational fishery users vary along multiple axes of species preference, catch rate, fish size, location, valuation, utility, avidity, and harvest opportunity (e.g., Johnston et al., 2010; Beardmore et al., 2015; Arlinghaus et al., 2017). Users place differing levels of importance on each of these aspects of the fishing experience, leading to divergent, and in some cases, competing, desires by fishery users and ultimately complex management problems. Given the limited ways in which managers can influence recreational fisheries (i.e., fishing regulations, stocking, habitat alteration, valuation), understanding and leveraging ecological interactions allows managers to make the most of the limited tools at their disposal to keep systems within a safe operating space and to meet the diverse goals of users in the system (Carpenter et al. 2017).

Here we use an example of a recreational fishery with two managed species to explore how managers can leverage ecological interactions between species achieve their goals. All models make necessary simplifying assumptions to balance tractability with realism. We use a relatively simple fishery model that allows for the interaction and harvest of two species which is itself an improvement of many of the single species models used to date. While here we evaluate the complexity in a two-species system, these concepts are important to assess at increasing levels of biological complexity. We use this two species model to explore how ecological interactions, combined with human intervention can result in unexpected fisheries outcomes, including alterations to the stable state of the system. Our hypothesis that inter-specific interactions play an important role in determining the appropriate management action leads us to predict that consideration of non-linear dynamics arising from inter-specific interaction leads to more positive and predictable outcomes for managers. Outcomes that are of specific interest here include economic benefits, high angler satisfaction, and a stable state in which the desired species dominates.

**Model Experiments**

In our modeling experimental, species 1 is considered a strongly harvest-oriented species. Species 2 represents a less harvest-oriented species. Species 1 is highly valued over species 2 by anglers, because of this, the management goal here to promote dominance of species 1 over species 2. We focused on four different model experiments that reflect scenarios that are likely commonly encountered by fisheries managers. First, we sought to understand how the fishery in this model functioned over a range of harvest levels (both species 1 and 2). The aim of this simulation was to understand species dynamics and the stable states that are present in our simulated fishery system. Second, we sought to compare the impact of active management of only one species (species 1) *versus* both species (species 1 and 2), and the resultant impact on species dynamics, with a particular interest on managing the system for dominance of species 1. Our third model experiment focused on the interactive effects of management on both species in the system. Here, we sought to understand the impact of different management levers for different species, and the resultant outcomes in terms of dominant species. Finally, we explored the impacts of slow changes in habitat availability and the resultant impacts on stable states. Within this model experiment, we sought to understand how management action can prevent changes in stable states caused by changes in habitat availability. Different modeling runs used slightly different parameterizations for harvest, stocking, and habitat availability (Appendix/Supplement). Species interaction parameters, mortality, survival, and fecundity are all held constant across simulations (Appendix/Supplement). Model simulations were performed in R using RStudio and the deSolve package (Soetaert et al. 2010, R Core Team 2020, RStudio Team 2020).