Title

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**Keywords**

**Statement of Significance**

**Abstract**

# Introduction

Interactions between species are often not heavily considered in natural resource management in order to simplify complex management problems (Walters and Martell 2004, Baum and Worm 2009). This simplification may lead managers to make decisions that in hindsight, were ineffective or even detrimental (Walters et al. 2000; Springer et al. 2003; Myers et al. 2007; Hansen et al. 2015; Sass and Shaw 2020). For example, Barents Sea capelin (*Mallotus villosus*) stocks have crashed due to interacting effects of overfishing and predation by Atlantic herring (*Clupea harengus*), and subsequent predation of Atlantic herring by Atlantic cod (*Gadus morhua*) delayed the stock’s recovery (Hjermann et al. 2004). These unexpected outcomes, and similar outcomes around the world occurred at least in part because managers failed to consider interactions between multiple species and life stages (Walters et al. 2000; Jackson et al. 2001; Hansen et al. 2017; Embke et al. 2019; Hutchings 2000). Although difficult, ecosystem-based management, which uses a holistic approach to manage natural resources that includes accounting for inter-specific interactions and human decision making, can help managers avoid unexpected, and often undesirable, outcomes (Pine et al. 2009).

The most undesirable scenario for a manager whose single-species focused intervention has led to an unexpected response is that this action pushes the system to an undesirable alternative stable state. Regime shifts like this are well documented in aquatic systems and exceedingly difficult to reverse once they’ve occurred (Carpenter and Kinne 2003). Regime shifts represent an abrupt change in ecosystem configuration that can be self-reinforcing (Carpenter, 2003). 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 due to cultivation effects could create two alternative stable states in a “trophic triangle” food web consisting of the adult and juvenile stages of a top predator and a forage species. Further, De Roos and Persson (2002) describe how size- and food-dependent individual growth can result in depensatory population growth, also known as ‘Allee Effects’. Under low exploitation, the top predator 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. Depensatory growth effects on the predator population further limit its ability to rebound and become abundant again.

In addition to interactions with non-targeted species as in the simple trophic triangle described above, harvested populations are often 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 exploited species in recreational fisheries are often not considered; however, some notable exceptions do exist in commercial fisheries (e.g., Essington et al. 2015, Oken et al. 2016). Essington et al. (2015) used competing objectives for a predator fishery (Atlantic cod, *Gadus morhua*) and a forage species fishery (Atlantic herring, *Clupea harengus*) and showed how ecological interactions between the two and the market price of each species could be combined to determine the appropriate level of mortality for each species given specific management goals (maximizing combined profit of both species at equilibrium). Although understanding interspecific interactions may reduce unexpected outcomes in fisheries management decisions and avoid catastrophic regime shifts, they can also be leveraged by managers to creatively achieve their goals.

Recreational fisheries are model systems where managers could take advantage of interspecific interactions to solve complex problems through an ecosystem-based or adaptive management approach. Inland recreational fisheries specifically are well suited to this because of their well-defined boundaries and widespread occurrence across the landscape allowing for replication and comparison (Walters 1986). Adaptive management using experimental management actions across many independent systems could allow managers to generate new knowledge about how to creatively manage these systems, however, this is not always feasible. Management goals, in systems that exhibit multiple stable states, are primarily to maintain fisheries in the ‘desired’ stable state, or the state in which the species most desired by anglers dominates the system. While these desired stable states exist within a broader safe operating space, certain management interventions can result in shifts into ‘undesired’ states – or states outside that safe operating space. Managers are limited in the ways in which they can influence recreational fisheries (i.e., fishing regulations, stocking, habitat alteration, valuation), yet fisheries users have diverse goals. Given their complexity, understanding and leveraging ecological interactions may allow 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 recreational fishery users in the system (Carpenter et al. 2017).

Here, we use a model of a recreational fishery with two managed species to explore whether managers can leverage ecological, inter-specific interactions to achieve desired outcomes. The hypothetical manager’s motivation in our model experiments is to promote stable states where the desired species dominates, resulting in higher economic benefits and user satisfaction. Our model, like all models, makes 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 an improvement over many of the single species models used to date. We hypothesize that management activities taking species interactions into account will be more successful at keeping a system in a safe operating space. Managers can take advantage of this interactions to creatively influence system dynamics to reach their goals. As such, we predict that consideration of these inter-specific interactions and the resulting non-linear dynamics will lead to more positive, predictable, and desired outcomes. We use modeling experiments to understand the impact of simultaneous management of two species in a recreational fishery, the increased diversity of management options when accounting for species interactions, and the impacts of slow change on the stable state of the system.

# Methods

To explore the implications and opportunities of a systems-based approach to managing regime shifts in recreational fisheries, we have adopted a modeling approach. Given the long time scales over which management decisions and fisheries dynamics play out, alternative avenues of inference, like long-term observations, comparative surveys, or experiments, are not feasible. Our modeling framework allows us to conduct a series of model experiments to explore the risks of not considering interactions amongst species, including harvest of multiple species, and potential opportunities afforded by an ecosystem-based management approach. For example, we use our model to explore management outcomes for scenarios where the hypothetical manager either ignores or accounts for the interspecific interactions. Our theoretical model was developed with interactions between walleye (*Sander vitreus*) and largemouth bass (*Micropterus salmoides*) in mind, but we’ve adopted a general model parameterization that should apply to many interacting, harvested species.

## *Model*

For our model experiments, we adapted a stage-structured food web model previously been used to explore alternative stable states in lake ecosystems (Carpenter and Brock 2005, Roth et al. 2007; Carpenter et al. 2008, Biggs et al. 2009). The original model used the classic trophic triangle structure that included interactions between a harvest-oriented sport fish with juvenile and adult stages, and a single-stage planktivorous fish not subjected to harvest. We modified this model to include two stage-structured fish populations that are simultaneously harvested. Our model contains basic foraging arena dynamics where juvenile sportfish move between the foraging arena and refuge (Walters and Martell 2004). In our model, adult sportfish can prey upon their own juveniles and juveniles of the competing sportfish species when they are in the foraging arena. The survival and fecundity of the two species are identical while the competition coefficients are not. Juveniles of both species have equal effects on each other while adults have asymmetrical effects on the juveniles of the opposite species (Table 1). Unless noted, all parameters are constant through time.

### *Adult Dynamics*

Eq. 1

Eq. 2

Adults are produced through the maturation of juveniles at a constant rate or . Adults undergo natural mortality, and , and are harvested at rate and . Harvest rate can be either constant or time-dependent in our model.

### *Juvenile Dynamics*

Eq. 3

Eq. 4

Juveniles are produced through Ricker stock-recruitment relationships (Ricker, 1975). Additionally, stocking of juveniles can be imposed through and . Juveniles are removed from the population in one of three ways. The strength of each mortality source is represented by the parameter which can be thought of in general terms as the ‘effect’ of one species/life stage on another. First, juvenile mortality can occur through cannibalism, for example (read this as ‘the effect of on ’), which is dependent on refuge dynamics. Second, juveniles can be removed through predation by adults of the opposite species . These dynamics are dependent on refuge and are controlled by two rates, the rate at which juveniles leave refuge and enter the foraging arena, and the rate at which they leave the forage arena and enter refuge. It is important to note however that the influence of refuge availability on juvenile mortality is still debated in some systems (Zeigler et al. 2018). Last, juvenile mortality is imposed through direct competition with juveniles of the opposite species either through competition for resources or direct predation. This competition occurs independent of refuge dynamics such that all juveniles compete in all areas. We assumed that juveniles of both species occupy the same refuge and same foraging arena. The three processes described above account for all juvenile mortality in our model. All juveniles not claimed by the three sources of mortality then mature to adults at some proportion ().

Table 1. Model parameterization

|  |  |  |
| --- | --- | --- |
| Term | Definitions+ | Value/Range |
|  | survival, species 1 juvenile | 0.1 |
|  | natural mortality, species 1 adult | 0.5 |
|  | cannibalism, species 1 | 0.001 |
|  | predation by species 2 on species 1 | 0.5 |
|  | juvenile competition | 0.003 |
|  | rate at which species 1 juveniles enter FA\* | 1 |
|  | rate at which species 1 juveniles leave FA |  |
|  | stocking, species 1 | 0-2000 |
|  | harvest rate, species 1 | 0-8 |
|  | survival, species 2 juvenile | 0.1 |
|  | natural mortality, species 2 adult | 0.5 |
|  | cannibalism, species 2 | 0.001 |
|  | predation by species 1 on species 2 | 0.3 |
|  | juvenile competition | 0.003 |
|  | rate at which species 2 juveniles enter FA | 1 |
|  | rate at which species 2 juveniles leave FA |  |
|  | stocking, species 2 | 0-2000 |
|  | harvest rate, species 2 | 0-8 |

\*foraging arena

+Units are listed in parentheses where applicable

## *Model Experiments*

Recreational fisheries are complex systems where human influences and ecological interactions feedback on each other to make management of any species difficult. A key challenge facing many managers is how to maintain or improve abundances of highly-valued and exploited species in the face of competition with other less valued and exploited species. Our modeling experiments are designed to mimic this situation. Species 1 in our models represents the dominant, highly-valued and highly exploited species that managers are seeking to maintain, while species 2 represents a less valued, and less exploited species. When managing the focal species (species 1) alone managers have control over harvest limits and stocking rates. When managing both species together managers have control over harvest limits and stocking rates for both species. Given the hypothetical goals of managers in our simulations, managing species 2 will always take the form of setting harvest limits and not stocking.

We focused on three different model experiments that reflect scenarios that are likely commonly encountered by fisheries managers. Although not an experiment, we 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 (Fig. 1). In our first experiment, we sought to understand the implications of active management of only one species (species 1) *versus* both species (species 1 and 2), on the size of the safe operating space of the system (Fig. 2). In this model experiment, we sought to explore the impacts of leveraging ecological interactions to achieve a manager’s goals. Our second model experiment focused on the diversity of management options available to managers when accounting for interspecific interactions (Fig. 3). Here, we sought to understand the different paths managers may take to the same outcome through managing one or both species. We then discuss how some of these paths may be more feasible or cost-effective for managers. Finally, we explored the influences of slow changes in adult fecundity and the resultant influences on stable states (Fig. 4). Within our model experiments, we take a safe-operating space approach where managers use the tools at their disposal, including leveraging species interactions, to keep a system in the desired stable state despite slow moving changes outside their control (Carpenter et al. 2017). Different modeling runs used slightly different parameterizations for harvest, stocking, and fecundity (Appendix/Supplement). Species interaction strengths, mortality, survival, and habitat availability were held constant across simulations (Table 1). A sensitivity analysis found alternative stable states persisted across different values for species interaction strengths, mortality, survival, and fecundity with a few exceptions for extreme parameter values (Figs S5-13). The model was most sensitive to changes in the juveniles competition effects on each other, and Ricker stock-recruitment parameters (Figs S9,10,12,13**)**. Model simulations were performed in R using RStudio and the deSolve package (Soetaert et al. 2010, R Core Team 2020, RStudio Team 2020).

# Results

Model exhibits alternative stable states in this two species fishery. Initial species abundances and species harvest determine which stable state the model goes to (Fig. 1). These alternative stable states persisted across all but the most extreme values for species interaction strengths, mortality, survival, and fecundity though the harvest values at which the system flipped varied with variation in parameter values (Figs S5-13). Across the range of harvest rates when run to equilibrium, the model outcomes differed depending on the initial system state, demonstrating alternative stable states (Fig. 1). For example, a moderate harvest of species 1 resulted in scenarios where species 1 dominates over species 2 or vice versa depending on initial system state. In general, in scenarios in which species 2 initially dominates, increasing harvest on species 1 results in a stable state in which species 2 remains dominant. However, when reversing this scenario (initial system dominated by species 1), increasing harvest on species 1 results in the eventual transition to an alternate stable state in which species 2 dominates. Harvesting in the model decreases the target species’ abundance and eventually leads to regime shifts (Fig. S1).



Figure 1. Model exhibits alternative stable states. The model is run to equilibrium over a range of harvest rates for species 1, species 2 harvest is held constant at 2. Top panel shows equilibrium abundances for the range of harvests when species 1 is initially dominant. Bottom panel represents outcomes when species 2 is initially dominant.

Managing both species simultaneously produced different outcomes than single species management in our first model experiment. In this experiment, species 1 began as the dominant species, the areas above the isoclines describe stocking and harvest reductions which could be used separately or in combination, at different magnitudes, to maintain species 1 dominance. As harvest increased, stocking was required to maintain the stable state and retain dominance; higher harvest resulted in greater stocking need. The counterintuitive response to stocking that has been well documented in previous work (Pine et al. 2009, Lorenzen 2014), occurred in our simulations as well. When managing only species 1, stocking species 1 can result in regime shifts when the number of fish stocked was too low (Fig 2 and S3). This occurred under all species 1 harvest levels except the very lowest (Fig 2). However, when the manager considers the interaction between species, the options expand from stocking and harvest regulations for species 1 to stocking and harvest regulations for both species, doubling the number of options available to the manager. When species 1 is established as the dominant species and a small amount of fishing mortality is applied on species 2, the system can maintain species 1 dominance under all but the most intense harvest scenarios on species 1 with no stocking necessary. Allowing increased harvest on species 2, in combination with a small amount of species 1 stocking, was able to overcome extreme harvest effects on species 1 allowing it to dominate across any harvest rate (Fig. 2). In other words, accounting for the ecological interactions between species allowed the manager to use harvest of species 2 to increase the number of species 1 management options that would maintain its dominance. These analyses were also conducted in a model scenario where the undesirable species (species 2) was initially dominant and the management goal was to flip the system to favor species 1 (Fig. S3). The dynamics in that scenario mirror those presented in figure 2, but because of the initial dominance of species 2, the magnitude of management action (stocking or harvest) needed to flip the system towards species 1 is higher to account for initial dominance of species 2.



Figure 2. Isoclines here separate different outcomes for two management approaches. Species 1 dominates in areas above line. Areas below the isoclines represent outcomes where species 2 dominates. In this model experiment, species 1 is initially dominant and the management goal is to maintain this dominance. Solid line separates outcomes when the manager considers species interactions, while the dashed line separates outcomes where the manager only manages species 1.

Investigation of the interactive effects of management on both species revealed that species 1 dominance can be maintained through diverse management actions when accounting for interspecific interactions. Consideration of species interactions allowed managers to combine direct management action (i.e. stocking) with indirect action (i.e. managing a competitor); these strategies can be implemented singly or in combination to achieve the same outcome (Figure 3). The trade-off between stocking and harvest of the competitor is consistent across different levels of harvest on the desired species; only the magnitude of management action necessary changes. At low levels of species 2 harvest, more stocking is required to maintain the stable state of the system in which species 1 remains dominant. Managers can decrease stocking effort by encouraging harvest of species 2 in order to maintain the stable state of a system. These dynamics were also explored for a scenario where the manager aimed to flip the system from species 2 dominated toward species 1 (Fig. S4). Because of the initial dominance of species 2 in that scenario, the magnitude of management action (stocking or harvest) needed to flip the system towards species 1 is higher to account for initial dominance of species 2.



Figure 3. Stocking of species 1 and harvest of species 2 can, on their own, result in maintaining the desired stable state of a system (species 1 dominance). Tradeoff between stocking and competitor harvest are presented for various levels of harvest on species 1 (solid and dashed lines). Areas above/to the right of the lines represent positive outcomes (species 1 dominance), areas below/to the left represent regime shifts to species 2. The negative relationship between stocking species 1 and harvesting species 2 allows managers to achieve similar outcomes through implementation of either strategy or a combination of both.

Finally, a scenario was explored where slow moving changes in some system variable outside a mangers control may drive an eventual flip in stable state from species 1 to species 2. For the purposes of this experiment we describe a hypothetical change in adult fecundity for species 1. Recruitment declines have been observed in fisheries for a wide array of reasons (Walters and Martell 2004, Lynch et al. 2016). Similar slow moving changes in juvenile refuge availability, though in some cases managers may be able to control this variable, or angler preferences may also drive regime shifts. Investigation of slow change towards a tipping point in the system revealed the effectiveness of management intervention for the prevention of shifts to alternate stable states. Management action can delay an inevitable transition through either harvesting species 2 (Fig. 4b) or stocking species 1 (Fig. 4c). In combination, managing both species (through stocking of species 1 and harvest of species 2) may be able to prevent a regime shift altogether (Fig. 4d). Our model results show that with a combination of strategies, species 1 population can decrease without a compensatory increase in species 2, thereby effectively maintaining conditions for species 1 even under slow change scenarios. Management action here was limited to what might be feasible given time and budget constraints for most managers.

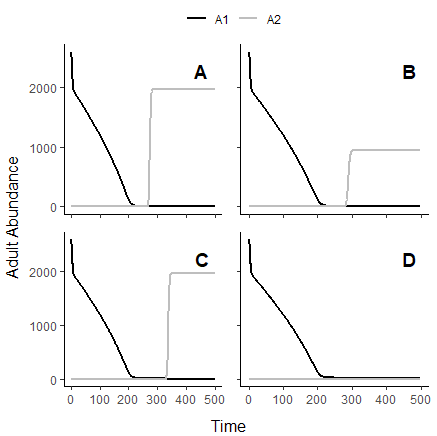


Figure 4. Delaying transitions. Slow declines in recruitment represents a factor outside a manager’s control which will inevitably flip system from sp1 dominated to sp2 (panel A). The flip in system state can be delayed through either harvest of species 2 (panel B), or stocking of the desired species (panel C), or perhaps prevented altogether by stocking and harvesting (panel D).

# Discussion

Sudden, unexpected regime shifts represent a growing threat to aquatic systems as human influences on these systems grow and erode system resilience (De Roos and Persson 2002, Carpenter and Kinne 2003, Persson et al. 2007). We demonstrate how management interventions can be used to maintain stable states of a system through careful consideration of human influences and species interactions within the system. Where a single species management approach is infeasible or unable to achieve the desired stable state, our relatively simple model of a multi-species recreational fishery demonstrates how understanding the ecological interactions between species can allow a manager to creatively manage a system to reach desired outcomes. Although species interactions have long been known to exert influence on a system, here we show how direct management can use those interactions in order to influence fishery outcomes. Although our model is a simplification of a complex system, it demonstrates the need to incorporate our understanding of the ecology of aquatic ecosystems into a holistic view of managing these important resources. In practice, this is difficult to do as interactions within aquatic communities and our understanding of them continue to change, however, integration of species interactions is a step in the right direction towards a more holistic view of inland fishery systems.

Traditionally, fisheries have been managed through a single species lens (Hjerman et al. 2004, Walters et al. 2005, Carpenter et al. 2017), however, this does not always result in positive outcomes. Our results, and the research of others, demonstrates why positive feedback loops which are unaccounted for, often produce unexpected outcomes in the eyes of decision makers (Tonn et al. 1992, Pine et al. 2009). In our model, the key feedback loop is through juvenile competition and predation by adults. When maintaining the abundance of species 1, the manager’s ultimate goal is to maintain or increase the number of maturing to adulthood. This can be done directly through stocking, but because of density –dependent mortality due to limited predation refuge or prey availability, simply adding more individuals is often insufficient. Furthermore, the costs associated with stocking often limit how many individuals can be added to any one system. Our model demonstrates how stocking can be rendered ineffective when a portion of the stocked fish will feed species 2, promoting their abundance increase and beginning a feedback loop where their own juveniles, , grow more abundant (Fig 4). Thus, the magnitude of stocking that is necessary to maintain the system is greatly increased when it is used in isolation, which may also not be feasible given the expense of stocking and density-dependent mortality associated with stocking more fish (Fig. 2). Alternatively, if fishing mortality is increased on species 2, with or without stocking, survival increases as predation pressure is alleviated, allowing to maintain dominance (Figs. 2 &3). An understanding of how ecological interactions create positive feedback loops (e.g., Pine et al., 2009) that result in stable ecosystem states can allow managers to make decisions that leverage these feedback loops to increase the probability of maintaining the desired stable state.

Managers are limited by political, monetary, mechanical, and technological constraints when confronting complex management problems. Most commonly, fishery managers turn to one of four different tools for preventing or mitigating the negative influences of humans on the system; (1) stocking (e.g., Cowx, 1994), (2) harvest regulation (e.g., length and bag limits; Post et al., 2003), (3) habitat modification (Jennings et al., 1999, Sass et al. 2017), and (4) fishery closure (either temporary or permanent). Although each of these management interventions has a history of success in certain circumstances, management responses in complex systems (beyond single species) is not always straightforward. Often, these actions produce no response or a counterintuitive response when interactions between species are not acknowledged (Fig. 2). For example, stocking of lake trout (Salvelinus namaycush) in Lake Granby, Colorado resulted in declines in Kokanee salmon (Oncorhynchus nerka) and other meso-predator populations (Johnson and Martinez, 1995). However, by investigating feedbacks in species interactions, we provide a strategy for using those tools already available in innovative ways to produce positive fishery outcomes. Not only must a manager consider direct and indirect management, but timing of management interventions and lags in implementation can also influence the outcome of action (Biggs et al. 2009, Martin et al. 2020).

Consideration of alternative management strategies, such as leveraging ecological interactions, can aid managers in reinforcing the desired stable state of a system. Although the limited set of options available to managers may be ineffective or even detrimental when implemented without consideration of species interactions, these interactions can be leveraged to create more avenues for maintenance of a stable state. For example, stocking has the potential to be ineffective at maintaining the stable state of a system (Figure 4b). Here, we highlight how ecological interactions can be a reason why stocking is not effective at times. Our model shows that lower cost options, such as harvest controls of the target species, or through management of a competitor species can often be more effective than stocking in producing favorable outcomes (Figures 2 & 3). Although there are other drivers that influence the effectiveness of stocking in a system (e.g., habitat loss, climate change, genetics; Lorenzen, 2014; Hansen et al., 2015; Ziegler et al. 2017; Tingley et al. 2020), our research emphasizes the critical need to integrate species interactions into management scenarios. Of course the idea of taking advantage of ecological interactions to manage a system is not entirely new; indeed, invasive species management has long included introducing ‘biocontrol’ agents into the system in an effort to reduce invasive species abundance (Messing and Wright, 2006). A key distinction we make between our multispecies fishery and invasive species management that here we suggest using existing ecological interactions between the species already present, as opposed to the introduction of a novel agent.

Certain drivers of regime shifts in ecosystems may be outside a manager’s control, such as slow moving changes in recruitment as a result of climate change (Hansen et al. 2017). Increasing consideration of these drivers has resulted in the emergence of a safe operating space theory, increasing the call for adapting management to respond to ecological variables and complexity in the system (Carpenter et al., 2017, Hansen et al. 2019). Although safe operating space management allows for management of complexity, we highlight maintaining such a space through consideration of non-linear management strategies. Tradeoffs are likely to arise between directly managing a species or indirectly managing that species through its competitor; however, a better understanding of those interactions is likely to increase our predictive ability when proposing alternative management options. Incorporation of the feedbacks and complexity contained within inter-specific ecological interactions can provide managers with a new dimension they can use to maintain the safe operating space of their system, even in the face of other slow change variables.

Our two-species model, although relatively simple, illustrates the need to incorporate ecological interactions in fisheries management within complex fishery systems. Human influences on ecosystems will continue to increase (Sih et al., 2011), and understanding species interactions can help to creatively manage these systems given the constraints on what managers can feasibly do. Although our model adds a layer of complexity not usually considered in most fisheries management models, we understand that there is still significant complexity inherent in these systems that is not simulated here. Further exploration of this complexity will allow the integration of multiple ecological and social interactions into fisheries management, as well as provide managers with the tools necessary to sustainably manage fisheries in the most cost- and time-effective ways possible. Future research incorporating the cultivation-depensation effects of species interactions can provide empirical evidence supporting the importance of considering ecological interactions in managing complex systems. Increasing complexity of these models to include energetics may also reveal the consequences of alternative stable states on the life histories of the dominant and non-dominant species. Another layer of complexity to consider is the social component of fisheries. We model a 2-species recreational fishery, 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. For example, anglers may choose to voluntarily catch and release certain species. When managers try to promote harvest of said species, through liberalized bag and length limits, anglers may simply choose to continue releasing their catch, rendering this management strategy ineffective. Management goals are often focused on maintaining a system in a ‘desired’ stable state, however, what is ‘desired’ is determined by human desires and may conflict with overall sustainability of the resource. An understanding of how ecological interactions (specifically through cultivation-depensation mechanisms) will respond to changing harvest pressure can reveal how managers may respond to changing demands from stakeholders in their system. Ultimately, sustainability of the resource in the long-term should trump human desires. Considering and leveraging species interactions may be able to achieve both goals and allow for adaptation to changing human desires.

Integration of ecological dynamics into ecosystem-based management of freshwater fisheries can increase a manager’s ability to maintain systems in a desired stable state, reduce the likelihood of unexpected or undesirable outcomes, while using standard interventions, reducing overall costs, and sustaining the resource. Experimental reductions in competitor abundance coupled with various stocking regimes is one example of how our modeling results can be used to design an adaptive management experiment that generates new knowledge about how to creatively manage a fishery. Furthermore, our existing understanding of ecological interactions can and should be incorporated into the management of aquatic systems to help solve complex problems now. Adaptive management experiments could allow managers to update our understanding of ecological interactions to effectively account for them in managing these systems. Again, in practice adaptive management is difficult to implement and often fails, however, the causes of these failures are well studied and provide a way forward towards success (Walter et al. 2007, Allen and Gunderson 2011). The wide breadth of knowledge accumulated can play an integral role in building resilient fisheries. By taking a more ecosystem-oriented view of management, outcomes can be improved and areas can be identified for further exploration when actions produce unexpected outcomes.