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12/19/2020

# Introduction

Interactions between species are often not 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 herring (*Clupea harengus*), but subsequent predation of herring by cod (*Gadus morhua*) delayed the stocks 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,

The worst-case scenario for a manager whose single-species focused intervention has led to an unexpected response is that this action leads to a switch to an undesirable alternative stable state of the system. Regime shifts, as they are often referred to, are well documented in aquatic systems and exceedingly difficult to reverse once they’ve occurred (**citations**). They represent a shift in ecosystem configuration that is self-reinforcing (**citations**). 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 can 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. 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.

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 are often not considered; however, some notable exceptions do exist in commercial systems (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). While understanding interspecific interactions can reduce unexpected outcomes in fisheries management and avoid catastrophic regime shifts, they can also be leveraged by managers to creatively achieve their goals.

Recreational fisheries are another system where managers could take advantage of interspecific interactions to solve complex problems. 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 dominate 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 users in the system (Carpenter et al. 2017).

Here, we use a model of a recreational fishery with two managed species to explore how managers can leverage ecological interactions between species to achieve their goals. 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. Our hypothesis that management activities that take species interactions into account are more successful at keeping a system in a safe operating space leads us to predict that consideration of these interactions and the resulting non-linear dynamics can lead to more positive, predictable, and potentially cost-effective 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 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 that has previously been used to explore alternative stable states in lake ecosystems (Carpenter and Brock 2005, Carpenter et al. 2008, Biggs et al. 2009). The original model used the classic trophic triangle structure that included interactions between a harvested 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. The model contains basic foraging arena dynamics where juvenile sportfish move between the foraging arena and refuge. 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** ref). 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 density-dependent recruitment based on Ricker stock-recruitment relationships. Additionally, stocking of juveniles can be imposed through and . Juveniles are removed from the population by 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. Juvenile mortality occurs through cannibalism (read this as ‘the effect of on ’), which is dependent on refuge dynamics. Second, juveniles undergo mortality 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). Changes in the amount of refuge available to fish are simulated through changes in the parameter, which determines how many juveniles are in the foraging arena. The last juvenile mortality source is 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 the system. All juveniles not claimed by the three sources of mortality above then mature to adults. These fish then survive at some proportion to join the adult population ().

Table 1. Model parameterization

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

\*foraging arena



## Model Experiments

Recreational fisheries are complex systems where human impacts and ecological interactions feedback on each other to make management of any one species difficult. A key challenge facing many managers is how to maintain or improve abundances of certain 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. While not an experiment, 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. 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.. In this model experiment, we sought to understand 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. 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 juvenile refuge availability and the resultant influences on stable states. Within this model experiment, 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. Different modeling runs used slightly different parameterizations for harvest, stocking, and habitat availability (Appendix/Supplement). Species interaction strengths, mortality, survival, and fecundity were 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).

# Results

Across the range of harvest rates when run to equilibrium, the model outcomes differed depending on the initial system state, ing). 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 results in a stable state in which species 2 remains dominant, however, reversing this scenario resulted (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 (**Supplement** fig). In the absence of harvest on either species, declines in refuge availability cause declines in abundance, but the initially dominant species is able to maintain dominance because both species juveniles are equally effected by loss of refuge (**supplement fig**).



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 drastically different outcomes than single species management in our first model experiment comparing outcomes in a single species *versus* two-species management scenario. In scenarios in which 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 species1 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), 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 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 achieve desired outcomes. In this scenario in which both species are managed (Figure 2), the manager can regulate harvest on both species and stocks species 1 in order to allow species 1 to dominate over species 2. When species 1 is established as the dominant species and a small amount of fishing mortality is applied on species 2, the system is able to 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 and allow for species 1 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. 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 to 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. 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 the desired stable state 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). 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.



Figure 3. Stocking of species 1 and harvest of species 2 can both, 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 juvenile refuge availability that are outside a manager’s control can drive an eventual flip in system state from species 1 to species 2. Investigation of slow change towards tipping points in a 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 stocking species 1 (Fig. 4b) or harvesting species 2 (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. Other work has explored the importance of timing in management intervention and lags in implementation once a decision has been made on the outcome of the action (Biggs et al. 2009, Martin et al. 2020).



Figure 4. Delaying transitions. Slow moving variable ’h’ represents changing juvenile refuge availability which will inevitably flip system from sp1 dominated to sp2 (panel A). The flip in system state can be delayed through either stocking of the desired species (panel B), harvest of its competitor (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. 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 reach those outcomes, 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. While 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.

Traditionally, fisheries have been managed through a single species lens (Hjerman et al. 2004, Walters et al. 2005, Carpenter et al. 2017). Our results, and the work 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, adding more juveniles such that more survive to adulthood. Our model demonstrates how this may be less effective than expected because 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 to stocking that is necessary to maintain the system is greatly increased when it is used in isolation (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 that result in stable ecosystem states can allow managers to make decisions that leverage these feedback loops to create the desired stable state.

Understanding the possible outcomes of systems that exhibit this non-linearity can result in more efficient management while utilizing those management tools that have been proven to be effective in single species management. 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), and (4) fishery closure (either temporary or permanent). Although each of these management interventions has a history of success in certain circumstances, management response in systems with increased complexity (beyond single species) is not always straightforward. Often, these actions produce no response or a counterintuitive response when we don’t think about interactions between species (Fig. 2). For example, stocking of lake trout in Lake Granby, Colorado resulted in declines in kokanee and other mesopredator 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.

Consideration of alternative management strategies, such as leveraging ecological interactions, can aid managers in reinforcement of the desired stable state of a system. Although the limited set of options available to managers are often 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 in particular 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). While there are other drivers that influence the effectiveness of stocking in a system (e.g., habitat loss, climate change; Hansen et al., 2015; Ziegler et al.,2017), this work emphasizes the need to integrate species interactions into management scenarios.

Increasing consideration of variability and slow change that is outside a managers control in a system 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). While 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, increasing our understanding of those interactions in likely to increase our predictive ability when proposing alternative management options.

Our two-species model, while relatively simple, illustrates the need to incorporate ecological interactions in fisheries management within complex fishery systems. Human influences on ecosystems will continue to increase, and understanding species interactions can help us creatively manage these systems given the constraints on what managers can feasibly do. While 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 modeled here. The 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 way possible. Future work 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 can also reveal the consequences of alternative stable states on the life history of both the dominant and non-dominant species. Another layer of complexity to consider is the social component of fisheries. Management goals, ultimately, are focused on maintaining a system in a ‘desired’ stable state, however, what is ‘desired’ is determined by human desires. An understanding of how ecological interactions (specifically through cultivation-depensation mechanisms) will respond to changing harvest pressure can reveal how managers can respond to changing demands from stakeholders in their system.

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.

Integration of ecological dynamics into adaptive management of freshwater fisheries can increase managers’ ability to maintain systems in a desired stable state, reducing the likelihood of unexpected or undesirable outcomes, while using standard interventions and reducing overall costs. Experimental reductions in competitor abundance coupled with various stocking regimes is one example of how the knowledge here 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. The wide breadth of knowledge we do have can play an integral role in building resilient fisheries. By taking a more ecosystem-oriented view of management, we can improve outcomes and identify areas for further exploration when our actions produce unexpected outcomes.