Reworking intro for q2 a little

Topic sentences for q2 draft

Interactions between species are often overlooked in natural resource management for simplification.

Several examples of the causes and effects of ineffective management action on fisheries were reviewed in Pine et al. (2009).

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.

The non-linearity that can arise when dealing with inter-specific interactions, as demonstrated by cultivation-depensation theory, can lead to counterintuitive outcomes and pose a problem for managers who are often limited in the options available to them (Carpenter et al. 2017).

To date, much of the research addressing stable states and ecosystem-based management has focused on the management of a single species.

Here, we use an example of a recreational fishery with two harvested species to explore how limited management levers and a linear, single species system view can lead to counterintuitive responses by fish populations to management intervention.

New topic sentences

Interactions between species are often overlooked in natural resource management in order to simplify complex management problems.

~~A failure to consider ecological interactions has led managers to implement strategies that have produced unexpected, and in some cases detrimental, results (Pine et al. 2009).~~ **~~– flip this and talk about how if we do understand this, we can use it to our advantage.~~**

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.

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.

Where consideration of ecological interactions has occurred, researchers and managers alike have typically considered only one managed species interacting with other non-managed species. **– reword this so it doesn’t feel like a circle back to ecosystem management.**

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.

Interactions between species are often overlooked in natural resource management in order to simplify complex management problems. However, as human influences on ecosystem continue to grow, so does the need to move from single species management to ecosystem-cased 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 states of interest 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). A central theme of these incorrect predictions was a 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 the ecological interactions between the two and the market price of each species 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. 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 multiple levels of biological complexity. 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.