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Potentials and Limitations of Stock Enhancement in Marine Recreational Fisheries Systems: An Integrative Review of Florida's Red Drum Enhancement

EDWARD V. CAMP,[1] KAI LORENZEN,[1] ROBERT N. M. AHRENS,[1]
LUIZ BARBIERI,[2] and KENNETH M. LEBER[3]

[1]Fisheries and Aquatic Sciences Program, School of Forest Resources and Conservation, University of Florida, Gainesville, Florida, USA
[2]Fish and Wildlife Research Institute, Florida Fish and Wildlife Conservation Commission, St. Petersburg, Florida, USA
[3]Mote Marine Laboratory, Sarasota, Florida, USA

In this study, an integrative review of the potential for stock enhancement is conducted to support desirable management outcomes in marine recreational fisheries, focusing on the Florida, USA, red drum fishery as a case study. Here, stock enhancement is implicitly seen as a way of simultaneously achieving both ecological objectives of sustained wild fish populations and socioeconomic objectives of high fishing effort and/or catch rates. However, the review suggests that a fundamental tradeoff remains between these objectives in the short-term because stocking of hatchery fish is likely to result in at least partial displacement of wild fish through biological interactions as well as increased fishing pressure. Contrary to the perception of enhancement as a "quick fix," successful use of the approach in the marine recreational fishery is likely to require sophisticated stock management and some adaptation in governance. In developing the enhancement, it will be necessary to address uncertainty in key attributes, specifically dynamics of recruitment, angler-effort responses, and stakeholder involvement. This may be achieved by combining quantitative modeling, monitoring, and stocking experiments in an active adaptive management framework to consider enhancement in the context of alternative management strategies. It is suggested that any interim enhancement should minimize ecological risk per socioeconomic benefit by stocking larger fish in areas where high fishing mortality limits abundance of wild fish. These conclusions are largely generalizable to other recreational enhancements, and this work serves as a model of rarely published a priori enhancement evaluation.

Keywords stocking, management, synthesis, angling, *S. occelatus*

INTRODUCTION

Besides control of fishing mortality and habitat protection or restoration, aquaculture-based enhancement is a third principal means by which fisheries can be sustained and improved (Lorenzen et al., 2010). Aquaculture-based fisheries enhancement is a set of management approaches involving the release of cultured organisms to enhance, conserve, or restore fisheries. This definition covers a great diversity of enhancement fisheries systems, including "sea ranching," "stock enhancement," and "restocking" (Bell et al., 2008). Aquaculture-based enhancements can, at least in principle, generate a range of benefits, including increasing stock abundance and fishery yield or catch opportunities, as well as aiding the conservation and restoration of depleted, threatened, and endangered populations (Lorenzen et al., 2012). This may give rise to economic and social benefits, including new opportunities for fisheries-related livelihoods or

Address correspondence to Edward V. Camp, Fisheries and Aquatic Sciences Program, School of Forest Resources and Conservation, University of Florida, P.O. Box 110600, Gainesville, FL 32611, USA. E-mail: edvcamp@ufl.edu

recreation, and may also provide incentives for active management and better governance of common pool fisheries resources (Pinkerton, 1994; Arbuckle, 2000; Lorenzen, 2008). However, many enhancements have failed to deliver significant increases in yield or economic benefits and/or have had deleterious effects on the naturally recruited components of the target stocks (Hilborn, 1998; Arnason, 2001). Much work on marine enhancements has focused on commercial fisheries, but the approach is also—and increasingly—used in recreational fisheries.

Recreational fisheries are compositionally and dynamically complex and present management challenges worldwide. Constituting an important and sometimes dominant use of fresh and coastal fisheries resources in many countries (Cowx, 2002; Arlinghaus and Mehner, 2006), recreational fisheries provide social welfare (e.g., supply subsistence or satisfaction benefits) and support economies (largely resulting from expenditures anglers incur while fishing) (Weithman, 1999; Cowx et al., 2010). Recreational fisheries can also produce unsustainable fishing levels or even lead to population collapse (Post et al., 2002; Figueira and Coleman, 2010) through direct (e.g., overharvest) and indirect pathways (e.g., habitat alteration from fishing gear) (Cooke and Cowx, 2006; Lewin et al., 2006). The magnitude of these effects is driven largely by fishing effort, which can be especially high in recreational fisheries. Relationships between recreational fishing effort and fish populations are often more variable than those in commercial fisheries, partially due to heterogeneity in how recreational fishers attain satisfaction or utility (e.g., harvesting fish, high catch rates, catching trophy fish, enjoyment of natural surroundings, etc.; Hunt et al., 2005; Arlinghaus, 2006; Johnston et al., 2010). Heterogeneity in utility attainment leads to multiple "typologies" of recreational anglers (Johnston et al., 2010) and complicates predicting recreational fishing effort, its impacts, and fisher satisfaction. Recreational fisheries assessments and management must account for this and other (e.g., multi-species targeting, spatial, etc.) complexities.

Despite this complexity, recreational fisheries management can be characterized by two primary objectives—(1) maximize socioeconomic benefit from fishing and (2) sustain populations and ecosystems at desired levels or states (Cowx et al., 2010; Koehn, 2010). While such objectives are mutually obligate over the long run (Hilborn, 2007), they often conflict in shorter time spans (Koehn, 2010; Garcia-Asorey et al., 2011; van Poorten et al., 2011). Stock enhancement is often seen and promoted in recreational fisheries as a way of mitigating such conflicts in objectives by sustaining fish populations even under very high fishing pressure (Halverson, 2008; van Poorten et al., 2011).

Enhancement of recreational fisheries, defined as releasing hatchery-raised fish to augment existing wild populations (Lorenzen, 2005; Lorenzen et al., 2012), can impact both socioeconomic and ecological systems, producing complex, feedback-driven processes and occasionally unintended outcomes (Lorenzen, 2008). Thus, predicting outcomes of enhanced recreational systems requires integrated assessment. Integrated frameworks have been developed to first understand (generally commercial) enhancements in terms of attribute groups (e.g., biological, market, stakeholder, etc.) and then by relating these attributes to overall system outcomes (Blankenship and Leber, 1995; Molony et al., 2003; Taylor et al., 2005; Lorenzen, 2008, Lorenzen et al., 2010). Despite the widespread use of enhancement and repeated calls for case-specific evaluation, there are few examples of integrated assessments of enhancement programs (Taylor et al., 2005), especially for recreational fisheries.

CASE STUDY: RED DRUM ENHANCEMENT IN FLORIDA

This article provides a first integrative assessment of the role of enhancement in the current and potential future management of a marine recreational fishery: the Florida red drum (*Sciaenops ocellatus*) fishery. The potential enhancement of Florida's red drum fishery exemplifies a complex recreational enhancement system and is useful as a case study. Red drum is one of the most desired species of Florida's marine recreational fisheries, but this recreational fishing imparts substantial mortality on the species (Murphy and Munyandorero, 2009). Most importantly, recreational fishing effort has been increasing over the past decades and is expected to continue to rise. This creates a challenge of maintaining stakeholder-supported management goals for red drum populations while meeting implicit management goals of sustaining the great socioeconomic utility realized by their exploitation. Stock enhancement is seen by stakeholders as a potential avenue for achieving these goals, which are in conflict in an entirely capture-based fishery (Lorenzen, 2005). Stock enhancement in Florida enjoys support from many fishing stakeholders, but so far, the efforts have been primarily small scale and research focused. A larger-scale marine enhancement initiative is currently being pursued by a public–private partnership in Florida. Against this background, the objective of this work was to synthesize information critical for integrated assessment of enhanced recreational fisheries through use of a case study: the potential enhancement of Florida's red drum fishery.

ANALYTICAL FRAMEWORK

Undertaking a broad-based, integrative review of the role or potential role of enhancement in the fisheries system is an important first step in the recently updated responsible approach to fisheries enhancement (Blankenship and Leber, 1995; Lorenzen et al., 2010). To structure this review and analysis, a broad framework is used for analyzing enhancement fishery systems as described in Lorenzen (2008). The framework sets out how situational variables (attributes of the resource: fishing, aquaculture production, habitat and environment, stakeholders, markets and governance arrangements) influence outcomes of enhancement initiatives through physical–biological pathways and through those mediated by stakeholder action (Figure 1). Criteria that may be used to evaluate outcomes include biological production,

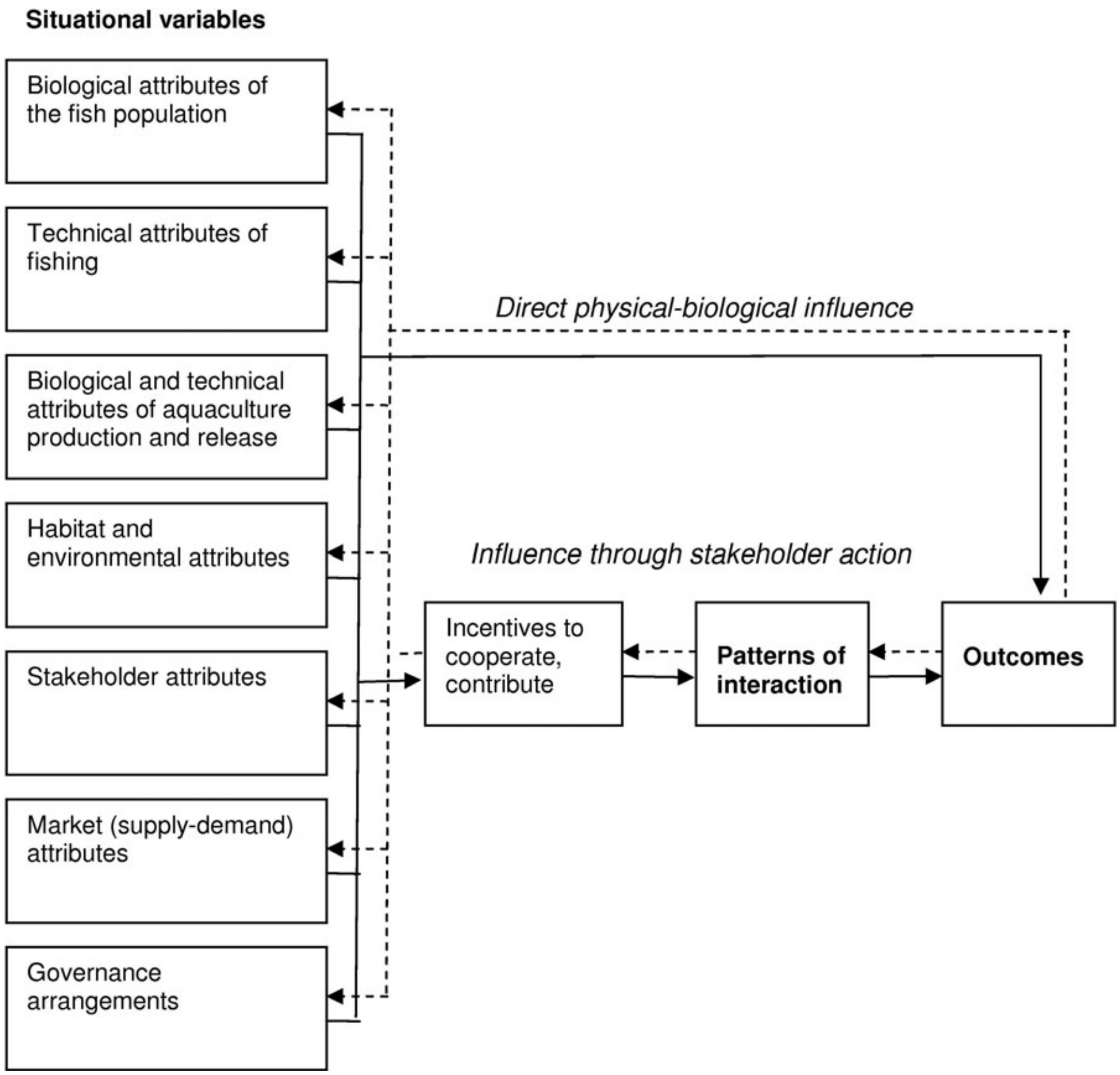

Figure 1 Framework for analyzing enhancement fisheries systems used in this study. Operational interactions between elements are shown as solid lines and determine outcomes in the short term when the situational variables are fixed. In dynamic interactions, shown as dashed lines, situational variables are modified in response to the outcomes of operational interactions (from Lorenzen, 2008).

resource conservation, economic benefits and costs, contribution to livelihoods, and institutional sustainability. While not a fully specified model, the framework provides an aid for thinking through the logic of the fisheries systems and exploring options for its development. This is done in three steps: (1) establishing current outcomes and future scenarios with desired outcomes, (2) reviewing the situational variables that may impinge current and future outcomes in order to reveal the most important drivers of outcomes, and (3) exploring the dynamics of the most important drivers and the uncertainties associated with them further in order to derive management and research recommendations. Current outcomes were assessed by reviewing pertinent literature to describe red drum population status in Florida, their socioeconomic value, and how stock enhancement of red drum has been used in Florida and nearby areas. This synthesis was used to explore attribute values necessary to produce desired outcomes of red drum enhancement. From these key attribute elements, knowledge gaps and uncertainties were deduced. Finally, the way in which management of red drum enhancement should move forward is suggested—first describing potential methods for reducing uncertainty in the key attributes determining system outcomes and then proposing interim recommendations for enhancement in the absence of this uncertainty reduction.

OUTCOMES AND SCENARIOS

Current Outcomes

Population Status

Florida's red drum stock is considered sustainably fished, i.e., it is not considered overfished or subjected to overfishing

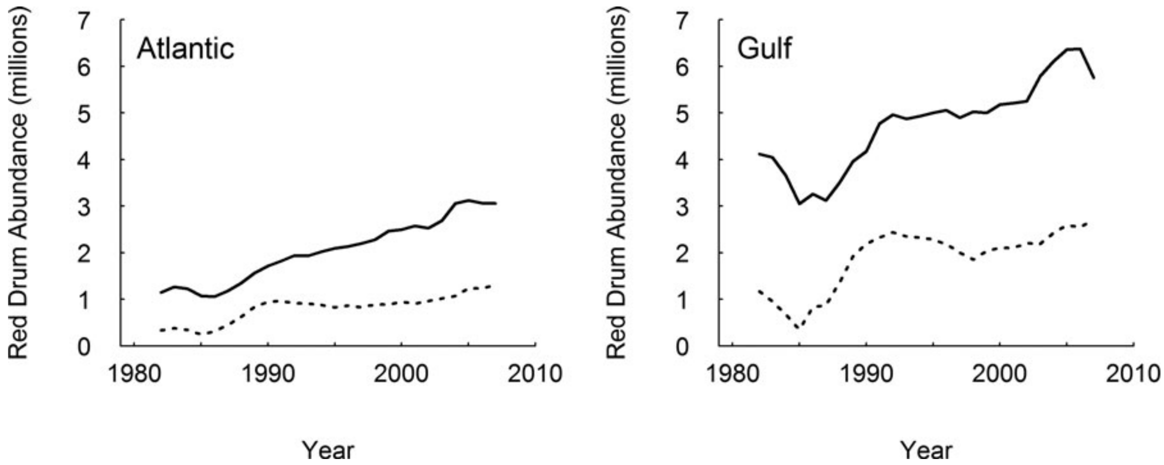

Figure 2 Red drum abundance estimated from the most recent stock assessment (Murphy and Munyandorero, 2009) for all ages (solid) and most catchable fish, ages 1–4, (dashed) for the Atlantic (A) and Gulf coasts (B).

according to the most recent stock assessment (Murphy and Munyandorero, 2009). Since 1986, when commercial sale of native red drum was outlawed, estimated numbers of sub-adults (ages 1–4 that are typically targeted by the fishery) have increased to current levels of 2.7 million on the Gulf coast and 1.3 million on the Atlantic coast (Figure 2). This abundance meets the management goal of 40% escapement, though some regions are above or below this number (Murphy and Munyandorero, 2009). In this fishery, escapement (defined as the proportion of estimated number of age-5 fish currently to estimated number of age-5 fish in unfished conditions) was used as a proxy for the more traditional biological reference point, spawning potential ratio (SPR), due to a dearth of information about spawning adults (Murphy and Munyandorero, 2009).

Socioeconomic Outcomes

Red drum are important to Florida's recreational marine fishery (Murphy and Crabtree, 2001), which is a substantial market with a direct (e.g., license sales) and indirect (e.g., transportation costs) value of $6 billion (American Sportfishing Association [ASA], 2001). The economic contribution specific to red drum is difficult to assess (Murphy and Munyandorero, 2009), as red drum are generally targeted as part of a multi-species inshore fishery. However, targeted red drum effort has markedly increased since 1999 on both Gulf and Atlantic coasts (Figure 3; Murphy and Munyandorero, 2009), and this is assumed to result in a proportional increase in economic value. Relative changes in angler satisfaction are unstudied; however, satisfaction is often directly related to catch rates (Ditton and Fedler, 1989; Cox et al., 2003; Arlinghaus, 2006), which have increased over the last decades (Figure 3; Murphy and Munyandorero, 2009).

Role of Enhancement

Red drum stocking has occurred on a large production scale elsewhere in the southeastern United States (e.g., millions released per year in Texas), but in Florida enhancement has been

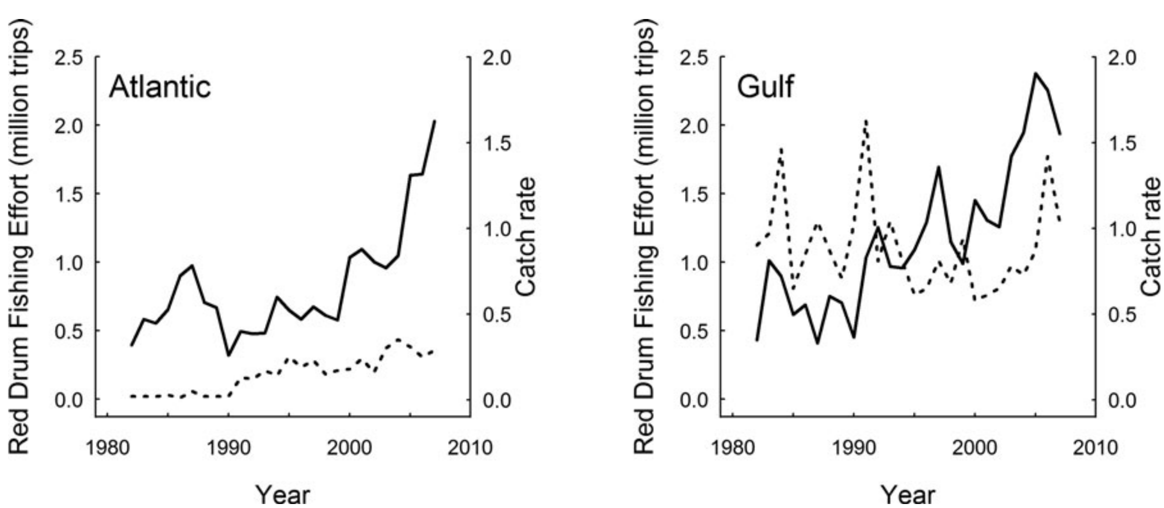

Figure 3 Estimated red drum targeted effort (solid) and catch rate (dashed), where catch rate is estimated catch per estimated fishing trip for the Atlantic coast (A) and Gulf coast (B), from the most recent stock assessment (Murphy and Munyandorero, 2009).

generally smaller-scale and often research-oriented. Research-oriented stockings are often smaller scale by design; however, understanding why enhancement in Florida has not progressed to larger-scale production is insightful. Enhancement has been discouraged partly by a perception that stocked red drum experience acute mortality from the stocking event (Serafy et al., 1999; Sherwood et al., 2004) and very low survival thereafter (Tringali et al., 2008b). This perception largely originated from a very poor survival of a past enhancement in Biscayne Bay, Florida, where post-larval red drum were stocked on a large scale (millions) into what was later determined to be quite poor post-larval habitat (Tringali et al., 2008b). Concerns that stocking might not be effective may not have been allayed by recent research-oriented enhancement in Tampa Bay, Florida, which suggested survival of stocked red drum in certain areas to be similar to that of wild fish (Tringali et al., 2008b). However, large-scale red drum stocking has persisted elsewhere (e.g., Texas) despite likely low survival of stocked fish (Scharf, 2000). Alternatively, lack of production level enhancement in Florida may be superficially due to a current lack of production-level hatching and rearing facilities. This, however, would suggest ultimately a lack of stakeholder motivation to advance production level enhancement. It is possible that stakeholders are satisfied with the observed increase in wild red drum abundance over the last 20 years, as well as the abundance of alternative species targeted by recreational anglers (Sutton and Ditton, 2005).

Future Scenario, Desired Outcomes, and Management Options

Scenarios

The most recent stock assessment for red drum suggests future scenarios for ecological outcomes likely include declining red drum populations. Increases in recreational fishing effort for red drum are projected to lead to increases in total mortality of 20% over a five-year period (i.e., 4%/year for 2007–2012) on the Atlantic coast and approximately 50% (i.e., 10%/year for 2007–2012) on the Gulf coast, according to the last stock assessment (Murphy and Munyandorero, 2009).

Ecological Outcomes

These increases in total kill were expected to lead to declines in escapement on the Atlantic coast to roughly 40% but to approximately 22% on the Gulf coast (i.e., below the 40% escapement management goal; Murphy and Munyandorero, 2009). While effort may not have increased as sharply as predicted due to a national economic downturn, the prediction that future red drum escapement will likely fall below the management threshold is valid. The desired future outcome is that wild Florida red drum populations remain above the 40% escapement threshold, which is anticipated to meet fundamental conservation objectives as well as promote long-term sustainable socioeconomic value. The distinction of wild fish is noteworthy because wild fish are expected to maintain maximal fitness and genetic diversity (Lorenzen et al., 2012).

Socioeconomic Outcomes

While the ecological and socioeconomic objectives of Florida's red drum fishery appear well-met currently, they may not be in the future. Increasing effort may outstrip the stock's potential or lead to local depletions. This might reduce catch rates (and thus angler satisfaction) if effort is stable and independent of fish abundance/catch rates, or it could decrease effort if effort is related to abundance or catch rates. If effort is weakly related to catch rates, both might decrease following declining red drum populations. Regardless, decreased effort or catch rates would result in decreased socioeconomic value. Conversely, the desired socioeconomic outcomes are to maintain or increase both economic effects and social satisfaction.

Options and the Role of Enhancement

Enhancement of red drum in Florida is seen as a potential way to maintain or increase socioeconomic value of the red drum fishery without harming wild populations. This may be accomplished in three ways: (1) stocking increases catch rates when effort is stable, (2) stocking maintains stable catch rates when effort is increasing due to external drivers (e.g., human population growth), or (3) stocking motivates initially greater catch rates and ultimately increased effort. In all cases, socioeconomic value of the fishery would increase as a result of stocking increasing total red drum abundance. In order for this increase in economic value to be sustainable, the increase in value must exceed the costs associated with the enhancement program increasing fish abundance.

Alternatively, enhancements may support positive changes in socioeconomic outcomes even when a direct impact of stocking on red drum abundance or fishing effort is not discernible if stakeholders either believe fishing quality is improved or value stocking as a form of active resource stewardship.

Enhancement is not the only option by which the projected pressures could be handled. Others include (1) switching to a catch-and-release fishery and (2) restricting access to the fishery. Reducing or eliminating harvest, i.e., making the fishery predominantly or exclusively catch-and-release, allows maintaining fishing mortality and escapement in the face of increasing effort. This approach is limited in scope by the fact that even released fish suffer increased mortality (discard mortality—i.e., mortality of released fish due to capture-related injuries), but nonetheless, a change toward catch and release could absorb some level of effort increase. Such a change could be mandated in regulations but could and often is made voluntarily by anglers, for example, in the Florida bass (freshwater) and snook (inshore costal) fisheries. Restricting access to the fishery, in theory, is the most effective way of limiting fishing mortality and it could be done at different levels to maintain a desired escapement level while allowing or not allowing some level of harvest.

ATTRIBUTES OF THE ENHANCEMENT FISHERY SYSTEM AND THEIR ROLE IN DETERMINING CURRENT AND FUTURE OUTCOMES

Biological Attributes

Several biological attributes of red drum are important in influencing fisheries and enhancement outcomes: basic life history and ontogenetic shifts in habitat use (which influence vulnerability of life stages to fishing and to habitat degradation and inform release strategies for hatchery-reared juveniles) and the strength and ontogenetic pattern of compensatory density dependence (which influences the extent to which stocking can raise abundance and its impacts on the wild population component). Red drum are a large (maximum weight $\sim$30 kg), long-lived (maximum age 40–60 years) marine fish of the southwest Atlantic and Gulf of Mexico that, as adults, occupy near and offshore areas. As juveniles and sub-adults (ages 0–5), red drum loosely associate year-round with structural habitat (e.g., sea grass beds, oyster bars) in estuaries and inshore areas where they grow rapidly to large size ($\sim$5–8 kg), feeding on small fish, shrimp, and invertebrates. These inshore areas are where recruitment dynamics take place, which are critical to all enhanced system outcomes. Red drum probably exhibit strong compensation and populations are relatively abundant (Murphy and Munyandorero, 2009). For enhancement to potentially augment wild populations, stocking must occur either after highly compensatory survival stages or when abundances are low enough for potential gains in total recruitment (Lorenzen, 2005). However, Florida red drum compensation with age/length has not been well characterized. In Texas, Scharf (2000) found compensation was substantial through the end of the first year. Alternatively, Bacheler et al. (2008) suggested that, in North Carolina, year-class strength was set shortly after larval settlement. Stewart and Scharf (2008) similarly suggested that red drum recruitment in South Carolina was set shortly after settlement in the first year, although some unexplained variation suggested later compensatory processes might also occur. The spatial scale of density-dependent processes also influences enhancement outcomes—locally defined, low recruitment areas hold potential to avoid competition between wild and stocked fish. Studies from Texas and North and South Carolina suggest that recruitment probably varies on somewhat local (10s–100s km) scales (Bacheler et al., 2008; Stewart and Scharf, 2008), though it may be even estuary specific (Scharf, 2000). Locally defined recruitment likely translates into local populations of (catchable) sub-adults. Studies suggest sub-adult red drum exhibit high site fidelity (Reyier et al., 2011) and move little outside of their nursery estuary (Adams and Tremain, 2000; Rooker et al., 2010), though they are capable of large-scale (100s of kilometers) movements. However, adult red drum are quite mobile. In Florida, populations are assessed on coast-wide scales, and females are likely to spawn within 500–600 km of their natal estuaries (Gold et al., 1999; Murphy and Crabtree, 2001; Gold, 2008). Genetic structure is likely commensurate to these spawning areas, with evidence existing of genetic differentiation between Atlantic and Gulf stocks (Tringali, personal communication). In concert, these studies suggest generally well-mixed adult populations spawning at large spatial scales along each of the Gulf and Atlantic Florida coasts but probably more discreet sub-adult populations existing at local estuarine scales.

Red drum biological attributes may relate to outcomes through indirect feedback loops. For example, red drum recruitment processes (i.e., the need to raise fish large enough to bypass compensatory survival) affects the cost of raising fish, and thus the opportunity cost (in terms of alternative management) of stocking. Red drum biological attributes also affect system outcomes by route of governance and fisheries attributes. Specifically, the ontogenetic shift to offshore waters where they become semi-pelagic ensures the spawning population is largely invulnerable to recreational anglers (it is also protected from commercial fishing by a regulation that bans harvest in federal [offshore] waters). Perhaps the most obvious feedback is how biological attributes affect the population effect of stocking, with population changes influencing fishing effort and, therefore, red drum mortality. Many other feedback loops are possible, because nearly all outcomes of enhanced recreational systems are routed in some fashion through the biological attributes of the target species.

Fishery Attributes

Technical fisheries attributes directly influence both socioeconomic and ecological outcomes of enhanced recreational fisheries by determining catch and fishing mortality (Taylor et al., 2005; Lorenzen, 2008), which are functions of effort, catchability, and discard mortality. Effort can change related to stock abundance (Loomis and Fix, 1998; Walters and Martell, 2004; van Poorten et al., 2011), fishing regulations (Beard et al., 2003), alterations in stakeholder attitudes or typologies (Johnston et al., 2010), or knowledge of stocking efforts (Baer and Brinker, 2007). Although red drum fishing effort in Florida has increased over the last several decades (Murphy and Munyandorero, 2009) with growing fish and human populations and knowledge of the species, causality has not been determined. Due to the aforementioned ontogenetic shifts in habitat use, and restriction of recreational fishing for red drum to nearshore waters, red drum catchability in Florida is limited to juveniles below the ages of 4–6 and, therefore, is generally described as dome shaped with respect to age. Recent estimates of red drum catchability and effort indicate moderate fishing mortality rates—0.2 yr^{-1} and 0.15 yr^{-1} on the Gulf and Atlantic coasts, respectively (Murphy and Munyandorero, 2009). Harvest and discard mortality combine to produce an estimated 0.8 million red drum killed annually (Murphy and Munyandorero, 2009; Reyier et al., 2011). While recent Florida red drum assessment models assume discard mortality rates of 5% per catch and release event (Murphy and Munyandorero, 2009), other estimates from the Gulf and southeast Atlantic have ranged from 0 to 44% (Muoneke and Childress, 1994). Because even low discard mortality can profoundly affect total mortality when effort or catchability are high (Coggins et al., 2007), discard mortality may mediate enhancement outcomes as the mechanism for increased wild fish mortality, through stocking-induced effort increases.

Through harvest and discard mortality, effort and catchability directly drive ecological system outcomes and indirectly affect socioeconomic outcomes dependent on fish abundance. Additionally, effort relates directly to market outcomes by dictating the economic effects accrued by the fishery. Satisfaction is also strongly influenced by catch rate-oriented metrics, and so depends in part on effort (Ditton and Fedler, 1989; Arlinghaus, 2006). In turn, effort dynamics are related to biological attributes (as previously described), and likely also to attributes of stakeholders (often anglers) who find red drum substitutable for and by other species (Sutton and Ditton, 2005).

Fishing is unselective with respect to wild and stocked fish, but harvesting could be made selective to hatchery fish if these could be identified through tagging. Selective harvesting of stocked fish could be allowed to satisfy harvest-oriented anglers while discouraging or outlawing harvest of wild red drum. Selective harvesting of hatchery fish could also reduce their ecological and genetic interactions with the wild stock. Selective harvest policies in an enhanced red drum fishery could reduce some, but certainly not all, conflict between socio-economic and ecological objectives.

Technical Attributes of Aquaculture and Release

Technical attributes of aquaculture and release (including feasibility and efficiency of mass culture, domestication effects, size at release, microhabitat of release, season/tide of release) are particularly related to biological outcomes by determining the stocked fish survival, health, and contribution to total population dynamics (Leber et al., 1998, 2005; Lorenzen, 2008). Technical expertise required to spawn, hatch, and rear red drum exists, though production-level aquaculture still faces challenges. In Florida, all juveniles for stocking have been spawned from wild brood stock and reared intensively in tanks as well as extensively in ponds (Tringali et al. 2008b). Red drum post-stocking survival has been shown to increase with size at release (Willis et al., 1995; Tringali et al., 2008b); however, cost of hatchery production also increases. Understanding the trade-off between cost and survival is important to produce the greatest potential for population increase per unit cost (Leber et al., 2005). Stocked red drum may also experience high mortality immediately post-release regardless of stocking size (Sherwood et al., 2004). The causes of such mortality are unclear, but in other species, immediate post-release mortality has been related to microhabitat, tide, and season of release, as well as pre-release acclimation (Leber et al., 1997, 1998; Brennan et al., 2006). Low survival of stocked fish may also be related to domestication effects (Leber, 2002; Lorenzen, 2008). Hatchery red drum react more slowly to food and predators than do wild fish, and anti-predator "training" has had little effect on these behaviors (Stunz and Minello, 2001; Beck and Rooker, 2007, 2012). Additionally, domestication effects may result in less-fit hatchery fish that may contribute deleterious genes to wild populations (Lorenzen, 2008; Lorenzen et al., 2010). While past red drum enhancement projects in Florida posed little risk of genetic swamping (Tringali et al., 2008b), this is in part due to low absolute survival of stocked fish, and potential genetic risks of large scale stocking programs still exist. It must be understood that given red drum life history and the small size of stocked red drum, low absolute survival is expected (i.e., wild fish also experience low survival at this size/stage). While some stocking events have exhibited much lower survival than expected, the survival rates attributable to other stockings suggest the current enhancement technology and culture methods can result in some recruitment of hatchery fish—the challenge will be producing the desired quantity at desired sizes.

Habitat Attributes

Understanding stocked fish habitat needs is broadly acknowledged (Molony et al., 2003; Lorenzen, 2008), as structural habitat can mediate density dependent survival processes (Walters and Juanes, 1993) and impact the population level effects of enhancement activities. Unfortunately, controlled stocking experiments testing habitat effects on red drum survival are lacking. However, broader studies suggest habitat is important to red drum and thus may mediate stocking success. Juvenile and sub-adult red drum are strongly associated with structural habitat (Rooker et al., 1999; Murphy and Munyandorero 2009), and these habitats are predicted to be influential to total red drum population growth (Levin and Stunz, 2005), though recruitment, growth, and mortality may be related to non-structural habitats, such as river discharge (Purtlebaugh and Allen, 2010).

Stakeholder Attributes

Stakeholder attributes can directly alter outcomes by determining fishing effort and social utility dynamics. Because these dynamics are largely functions of primary stakeholder (i.e., angler) attitudes and values, assessing overall outcomes requires characterizing stakeholders into different typologies to better predict responses to enhancement (Johnston et al., 2010). Typologies may be characterized in terms of coarse motivations (e.g., outdoor recreation general versus fishing specific; Fedler and Ditton, 1994; Arlinghaus, 2006), as well as more specific motivation differences (e.g., species targeted or trophy oriented anglers versus harvest-oriented anglers; Sutton and Ditton, 2005; Johnston et al., 2010). Because diverse motivations require modeling multiple typologies to assess enhancement outcomes, understanding the breadth of motivations is critical. Florida red drum anglers' motivations have not been well studied, and so characterization of typologies is difficult. Florida anglers' view of other inshore species (e.g., spotted seatrout flounder and common snook) as potential substitutes for red drum (Sutton and Ditton, 2005) suggests that a generalist typology may be common. While studies of red drum anglers in Texas (Oh and Ditton, 2006) suggested different typologies (in terms of expected/desired angling experiences) existed, little is known of Florida red drum typologies.

A key stakeholder attribute that broadly affects outcomes is stakeholder social investment or "buy in" to enhancement (Lorenzen, 2008; Lorenzen et al., 2010). This investment is critical, since this is generally essential for broader system changes (Ostrom, 1990; Oakerson, 1992), such as enhancements (Lorenzen, 2008, Lorenzen et al., 2010). The importance of Florida red drum stakeholder's support (or lack thereof) for enhancement is illustrated by the changes in the Biscayne Bay red drum stocking—where stocking changed from experimentally stocking a wide range of fish sizes to mass production of small post-larval fish, based on stakeholder demand for increasing stocking density (Tringali et al., 2008b). While predicting stakeholder response to potential future red drum enhancement is difficult, support or buy in generally requires participation of stakeholders in the management process (Lorenzen et al., 2010; Miller et al., 2010). Non-angler stakeholders are also affected by and may influence enhancement indirectly (Arlinghaus, 2006) and so should also be considered (Lorenzen, 2008), but little is known of how such groups view potential enhancement in Florida. Given past red drum stocking in Florida, it is reasonable to assume that stakeholder opinions and support will play a large role in future enhancement outcomes and that such support is largely dependent on the extent and method by which stakeholders participate in enhancement decisions.

Market Attributes

Market attributes influence enhanced recreational fisheries by directly affecting economic and social outcomes and by indirectly altering ecological outcomes (Lorenzen, 2008; Lorenzen et al., 2010). While the Florida red drum fishery is valuable as part of a multi-billion-dollar fishery (ASA, 2001), the absolute economic or social value is difficult to ascertain (Murphy and Munyandorero, 2009). Absent absolute values, both economic and social values are generally considered proportional to fishing effort (Cox et al., 2003; Walters and Martell, 2004). While it may be fair to assume economic impact is somewhat positively correlated to effort, the ratio between effort and economic impact (e.g., 1:1, 10:1) is unknown. Fishing effort response is likely related to the social satisfaction anglers expect to attain from fishing (Arlinghaus, 2006), which is also important to gauge as a metric of social value. Expected satisfaction is a function of the motivations of anglers, and can vary by stakeholder typologies, but commonly responds to catch rates, crowding, facilities, etc. Though it is assumed that satisfaction of red drum anglers is positively related with catch rate, the shape of this relationship and how it may be mediated by other elements (e.g., harvest versus catch and release, boat ramps and facilities, congestion, etc.) is unknown.

The effect of scale should be very important for understanding the impact of changing market values but has not been well studied. For example, the extent to which potential increases in red drum effort are redistributions from others substitutable species is unknown. While the existence of substitutes (Sutton and Ditton, 2005) suggests that demand for red drum might be more elastic, red drum may be preferred over some of these substitutes (because of consistent availability, etc.). The lack of clarity of how recreational fishing and specifically red drum fishing is valued compared to alternatives (i.e., relative demand) makes it difficult to assess the gains possible from increasing red drum abundance via enhancement. Furthermore, the cost and funding sources associated with enhancing Florida's red drum fisheries must be understood to evaluate the effect of enhancement on market values. Currently, it is not known how hatcheries and enhancement activities will be funded. Depending on funding sources, enhancement may be viewed in terms of opportunity costs, such as habitat restoration, facility augmentation, etc. Public (i.e., general taxpayer) funding should be evaluated in a broader view of opportunity costs. This may requires assessing stakeholder response to these alternative actions, in addition to enhancement.

Governance

Governance attributes impact system outcomes primarily by directly controlling the type of enhancement allowable (Lorenzen, 2008; Lorenzen et al., 2010). Red drum recreational fisheries are regulated open access throughout the United States, with each state having autonomy to create its own regulations for harvest and for enhancement. Marine stock enhancement in Florida is organized jointly by the state management agency—Florida Fish and Wildlife Conservation Commission (FWC) through the Fish and Wildlife Research Institute (FWRI) and the stakeholder-led Florida Marine Fisheries Enhancement Initiative (FMFEI). The structure allows FMFEI to exert some influence on governance, which it does through raising funds for enhancement and indirectly by influencing stakeholders' opinions and expectations of enhancement. As such, governance and ultimately the outcomes of red drum enhancement in Florida is dependent on stakeholder opinions and actions. However, past and present enhancement initiatives in Florida have remained essentially unconnected with fisheries management, i.e., actual or potential stocking has not been considered in fisheries management plans, nor have enhancement initiatives made any specific claims as to desired changes in fishing regulations related to stocking. It is unclear whether the enhancement initiative is ideologically driven, i.e., stocking is fundamentally favored, or whether other motivations, e.g., greater angler satisfaction per trip, are the true fundamental objectives. The former limits governance actions, under the current co-management system, to shaping enhancement activities, while the latter allows for assessment of enhancement in the context of alternative management actions (e.g., habitat restoration, traditional fisheries regulations).

Governance attributes may directly control enhancement or may affect enhancement indirectly by influencing alternative management strategies and ultimately impacting fish abundance and angling effort (Aas, 2008; Lorenzen, 2008; Lorenzen et al., 2010). Florida management goals of 40% escapement is managed solely by size and bag limits, which, until recently, allowed for one red drum between 18–27 inches per day per person to be harvested with no closed season. The lack of a closed season probably elevates the value of this fish to stakeholders (especially fishing guides). On 01 February 2012, the bag limit increased to two red drum per day per person in northeast and northwest Florida waters. This increase both allows for the potential of increased harvest-oriented satisfaction that might occur if enhancement effectively increases catch rate and calls into question the necessity for stock enhancement in these areas. Governance arrangements relating to Florida's other fisheries can have impacts on the red drum fishery and its potential enhancement. For example, recent closures of the offshore reef fisheries could potentially shift additional effort toward inshore fisheries like red drum, although Fisher and Ditton (1994) found these inshore species to be considered poor substitutes by some offshore anglers. Similarly, an emergency closure to Florida's Gulf of Mexico common snook fishery could result in increased fishing effort or even harvest directed toward red drum, since these fish were thought of as substitutes (Sutton and Ditton, 2005).

KEY LINKAGES, UNCERTAINTIES, AND RECOMMENDATIONS

Outcome Linkages and Requirements

Enhancement outcomes are a function of dynamically linked attributes (Lorenzen, 2008), but in many recreational systems (e.g., this case study), key linkages exist where outcomes particularly hinge on certain attributes (Figure 4). In this case, socioeconomic outcomes (i.e., stakeholder satisfaction and local economies) depend directly on market, stakeholder, governmental, and fisheries attributes and indirectly on changes in red drum abundance (Tables 1 and 2, Figure 1). Ecological outcomes (i.e., red drum population status) are direct functions of biological and habitat/environmental attributes, but also are a function of fisheries attributes (namely the effort response; Tables 1 and 2, Figure 1). Thus, socioeconomic outcomes depend partially on red drum abundance, which are closely related to ecological outcomes, and ecological outcomes are in part functions of fishing effort/mortality, which is closely related to socioeconomic outcomes. In this way, socioeconomic and ecological outcomes depend on each other. However, realizing each objective also requires additional specific attribute values.

Desired socioeconomic objectives of red drum enhancement may be realized through multiple pathways, but each require certain attribute values. The primary pathway is for enhancement to augment red drum populations, leading to increased fishing effort and/or catch rates and finally increased economic impact and/or stakeholder satisfaction (Figure 4). Each of these steps has key requirements. For wild populations to be increased (the first transition in Figure 4), red drum must be stocked when survival compensation (and competition with wild fish) is low and in areas where adequate habitat is present. For augmented populations to translate into higher catch rates (the second

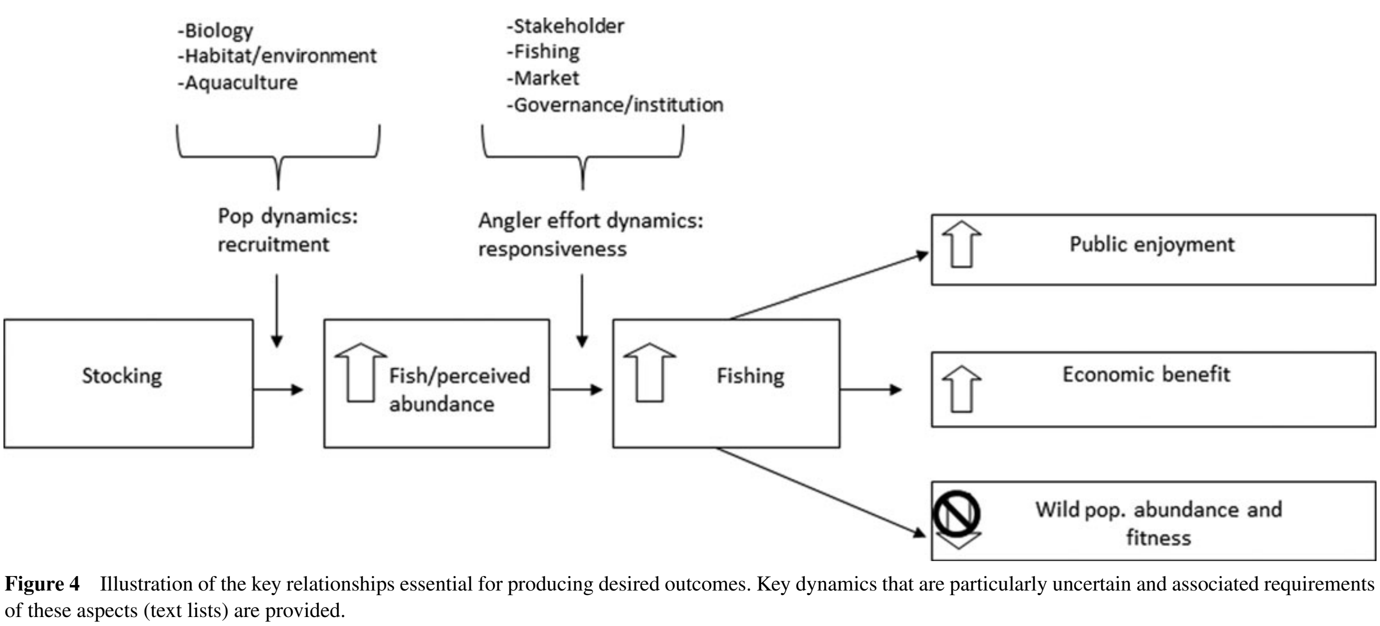

Figure 4 Illustration of the key relationships essential for producing desired outcomes. Key dynamics that are particularly uncertain and associated requirements of these aspects (text lists) are provided.

Table 1 Role of attributes in determining current outcomes

Attribute	Ecological outcome	Socioeconomic outcome	Role of enhancement
Current outcome	Population slightly more abundant than management threshold	Increasing effort and catch rate lead to high current socioeconomic value	Sporadic trial stockings have occurred but production or adaptively managed stockings not imminent
Biology	Red drum are relatively robust to recruitment overfishing, largely due to an ontogenetic shift to quasi-pelagic, offshore habits	Year-round availability of sub-adults makes red drum a seasonally consistent sportfish in Florida, which is valuable	High compensation may have led to low survival of stocked fish
Fishery	Moderate fishing mortality results in current sustainable exploitation, but increasing effort and non-negligible discard mortality leads to mounting concern	High effort/catch rates lead to high socioeconomic value	Dome shaped vulnerability leads to small temporal window for recapturing stocked fish, mediating the observed catch-related benefits of stocking
Aquaculture	Because little red drum stocking has occurred, ecological impacts are minor	Because little red drum stocking has occurred, socioeconomic impacts are minor	Occasional high survival of stocked fish suggests that issues in the culture techniques are unlikely
Habitat	May mediate recruitment and thus affect population status outcomes	Habitat mediates recruitment alterations and in turn socioeconomic and enhancement outcomes	May interact with compensation to result in locally poor survival in trial stockings
Stakeholder	Stakeholder engagement has motivated management thresholds (e.g., escapement) to be relatively high	Stakeholder perceived preference relative to other inshore species drives high value for red drum	Historically, stakeholders have encouraged stocking by the state and influenced stocking practices but not provided or helped to secure funding or wider support for enhancement
Market	Increasing total demand for red drum has indirectly led (realized through effort) to sustainability concerns	Perceived high value of the red drum fishery is due to the high and increasing effort and catch rate	Uncertainty in enhancement funding is likely related to lack of current production and perhaps stakeholder investment
Governance	Red drum regulations limit harvest to roughly one year, and this is likely responsible for current abundance of red drum	No closed season promotes year-round consistency in red drum value, and consistency is vital for guides and small businesses reliant on the fish sector	Governance-designed stakeholder involvement in enhancement has directly driven current outcomes

transition in Figure 4), catchability must remain unchanged and effort must increase proportionally less than red drum abundance (i.e., effort must not be too responsive to higher catch rates). Alternatively, for total red drum effort to increase (second transition in Figure 4), effort must be responsive to increased fish abundance or persist following temporarily higher catch rates. Finally, for total socioeconomic value to increase on a broad scale (third transition in Figure 4), increases in effort and satisfaction must be organically created, i.e., not redistributions from other fisheries or even other economic sectors, and increased effort must not cause substantial decreases in satisfaction (such as might occur from crowding). Since in Florida, substitutions and redistributions among at least inshore sport fish species are likely, economics and satisfaction of red drum enhancement should really be judged at a larger scale (e.g., total inshore effort/satisfaction). If the values of all of these attributes are favorable, stocking may achieve the socioeconomic outcomes desired. However, since these outcomes are the product of such a linked system, simply one misaligned value may jeopardize the desired outcomes. Alternatively, some desired socioeconomic outcomes (higher satisfaction) may be achieved if Florida stakeholders gain satisfaction in response to the act of enhancement alone, regardless of how red drum populations change. Similarly, if enhancement facilitates greater inclusion or investment of stakeholders in management processes, some socioeconomic objectives may be met without enhancement altering the availability of fish.

Meeting the desired ecological outcome of sustained wild red drum populations further constrains attribute values. For wild red drum exploitation/mortality to not increase, catchability must not increase and effort must not respond in greater magnitude than any increase in abundance. However, responsive effort is critical for achieving desired socioeconomic outcomes through the primary pathways. Additionally, aquaculture attribute values must result in avoidance of deleterious genetic effects; that is, less fit stocked fish must not spawn in appreciable numbers with wild fish. Ensuring that stocked fish are similarly fit to wild fish is not realistic, since this would require stocked fish go through full selective (i.e., compensatory) processes, which essentially negates the potential for population augmentation. Accordingly, two of the most critical links between attributes and outcomes are (1) the red drum recruitment dynamics, which are likely to mediate how population size could change with stocking, and (2) angler catch rate and effort dynamics, specifically as they relate to changing red drum population size (Figure 4). Simply, the values required for socioeconomic outcomes conflict with those required for ecological outcomes. Socioeconomic outcomes require motivating increased fishing effort and having high stocked fish survival and are likely to negatively impact desired ecological outcomes

Table 2 Likely influence of attributes on future outcomes

Attribute	Ecological outcome	Socioeconomic outcome	Role of enhancement
Future or desired outcomes	Sustained healthy wild populations above management threshold	Maintained or increased effort and catch rates leading to increased or sustained socioeconomic value	Accomplish both desired socioeconomic and ecological outcomes at a low cost relative to alternative management
Biology	High site fidelity and vulnerability of sub-adults mean catchable red drum may become seasonally locally depleted, particularly if effort increases	Reliability and popularity suggest an increase red drum targeted effort is possible	Region-wide population augmentation requires stocking after highly compensatory life stages, though local depletions may reduce compensation and allow for successful small scale stockings
Fishery	High, increasing, and/or responsive effort suggests positive socioeconomic outcomes and negative population status outcomes are likely	High, increasing, and/or responsive effort suggests positive socioeconomic outcomes and negative population status outcomes are likely	Reduced discard mortality can mitigate negative impacts of stocking-induced effort on wild populations
Aquaculture	Larger, post-compensatory red drum may be technically possible and pose a greater threat to wild genetic integrity	Desired outcomes more likely if culture methods are developed to produce larger, post-compensatory red drum	Producing high number of advanced fingerlings requires space, but that is difficult and costly to acquire in coastal Florida
Habitat	Likely to mediate recruitment and thus population status outcomes if habitat is altered	Changing habitat could alter desired outcomes indirectly through population status changes	Likely to mediate survival of stocked fish and thus enhancement outcomes (socioeconomic and ecological)
Stakeholder	Stakeholder behavior and opinions indirectly drive ecological outcomes by determining effort, percent harvest, management, etc.	Satisfaction may be strongly influenced by perceived involvement in, and buy in, to the management process	Future enhancements will likely require strong stakeholder engagement and are unlikely to be initiated and sustained without at least moderate support
Market	Demand and elasticity drive effort and thus population and ecological outcomes, but these (and thus effort dynamics) are largely unknown	Demand and elasticity drive total effort directly and likely satisfaction indirectly and thus socioeconomic outcomes, but these (and thus effort dynamics) are largely unknown	Costs of stocking and funding sources relative to alternative management (i.e., habitat restoration) likely to impact enhancement
Governance	Recent alterations in regulations may alter population status but, because of long adult spawning life, may not be noticeable soon	Regulation change may increase satisfaction in short term, potential to decrease in long term if population falters	Regulations (or their absence) that result in lower populations and satisfaction may motivate stakeholders to invest/embrace enhancement

of sustained wild populations through higher fishing mortality, increased competition with stocked fish, deleterious genetic impacts, or a combination of all of these. It is not clear how this trade-off between socioeconomic and ecological outcomes can be avoided.

Uncertainties

Several of the values of key requirements for achieving ecological or socioeconomic outcomes are uncertain, which ultimately results in uncertain outcomes of red drum enhancement. The main uncertainty in biological attributes surrounds red drum recruitment dynamics—specifically the timing, extent, and mediation by habitat of compensatory periods and spatial distribution of sub-adult (catchable) red drum. Another key uncertainty is market value attributes, specifically the responsiveness of effort to increased abundance/catch rates, and the source of this effort (redistribution versus original recruitment). Finally, there is substantial uncertainty in stakeholder attribute values, which affects stakeholder satisfaction functions, as well as how enhancement might affect stakeholder investment in management. So while many attribute values are uncertain, the most critical uncertainty surrounds stakeholder, biological, fisheries, and market attributes (Figure 5). Viewing these in concert with key linkages between attributes and outcomes, recruitment dynamics, angler effort dynamics, and stakeholder investment emerge as key uncertainties to reduce.

Recommendations

For responsible progression of red drum stock enhancement in Florida, reduction and accounting of uncertainty (not inherent variability) surrounding recruitment, effort, and stakeholder dynamics are needed. This may best be achieved using an active adaptive management approach that combines quantitative modeling, mensurative and manipulative experiments, and monitoring in an a priori designed structure to learn from uncertainty (Leber, 2002; Walters and Martell, 2004). In this framework, modeling and small-scale experiments reduce some uncertainty (e.g., recruitment timing) to inform initial enhancement, which,

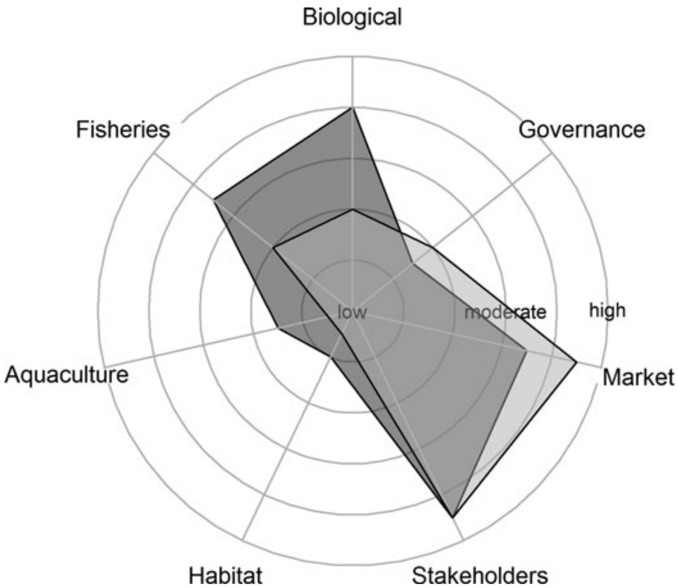

Figure 5 Uncertainty associated with attributes of red drum enhancement and difficulty in reducing this uncertainty. Radial distance is proportional to uncertainty or difficulty in reducing uncertainty.

when carried out experimentally, will help resolve "deeper" uncertainty (e.g., how the system responds to stocking). Multiple modeling efforts should be designed—general quantitative models addressing both the feasibility of achieving desired outcomes and spatially explicit models useful for predicting acceptable stocking locations and strategies. Pursuing multiple scales should both provide "reality checks" of the potential outcomes of enhancement (Lorenzen et al., 2010) and detailed information of conditions in which enhancement is most likely to succeed. Specifically, age-structured population models including multiple young-of-year red drum stages or types (e.g., hatchery, wild) can be used to simulate outcomes of alternative timing, intensities, and habitat mediation of compensation. Small-scale experimental stocking should be designed to provide starting estimates of uncertain variables in the quantitative models, such as the magnitude and variability of density-dependent survival of stocked red drum and variation in release-microhabitat mediated survival. Further compensation inferences may be gleaned from analysis of existing monitoring data, similar to Scharf (2000). Similarly, analyses of existing effort and catch rate data (e.g., Marine Recreational Information Program data from the United States' National Marine Fisheries Service) may be used to estimate effort response dynamics. Effort responses might also be evaluated through actual experimental stocking manipulations, as has been done in some freshwater systems (Baer et al., 2007), or inferences of redistribution of effort among fisheries gained from construction of random utility models, similar to Schuhmann (1998). Broader, multi-market economic analysis may be necessary to assess the total net effect of enhancement on the economics of the state.

To reduce uncertainty in the stakeholder response to enhancement through active adaptive management, it is critical to first develop and nurture existing participatory stakeholder involvement in future enhancement decisions. This should improve ability to detect changes in stakeholder satisfaction with experimental stocking, though this process will likely require initiation by managers, as has been previously done in Florida (Tringali et al., 2008a). An emphasis should be placed on finding strong leaders of this process who are trusted by stakeholders (Ostrom et al., 1999) and can help develop participatory approaches that function to guide and in fact design enhancement activities. Accomplishing this may be time-and-effort intensive but likely will result in a group of invested stakeholders who understand and participate in analysis of enhancement, as described in Miller et al. (2010). Such an approach seems to offer the best chance for enhancement to meet stakeholder objectives and should also result in stakeholder engagement sufficient for evaluating enhancement in the adaptive management framework. Synthesizing information from various stakeholder, angler effort, and recruitment dynamic studies should provide a basis for designing an active adaptive management process by which enhancement is experimentally conducted and the results monitored to reduce uncertainty and inform future enhancements.

It is worth acknowledging that few examples exist of successful active adaptive management and that informing the explicit a priori design of this process is costly. It may not be possible for all useful studies (particularly those including field work) to be completed with scarce time and funds prior to any enhancement, especially if stakeholder demands for stocking increase. Even in this case, key steps should be followed to maximize benefits per risk. First, existing knowledge of attribute values and uncertainty can be incorporated into translucent, quantitative models that predict ranges of outcomes and so inform any potential enhancement. Second, any potential enhancement can be well monitored, particularly with respect to key uncertainties. For example, if a certain region is stocked, perhaps creel surveys can be increased in that region and adjacent, unstocked regions to allow greater power to detect angler effort responses. Finally, any enhancements should be particularly adverse to risk to wild red drum populations, because any harm to them may be quite long term, given their life span, and incur high socioeconomic costs, given the value of the fishery. To minimize the probability of deleterious impacts on wild red drum populations and to maximize potential socioeconomic gains, the largest possible red drum—i.e., the closest to catchable size—should be stocked in high fishing pressure areas. Such fish are likely to have better post-release survival based on size-dependent mortality, are less likely subject to high-density dependent survival, and may not be as sensitive to habitat as smaller fish. Stocking larger sized fish in areas where abundance of wild red drum is low due to high fishing effort increases probability of augmented catch as a result of stocking, while possibly decreasing likelihood of negative genetic effects through interbreeding with wild fish (though Ryman-Laikre effects might be more prevalent). To allow the greatest potential of learning, such stockings would be completed experimentally (e.g., replicated within a blocked design) such that system uncertainties may be studied (e.g., Leber et al, 1997, 1998). Furthermore, all, or at least a large, known proportion of the fish stocked should be individually marked so that the effects of the stocking can be monitored (Blankenship and Leber, 1995; Walters and Martell, 2004; Lorenzen et al., 2010). While stocking in such a way may have a high financial cost of production per stocked fish, stocking large fish where wild fish are and anglers are not is likely to maximize catch of stocked fish per negative impact on wild populations.

CONCLUSIONS

Synthesis of past studies and current understanding shows that socioeconomic and ecological outcomes of potential enhancement are reflexively related and likely depend on combinations of multiple linked attributes. However, the simultaneous accomplishment of socioeconomic and ecological outcomes is doubtful, since trade-offs are clear—stocking that would achieve greater angler effort and satisfaction likely increases the probability of negative effects on wild populations. This trade-off can be perhaps better understood and more translucently presented by reducing uncertainty regarding recruitment/compensatory dynamics, angler effort dynamics, and stakeholder investment patterns. To measure the full impact of enhancement, ecological and especially socioeconomic outcomes must also be viewed in a much broader context that extends beyond the specific enhanced species. These assessments may be best made by combining simulated populations models, small-scale stocking experiments, and analyses of existing data. Regardless of these analyses, how and if red drum stock enhancement occurs may be determined by stakeholder interests, which play a large role in enhancement outcomes. Accordingly, fostering stakeholder understanding and investment may be the most crucial next steps for red drum stock enhancement in Florida.

The objectives of Florida's red drum fishery are largely universal to recreational fisheries, and so outcomes of this assessment may be widely applicable. Despite this overlap, few studies, regardless of species, have assessed the outcomes of enhancement, particularly in an integrated framework representing the complex coupled socio-ecological system of recreational fisheries. In most enhancement systems, key linkages will be how enhancement affects total population size and wild fish (i.e., recruitment dynamics), how fishing effort responds to population size (i.e., angler effort dynamics), and how stakeholders view and shape the entire process (i.e., stakeholder investment). Similarly, the trade-offs exhibited in this case study likely exist in nearly all recreational enhanced systems, since almost all recreational enhancement is an attempt to augment fishing effort and satisfaction while sustaining populations. It follows then, that the key recommendations of this case study—coupled quantitative and experimental evaluations and a greater emphasis on stakeholder inclusion in management—may be useful in other systems.

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