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Approaches to regulating recreational fisheries: balancing biology with angler satisfaction

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Abstract Recreational fishing is practiced by ∼ 350 million people globally, and while it historically has been thought to have minimal ecological impact relative to commercial fishing, numerous recreational fisheries have recently declined or collapsed. The potential for recreational fishing to contribute to ecological decline, as well as the incentives of recreational anglers that are distinct from those of commercial fishers, highlights the need for greater understanding of recreational fisheries regulatory options. To aid managers in the decision-making process, we conduct the first comparative review of all seven major approaches to recreational fisheries regulation: harvest size restrictions, harvest quantity restrictions, spatial management, temporal restrictions, accessibility restrictions, rights-based management, and gear restrictions. We provide a synthetic guide for students and practitioners covering how these regulations can benefit target stocks, their potential limitations in achieving sustainability, and angler perceptions of their relative effectiveness and behavioral impositions. Considering the strengths and weaknesses of each strategy, we identify three key fishery metrics that together can guide selection of a suitable combination of regulations that will achieve the requisite biological outcome without restricting angler behavior more than is necessary. With this perspective, we reflect on uncertainties that complicate informed and effective, recreational fisheries regulation.

Keywords Angler · Effort · Fishery regulation · Fishing mortality · Recreational fishing · Welfare

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Introduction

Recreational fishing provides pleasure, subsistence, or livelihoods to ∼ 350 million people globally (Arlinghaus et al. 2019); annual expenditures by these anglers total $190 billion and, in certain countries, the economic value of recreational fisheries exceeds that of commercial ones (World Bank 2012). The diminishing quality or collapse of numerous recreational

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fisheries (e.g., Post et al. 2002; Erisman et al. 2011; Lyach & Čech 2018; Rypel et al. 2018; Embke et al. 2019) highlights the potential contribution of this activity to ecological decline, and the need for sound management (Cooke & Cowx 2004, 2006; Coleman et al. 2004). Yet, most fisheries management approaches have been designed to handle commercial fishing and the economic drivers particular to that sector (Anderson et al. 2019). Instead, recreational fisheries managers must consider biological outcomes of target stocks alongside the satisfaction and unique motivations of participating anglers when selecting regulations (Johnston et al. 2010; Hunt et al. 2013; Brownscombe et al. 2019).

The biological objectives of recreational fisheries regulation primarily focus on quantifying and controlling fishing mortality, which is the sum of harvest and release mortality (Kerns et al. 2012). Harvest mortality occurs when an angler captures and retains a fish. Release mortality occurs when an angler captures and releases a fish but that fish subsequently dies from injury or physiological stress sustained during the angling event, or as a result of predation by another animal shortly after release while still physiologically impaired (Cooke and Schramm 2007). The number of fish caught, and potentially subjected to fishing mortality, is a function of the amount of fishing effort (both the number of anglers and how much time each spends fishing) and catchability (the fraction of a stock caught per unit effort, which may change in space or time due to fish behavior, with the fishing gear used, and by angler skill level) (sensu Arreguín-Sánchez 1996). The exact level of fishing mortality that is sustainable is dependent on the life history, demographics, population productivity, and natural mortality of the target species (sensu Post 2013), thereby varying among fisheries. In addition to regulation (of effort, catchability, harvest, and release mortality) via restrictions on angler inputs (e.g., where/when they fish and the gear they use) and outputs (e.g., size or number of fish they harvest) (Morison 2004), recreational fishery management approaches also include habitat enhancement and stocking programs to bolster target stocks or create new ones (Arlinghaus and Mehner 2005; Johnston et al. 2018). However, regardless of the status of the habitat as intact or modified, and the origin of a target stock as native or non-native and naturally- or hatchery-produced, fishing regulations ultimately govern how anglers exert pressure on target stocks in their habitats. We focus on providing a practical review of the literature informing this aspect of the broader recreational management problem.

The social objectives of recreational fisheries management focus on addressing the concerns of recreational fishing constituencies, reflected in the satisfaction of anglers based on the quality of the fishing experience from their perspective (i.e., the difference between what they expect or desire to experience and what they perceive to experience—sensu Peterson 1974). General attributes of the fishing experience that are shared with other activities, such as being outdoors and spending time in nature, motivate anglers to fish (Holland and Ditton 1992), as do fishing-specific attributes (Hudgins and Davies 1984; Arlinghaus 2006). Looking across fisheries, non-catch attributes, such as the number of anglers encountered, travel distance, and behavioral impositions of regulation, are notable or even universal considerations (Hunt et al. 2019), and catch attributes, primarily catch rate and fish size, are often important determinants of angler satisfaction (McCormick and Porter 2014; Beardmore et al. 2015; Knoche and Lupi 2016). However, anglers are heterogeneous (Johnston et al. 2010; Haab et al. 2012; Beardmore et al. 2015) and seek distinct experiences and outcomes from participating in different fisheries; failing to account for this can lead to incorrect conclusions about policy effects (Goldsmith et al. 2018).

Anglers are typically classified based on a number of attributes that describe their angling involvement and orientation (e.g., what aspects of the fishing experience they value and pursue, what type of fishing they specialize in—Bryan 1977; Beardmore et al. 2013). For purposes of considering their motivations to fish, preferences of fish and fishery characteristics, and reactions to regulation, there are three broad categories (e.g., Johnston et al. 2010)—general, harvest-oriented, and trophy-oriented—but intermediate and newly emerging categories do exist (e.g., Magee et al. 2018; Cooke et al. 2020). General anglers often have lower levels of expertise and may not have extensively integrated angling into their regular rotation of recreational activities. Harvest-oriented anglers typically want to capture and retain large numbers of fish to eat, but are relatively less focused on the maximum size of those fish and are less bothered when fishing in more crowded areas. Trophy-oriented anglers appreciate the technical challenge of fishing, areas with sparse angling pressure, and often target the largest fish, but are less concerned with the number of fish they catch, or the ability to retain them. Although there are anglers of each type in most fisheries, there is a significant degree of self-selection where anglers participate in fisheries that provide the type of experience that they most desire (Anderson 1993). This is particularly relevant to management, as anglers consider the trade-offs among the behavioral restrictions and fishing experience benefits provided by regulation when deciding what regulations are acceptable to them and, therefore, what fisheries to participate in (Johnston et al. 2010). Other sources of angler heterogeneity, such as the gear they use and their demographics, further nuance their assessments of these trade-offs (e.g., Hutt and Bettoli 2007; Arlinghaus et al. 2008). Thus, managers should consider how regulation affects the satisfaction of diverse angler groups through their experiences in a fishery, including catch and non-catch attributes (Johnston et al. 2010; Fenichel et al. 2013; Beardmore et al. 2015). Angler satisfaction (or utility) is the most commonly used metric for exploring angler welfare in dynamic, social-ecological (e.g., angler-stock) system models of recreational fisheries, and facilitates analysis when heterogeneous anglers are involved (Solomon et al. 2020), but it is important to recognize that there are other social objectives (e.g., equal opportunity, increased access to the resource, minimized conflict among user groups) that may be considered by managers (Pascoe et al. 2014). Although most fishery case studies report the biological outcomes predicted from or observed after a regulation change, they less commonly assess and rank the concomitant impacts on angler satisfaction (Fenichel et al. 2013).

Here we provide the first review of the major approaches to recreational fisheries regulation: harvest size restrictions, harvest quantity restrictions, spatial management, temporal restrictions, accessibility restrictions, rights-based management, and gear restrictions. Nearly all recreational fishery regulations we could find in the literature are directly represented by one of the aforementioned categories or constitute derivations thereof. We differentiated these seven categories, and assigned regulations into them, by whether they target angler inputs or outputs, the specific means of intervention (via effort, catchability, harvest, or release mortality), and the incentives or deterrents they present to anglers. This enabled us to conduct a generalized comparison among regulatory approaches, facilitating identification of patterns in their biological and social outcomes. In particular, we identified the mechanism by which each regulation is designed to control fishing mortality and specifically searched for literature highlighting examples where the mechanism worked as intended, where the mechanism failed or its benefits were negated by another mechanism, and how anglers were (or would be) affected. The studies included were intended to show the range of potential outcomes from each type of regulation but not to portray the relative frequency with which those outcomes may occur (the latter would be difficult to infer from case studies which were non-randomly selected for publication). We drew on peer-reviewed studies (model-based and empirical) of management intervention in freshwater and marine fisheries from across the globe, focusing on fishes captured by rod-and-reel, and supplemented these with white papers or information from recreational angling organization databases only when peer-reviewed examples were scarce.

Thus, we present and contrast examples of both regulatory success and failure for each approach to assess how these regulations can benefit target stock health, their potential limitations in achieving fishery sustainability, and angler perceptions of their relative effectiveness and behavioral impositions. Given the strengths and weaknesses of each regulatory strategy, we identify metrics that managers can apply to their fisheries to guide selection of an appropriate combination of regulations that should meet the requisite biological goals without undue social costs.

Harvest size restrictions

Harvest size restrictions prohibit the retention of individual fish that fall within specific length parameters. This reduces the contribution of harvest mortality to fishing mortality and helps ensure the fishery does not take individuals that are within age classes determined to be important to the current or future productivity of the target stock.

Minimum size limits

Minimum size limits only allow harvest of fish above a certain length, and typically are most successful when set to ensure most individuals reach sexual maturity and reproduce at least once before harvest. Higher minimum size limits result in an increased spawning potential ratio, which is the ratio of eggs produced in a population under fishing pressure to eggs produced under no fishing pressure, relative to lower minimum size limits (Coggins et al. 2007). For example, minimum size limits in a bull trout (*Salvelinus confluentus*) fishery that were set above the average size at sexual maturity, thereby allowing for at least one reproductive event before harvest, were projected to make the target population considerably more resilient to angler effort compared to lower size limits (Post et al. 2003). However, modeled studies of other fisheries found that minimum size limits, which promote harvest of larger fish while allowing smaller fish to reach sexual maturity, can result in a size-selective pressure that maintains or even increases biomass or stock abundance through an increase of small fish at the expense of the trophy-size fish in the population (Matsumura et al. 2011; García-Asorey et al. 2011).

Maximum size limits

Maximum size limits only allow harvest of fish under a certain length, with the intention of preserving large fish with the greatest reproductive potential and trophy-value in a fishery. In largemouth bass (*Micropterus salmoides*) fisheries in lakes of Minnesota, USA, implementation of a 12-inch maximum size limit improved size structure and increased abundance of large bass in lakes with no previous size limit (Carlson and Isermann 2010). Similarly, 16% of Atlantic salmon (*Salmo salar*) captured in rivers with maximum size limits were released by anglers while only 1% of those captured in rivers with no size limit were released; the maximum size limit also mitigated the selective harvest of larger fish with greater reproductive potential (Lennox et al. 2016). Lower maximum size limits, relative to higher ones, are modeled to increase stock abundance, particularly that of trophy-size fish (García-Asorey et al. 2011). In experiments and models of fishing-induced evolution, maximum size limits promote rapid juvenile growth into the protected size range, increase fish size, broaden age structure, and increase spawning stock biomass, which are seen as advantages over minimum size limits that reinforce size-selective harvest of large fish (Conover and Munch 2002; Matsumura et al. 2011).

Slot limits

Slot limits combine a minimum size limit with a maximum size limit, allowing harvest of fish within a specific size range, but not larger or smaller fish. These are often designed to simultaneously allow fish to reach sexual maturity and keep highly fecund older individuals in the population (i.e., maintain a trophy-size segment to the population). Increasingly strict minimum and maximum limits increase the ability of slot limits to augment target stocks and increase the spawning potential ratio (Vaughan and Carmichael 2002). A broad study comparing many different European and North American gamefish species modeled that appropriate slot limits could increase stock abundance and biomass 1.5–3 times more than minimum size limits alone for all species, and also more effectively mitigated changes in population age-structure (Gwinn et al. 2015). In fisheries where a management goal is to maintain trophy-size fish in the population, slot limits and maximum size limits substantially outperform minimum size limits (Wilde 1997; Arlinghaus et al. 2010; García-Asorey et al. 2011; Ahrens et al. 2020) by reducing negative selection on large maturation size and increasing positive selection on growth rate (Matsumura et al. 2011). Note that there is also a less commonly used, reverse or protected slot limit, which permits harvest only of the fish below or above the slot (rather than within the slot), but the minimal information on its efficacy suggests it may perform worse than other size restrictions (Kennedy and Sutton 2007; Shaw et al. 2018).

Limitations

Size limits may fail to sufficiently reduce fishing mortality if managers fail to account for the presence of release mortality and potential future upsurges in angler effort. All fish that are released because they are not of legal size may experience release mortality and, thereby, undermine the effectiveness of harvest size restrictions (Woodward and Griffin 2003); however, in some species the rate of release mortality is low and the sub-lethal effects are ephemeral (Cline et al. 2012; reviewed in Sass and Shaw 2020). High levels of release mortality may result in fishery collapse over time while lower levels of release mortality may allow the positive impacts of harvest size restrictions to manifest in the form of increased stock abundance (Coggins et al. 2007; Tetzlaff et al. 2013). However, if stock abundance increases in the short-term as a result of a strict size restriction, there may be a subsequent upsurge in angler effort that could result in delayed fishery collapse due to unsustainable harvest rates of legal fish and release mortality of fish not of legal size (Post et al. 2003). Thus, fisheries regulated with harvest size restrictions alone remain susceptible to potential increases in effort (Homans and Ruliffson 1999).

Angler perceptions

In general, anglers consider harvest size restrictions as one of the most preferred options out of the possible regulatory approaches. Positive angler impressions of harvest size restrictions are based in angler credence that they promote stock abundance, yield quality fishing experiences, and impose less restraint on angler behavior and fishing time than other regulations such as bag limits or gear quantity limits (Dawson and Wilkins 1981; Quinn 1992; Salz et al. 2001; Murphy et al. 2015). Because of this perceived benefit to overall fishing success and promotion of positive angler outcomes, anglers of all types are typically willing to sacrifice that portion of their catch that falls outside of harvest size restrictions in order to develop a more successful and healthy fishery over the long term (Hutt and Bettoli 2007). Anglers exhibit differing preferences for the various types of harvest size restrictions (Ditton and Hunt 1996; Fisher 1997; Loomis and Holland 1997), which may be due to their relative desire to harvest fish of a larger (or smaller) size. Although harvest-oriented anglers are generally willing to accept harvest size restrictions as a management tool due to the lesser impositions of size limits compared to bag limits or other harvest restrictions, their welfare is more adversely affected than that of other angler groups by restrictive size limits that curtail harvest (Fisher 1997; Hutt and Bettoli 2007; Dorow et al. 2010; Dorow and Arlinghaus 2012).

Harvest quantity restrictions

Harvest quantity restrictions limit or prohibit the harvest of fish by anglers for consumption or other purposes. As a management tool, harvest quantity restrictions are designed to reduce fishing mortality through a reduction in harvest mortality.

Bag limits

Bag limits restrict the number or weight of fish that an angler can harvest on a temporal (i.e., daily, seasonal, or annual) basis. Limiting the harvest of anglers with a bag limit can be more effective than with a size limit, and yield substantial increases in stock abundance (Woodward and Griffin 2003). In a study of the Atlantic salmon fishery in 222 Norwegian rivers, those with low daily or seasonal bag limits exhibited higher proportions of salmon released than rivers with high daily or seasonal limits, respectively, and seasonal limits outperformed daily limits by $\sim$ 3 times overall (Lennox et al. 2016). In addition to reducing harvest of participating anglers, more restrictive bag limits may reduce fishery attractiveness to harvest-oriented anglers and incentivize them to switch into fisheries with higher bag limits; angling effort was significantly lower even though walleye (*Sander vitreus*) catch rate was $\sim$ 2 times greater at Wisconsin lakes with bag limits of two versus five walleye per angler per day (Beard et al. 2003). Similarly, a choice experiment with surveyed European eel (*Anguilla anguilla*) anglers in Germany, found that lowering the daily bag limit from three to one would reduce effort by 15%, thereby further decreasing fishing mortality (Beardmore et al. 2011).

Catch-and-release

At the most constraining level of harvest quantity restrictions, no fish are allowed to be harvested and the fishery is catch-and-release only. Implementation of catch-and-release is often associated with increased abundance and improved catch rates, but imposes the maximum welfare cost to harvest-oriented anglers (reviewed in Arlinghaus et al. 2007). In German fisheries for northern pike (*Esox lucius*), a catch-and-release policy was modeled to more effectively maintain a natural age structure and result in higher catch rates of trophy pike than minimum size or slot limits (Arlinghaus et al. 2010). Relative to a minimum size limit, a year-round catch-and-release regulation was predicted to increase the abundance of adult largemouth bass (*Micropterus salmoides*) by 20 or 25% in low-productivity populations and by 38 or 42% in high-productivity populations, depending on the fraction of the stock caught by anglers (Gwinn and Allen 2010). Some species surviving capture and release may exhibit reduced reproductive success but still contribute substantially to a subsequent generation (e.g., Richard et al. 2013), and others may exhibit little to no detrimental effects (reviewed in Sass and Shaw 2020).

Limitations

Although bag limits can be effective at limiting fishing mortality through a reduction in harvest, under some conditions they have proven ineffective at creating beneficial biological outcomes. Bag limits set above the amount that anglers normally catch (i.e., permitting excessive harvest) will not appreciably curtail fishing mortality and may only affect the most successful anglers (Woodward and Griffin 2003; Askey and Johnston 2013). Since not all anglers reach the bag limit every day in most fisheries, a reduction in the bag limit results in a proportionally smaller reduction in mortality (Attwood and Bennett 1995a). For example, reducing the bag limit for kob (*Argyrosomus* spp.) by 80% (from 10 to 2 fish per angler per day) was predicted to reduce harvest mortality by only 20% (Attwood and Bennett 1995a).

The effectiveness of harvest quantity restrictions can be limited or completely eroded if release mortality rates are high. Progressively stricter combinations of harvest restrictions are needed to prevent overfishing (and become less effective at doing so) as the release mortality rate rises (Henderson 2009; Tetzlaff et al. 2013). The negative effects of release mortality on bag limit effectiveness can be mitigated by requiring that (1) the first fishes captured while filling a bag limit must be kept (regardless of their size or quality to prevent high-grading) and (2) that fishing activity must cease for the target species once a bag limit is reached. However, requiring that the first fishes caught be kept may cause the harvest of sexually immature fish or those with the greatest reproductive potential, and may only be applicable in fisheries targeting a single life stage of a species with comparatively less variability in fecundity (e.g., semelparous salmonids during their spawning migration). Requiring the cessation of fishing activity for the target species after reaching the bag limit is similarly limited in its applicability, as it may not be realistic in mixed-species fisheries where anglers have minimal ability to select among target species (Tetzlaff et al. 2013).

Aggregate bag limits applied to a complex of species, without underlying species-specific limits, may lead to overexploitation of individual species within the complex (Dunlop and Mann 2012). Furthermore, bag limits may insufficiently limit harvest during periods of increased catchability. For example, the Southern California, USA, fishery for barred sand bass (*Paralabrax nebulifer*) and kelp bass (*Paralabrax clathratus*), managed with an aggregate bag limit of 10 fish per angler per day for this genus, collapsed due to overharvesting of summer spawning aggregations that produced over 80% of the mean annual catch (Erisman et al. 2011). Lastly, under conditions of high effort, even a bag limit of 1 fish per angler per day or a catch-and-release policy may fail to prevent fishery collapse caused by overharvest and release mortality, respectively (Post and Parkinson 2012).

Implementing a catch-and-release policy for a target species may cause ecological imbalances and undesired outcomes in multispecies fisheries (reviewed in Sass and Shaw 2020). Completely freeing a particular target species from harvest pressure may allow its population to grow rapidly and directly outcompete or predate upon that of another target or non-target species that subsequently is depressed in the same ecosystem (e.g., Kelling et al. 2016). This problem may notably be compounded where a newly depressed species continues to be harvested or where an already threatened species declines further, while the focal target species' population can no longer be controlled through harvest, complicating restoration of ecosystem balance (reviewed in Sass and Shaw 2020). Furthermore, the release from harvest pressure caused by a catch-and-release policy can, in some situations, cause an increase in overall abundance but not of trophy-size fish (e.g., Haglund et al. 2016), potentially as a result of density-dependent growth

(Sass et al. 2004) or an inverse relationship between fishing and natural mortality (Hansen et al. 2011).

Angler perceptions

When surveying anglers about their attitudes and perceptions of management practices, harvest quantity restrictions are often viewed as a less preferred management option (Dawson and Wilkins 1981; Cardona and Morales-Nin 2013; Murphy et al. 2015). This distaste for harvest quantity restrictions is due to the value of a potential angler day being dependent on harvest expectations; stricter limits reduce fishing day value for harvesting anglers (Swallow 1994). For example, a survey of non-resident anglers' willingness to pay for a chartered Chinook salmon (*Oncorhynchus tshawytscha*) trip in Southeast Alaska revealed that the economic value of a fishing trip effectively doubled when going from a daily bag limit of one to two (Lew and Larson 2015). Anglers that are driven more by catch size (i.e., trophy-oriented) or rate, rather than the ability to harvest, often have positive perceptions of or favor the implementation of stricter bag limits or catch-and-release policies (Anderson and Nehring 1984; Gigliotti and Peyton 1993; Aas et al. 2000; Hutt and Bettoli 2007), reflecting that they believe harvest quantity restrictions do increase stock abundance—including of trophy-size fish.

Spatial management

Recreational fisheries can be regulated via the use of spatial management, which is the area-based structuring of angler effort in a fishery. This may entail eliminating all fishing effort from an area of high catchability or providing recreational anglers with areas segregated from commercial fishing effort and that sector's use of highly effective gear.

No-take zones

A no-take zone (NTZ) is defined as the complete spatial closure of an area within which all fishing activity is prohibited. Areas selected for NTZ protection often exhibit relatively higher catchability of the target species due to their association with spatially heterogeneous suitable habitat and/or the presence of spawning aggregations. A closed area provides a refuge for target species where their populations may grow and increase in spawner biomass, with the goal of adult fish emigrating and/or larvae being exported to increase fish size and abundance in the adjacent areas where fishing is permitted. NTZ networks are modeled to achieve management goals of rebuilding spawner biomass and increasing fishery yield (Attwood and Bennett 1995b; Hastings and Botsford 2003; Hopf et al. 2019), and both telemetry and genetic studies have demonstrated export of adult and juvenile fish of NTZ-origin to adjacent fishery areas (e.g., Johnson et al. 1999; Stevens and Sulak 2001; Harrison et al. 2012). Notably, there is documentation of increased numbers of world record fish in areas adjacent to NTZs after periods of time reflecting each species time to grow to trophy-size (Roberts et al. 2001; Bohnsack 2011).

Recreational-only fishing areas

Recreational-only fishing areas (ROFAs) prohibit commercial fishing activity while allowing recreational angling. ROFAs are intended to reduce conflict among the commercial and recreational sectors of a fishery, via spatial segregation, and to increase abundance and size of fish within the area, via elimination of commercial-scale fishing technology. ROFAs have resulted in greater catches in the years after than before implementation (Einarsson and Gudbergsson 2003) and larger fish than contemporary areas open to commercial and recreational fishing (Tobin 2006). The ability of ROFAs to augment fishing quality is particularly highlighted by Cuba's establishment of the Jardines de la Reina National Park and Cayo Largo Ecological Reserve—these two ROFAs (Perera-Valderrama et al. 2018) have produced (as of January 31, 2019) $\sim$ 15% of the inshore grand slams and $\sim$ 26% of the inshore super grand slams recorded globally by the International Game Fish Association; a slam occurs when an angler catches three (grand slam) or four (super grand slam) inshore species in a day from the list of bonefish (*Albula* spp.), tarpon (*Megalops atlanticus*), snook (*Centropomus* spp.), and permit (*Trachinotus falcatus*), and is a mark of angling achievement (Jack Vitek, IGFA marketing director, chief-of-staff, and former world records coordinator, personal communication; Scott Osborne, USA representative for Avalon Cuban Fishing Centers, personal communication).

Limitations

Spatial management may fail to adequately reduce fishing mortality when such regulations do not correspond to the scale of the home-range of the target species or the distribution and dynamics of angler effort. NTZs must be of appropriate spatial configuration to enable stock recovery within their boundaries and augment fisheries in adjacent areas via adult spillover and/or larval export (Gell and Roberts 2003). More resident species can be effectively managed with smaller NTZs, while more migratory species require larger NTZs: mismatching the size of a NTZ with the target species' home-range size will curtail or negate the regulation's intended benefits (Hilborn et al. 2004). Target species with limited mobility and range as adults may be more easily protected by a small NTZ but they may also only provide spillover benefits to the immediate peripheral area (Kellner et al. 2007). Similarly, larval dispersal distances can vary among species by multiple orders of magnitude, and those with limited range may only provide highly localized benefits (Botsford et al. 2009).

Although target species populations typically increase inside NTZs, these benefits do not necessarily accrue to adjacent fishery areas (Williamson et al. 2004). Concentration of fishing effort in the areas adjacent to NTZs, caused by the displacement of anglers from formerly open areas and/or an influx of new anglers, may increase mortality beyond the replenishment provided by adult spillover and/or larval export, thereby negating potential benefits to angler welfare (Hopf et al. 2016). In parallel, target species in ROFAs may experience increases in recreational effort leading to high harvest and release mortality (Ochwada-Doyle et al. 2014; Brown 2016), meaning that maintaining quality fishing experiences within these areas is dependent on other regulations that will prevent fishing mortality from reaching pre-ROFA levels. Lastly, in mixed-sector fisheries where recreational fishing mortality far exceeds commercial fishing mortality, establishing a ROFA will exert economic hardship upon displaced commercial fishers for the benefit of only minimally reducing fishing mortality (Brown 2016).

Angler perceptions

Anglers often object to the use of NTZs in favor of other regulations that do not limit spatial opportunity (Salz and Loomis 2005; Edison et al. 2006). Establishment of a NTZ (or network thereof) represents a significant trade-off for recreational anglers that many are unwilling to accept: a possibly permanent loss of fishing area and short-term reduction in yield for a potential long-term gain in yield that may only manifest after years or even decades (Hopf et al. 2016). An additional reason for opposition to NTZs may be the strong place bonding characteristic of recreational fishing. For example, local trout anglers in South Carolina, USA, exhibit high familiarity with, rootedness in, dependence on, belongingness to, and identity with the Chattooga River (Hammitt et al. 2006). Thus, anglers prefer most other management tools over NTZs, likely because other approaches do not prevent anglers from accessing places to which they have bonded, and only influence when/how they fish or their harvesting practices in those places. In direct contrast, anglers are highly receptive to the implementation of ROFAs, as they are specifically intended to improve recreational fishery outcomes without limiting angler activity in any way (Tobin and Sutton 2011).

Temporal restrictions

Temporal restrictions limit when angling effort is permitted, often closing fishing altogether or restricting effort to catch-and-release during certain periods. Temporal restrictions are primarily implemented during periods of increased catchability to reduce fishing mortality.

Fishing closures

A temporal fishing closure prohibits all fishing activity, both harvest and catch-and-release, during a portion of the year. This reduces effort to zero on closed days, temporarily preventing fishing mortality. In high-effort fisheries, protecting target stocks during periods of increased catchability eliminates effort when they are most vulnerable and thereby curtails fishing mortality (Dunlop and Mann 2012; Maggs et al. 2012). Spawning season fishing closures help to maintain a high spawning potential ratio, prevent recruitment overfishing, and increase adult fish abundance when the fraction of the stock captured is high and capture precludes successful spawning or rearing (Gwinn and Allen 2010). Under the same conditions, minimum size limit and year-round catch-and-release regulations may result in lower spawning potential ratios and fail to prevent recruitment overfishing (Gwinn and Allen 2010).

Harvest closures

A temporal harvest closure prohibits harvest but continues to allow catch-and-release during a portion of the year. Harvest closures represent a compromise between biological and angler outcomes; they provide population-level benefits to target species while not restricting recreational opportunity, but those benefits are less than those provided by a fishing closure that fully eliminates recreational opportunity. In a largemouth bass fishery model (Gwinn and Allen 2010), a spawning season harvest closure increased the abundance of older bass by 3–4% and 8–9% for low- and high-productivity populations, respectively, relative to a fishery regulated with a minimum size limit and no temporal closure. However, the proportional increases provided by a harvest closure were 4.5–20 times and 2.2–5.6 times lower than those provided by a full fishery closure for low- and high-productivity populations, respectively, depending on the fraction of the stock captured by anglers. Assuming reproduction was prevented by capture, the harvest closure resulted in a lower spawning potential ratio than a full fishery closure in all scenarios and resulted in recruitment overfishing when the fraction of the stock captured by anglers was high (Gwinn and Allen 2010).

Limitations

The benefits of temporal restrictions may be attenuated by effort dynamics and release mortality. Reductions of available angling days and expended angling effort by temporal fishing closures may not be proportional due to effort reallocation into open time periods (Cox et al. 2002; Gao and Hailu 2011). For example, a choice experiment with European eel anglers in Germany found that instituting a monthly closure of 14 days per month, which would reduce available eel angling days by 47%, would only reduce effort by 15% (Beardmore et al. 2011). Thus, overfishing may still occur in open seasons without sufficiently restrictive regulations (Wright 1992). Release mortality of fish during temporal harvest closures mitigates gains in abundance and spawning potential, especially if there is high catchability and/or effort during those times, and can lead to recruitment overfishing (Gwinn and Allen 2010). Interference with spawning or rearing behavior, and loss of adult fish, is a potential problem that could be notably compounded in fisheries for species that provide parental care and whose eggs and/or juveniles may suffer drastic reductions in survival if not attended by adults (Ridgway and Shuter 1997; Gwinn and Allen 2010). However, empirical studies suggest that targeted catch-and-release of such species during spawning may have detrimental effects only at the individual-level, as they do not scale up to cause demonstrable change in recruitment or abundance at the population-level (Trippel et al. 2017; Sass et al. 2018; reviewed in Sass and Shaw 2020).

Angler perceptions

Temporal restrictions that prohibit fishing altogether and reduce recreational opportunities are generally disliked by anglers, often more than most other types of regulations (Hutt and Bettoli 2007; Dorow et al. 2009; Abbott et al. 2018). However, in certain fisheries, casual anglers (for whom angling has low centrality to their lifestyle) do not express significant disapproval of temporal fishing closures whereas advanced anglers (with high centrality to lifestyle) significantly dislike such closures (Loomis and Holland 1997; Dorow et al. 2010). Compared to temporal fishing closures, temporal harvest closures are more acceptable because they still permit fishing activity through catch-and-release. Furthermore, temporal harvest restrictions requiring catch-and-release only during specific seasons are largely preferred over year-round catch-and-release policies, particularly by harvest-oriented anglers or in harvest-oriented fisheries (Edison et al. 2006).

Accessibility restrictions

Accessibility restrictions reduce the ability of anglers to transport themselves to or within fishing grounds by prohibiting or limiting the use of their motorized vessels/vehicles. These are intended to reduce fishing effort, potentially in areas of high catchability, and/or habitat degradation caused by angler traffic.

Transportation constraints

In 2002, the use of vehicles on beaches was banned in KwaZulu-Natal, South Africa, effectively restricting the effort of shore-based anglers only to areas immediately surrounding public beach access points. In an area fished before the ban, the four most commonly captured species in the fishery exhibited increased mean annual catch-per-unit-effort (CPUE) and mean fork length after 2–4 years, in some instances matching levels inside an adjacent NTZ (Mann et al. 2016). The mean annual CPUE of largespot pompano (*Trachinotus botla*), one of the four aforementioned species, increased across the coast after the ban, and the degree of increase was greater farther north where fewer beach access points were available than farther south (Parker et al. 2013). The ban also eliminated the negative effects of vehicles on vulnerable beach habitat and dependent shorebirds (Williams et al. 2004).

In Florida Bay, Everglades National Park, USA, anglers frequently operate their vessels in shallow waters that support seagrass beds that act as nursery grounds for many target fish species; from 1999 to 2004 the number of motorboat propeller scars in these marine vegetated areas increased 4–5 times (Hallac et al. 2012). In response, a “pole and troll zone”, within which the use of combustion engines is prohibited and only a pushpole, electric trolling motor, or paddles may be used for propulsion (Black et al. 2015), was established within the park and five years later exhibited marked reduction in total prop scar length (Atkins Ltd. 2017).

Limitations

Accessibility restrictions redistribute effort and concentrate it within more accessible areas where overfishing may result. The beach vehicle ban in KwaZulu-Natal reduced angling effort across the region but also concentrated effort at public access points; for example, the only beach along the coast still allowing limited vehicle use after the ban continued to experience declining CPUE of largespot pompano while other less accessible areas were recovering (Parker et al. 2013). Thus, limiting the means of angler transport may provide population-level benefits to target species in less accessible areas and thereby improve fishing quality for those anglers that are still able to access them; however, those anglers forced to relocate to more accessible areas may experience reduced fishing quality if effort becomes overconcentrated. Parallel to ROFAs, an influx of new anglers into the fishery, and its less accessible areas, could negate the benefits of transportation constraints on target stocks.

Angler perceptions

Anglers exhibit mixed perceptions of accessibility restrictions because a subset of anglers may effectively be forced to relocate to potentially poorer fishing grounds while others retain the ability to access prime areas with greater fishing quality. Only 49% of anglers in KwaZulu-Natal, South Africa agreed with the 2002 beach driving ban (Dunlop and Mann 2012). Similarly, anglers in Florida were split in their opinions on pole and troll zone desirability, and also expressed differing perceptions of their effect on fishing quality after implementation (National Park Service 2014, 2015). At a given level of catch, anglers experience greater satisfaction when there is less effort by other anglers in the vicinity (Pitman et al. 2019); thus, anglers still able to reach and fish in less accessible areas may exhibit positive perceptions of the accessibility restrictions if fishing quality improves and/or angler crowding is mitigated. In contrast, anglers may exhibit negative perceptions of accessibility restrictions if they are no longer able to fish in areas to which they have bonded, paralleling angler opposition to NTZs.

Rights-based management

Rights-based management allocates exclusive rights to harvest or participate in certain recreational fisheries, so that only a subset of potential anglers may access or catch fish. As a recreational management tool, a rights-based approach provides increased control over fishing effort and may reduce uncertainty in the magnitude of fishing mortality.

Harvest tags

Harvest tags grant harvesting rights only to the anglers that obtain them; anglers without harvest tags may engage in catch-and-release fishing but cannot harvest the target species. This management approach is designed to constrain harvest by creating an additional financial cost for harvesting and/or by setting a cap on the number of available tags. Increasing the cost of participation in a fishery can discourage anglers with a lower willingness-to-pay and eliminate their contribution to fishing effort (O'Malley and Crawford 1995; Sutton et al. 2001; Beardmore et al. 2011), thereby reducing total harvest and allocating it to anglers who particularly value the experience (Johnston et al. 2007). Alternatively, tags could be numerically limited (and potentially allocated via a lottery), which would create a hard harvest limit for the entire fishery if implemented in conjunction with a bag limit (Johnston et al. 2007). An evaluation of eight recreational fisheries regulated with harvest tags found that this regulatory approach provided increased control over total harvest; in certain circumstances, they also reduced angler crowding and generated funds to support management of the tag-regulated species (reviewed in Johnston et al. 2007). The catch level data provided by harvest tags is particularly valuable, as it can be used to assess effects of recreational harvest on the target species, better inform the application of other regulations, determine appropriate resource allocation among recreational and commercial (or tribal) sectors of a fishery, and, thereby, increase the legitimacy of recreational harvest rights in mixed-sector fisheries (MacKenzie and Cox 2013).

Limited entry

Limited entry management restricts the number of anglers that can participate in a particular fishery or area by capping the number of available licenses. This reduction in angler effort is intended to increase target stock abundance and improve the fishing experience of those anglers still permitted entry. Limiting the number of anglers substantially reduces the uncertainty involved in estimating both the harvest and release mortality of the target stock, leading to more effective fishery management (Cox et al. 2002). At the local scale of a single fishery (e.g., one lake), reducing effort leads to higher fish density, lower probabilities of stock collapse and extinction, and increased angler satisfaction (Cox et al. 2003; Schueller et al. 2012). Similarly, at the regional scale with many fisheries for the same species (e.g., multiple lakes in a district), lower regional effort results in greater stock abundance, lower proportions of fisheries being overfished or collapsed, and higher angler catch rates (Hunt et al. 2011; Matsumura et al. 2019). Furthermore, limiting entry via a license cap may be necessary to reduce the human contribution to target stock decline when uncontrollable environmental stressors are present (Cahill et al. 2018), to achieve regional maximum sustainable yield while preventing localized collapses (Parkinson et al. 2004; Post and Parkinson 2012; Matsumura et al. 2019), or to create a safe operating space in which the fishery will remain sustainable under dynamic conditions (Carpenter et al. 2017).

Limitations

The efficacy of harvest tags may be undermined by variable effort and release mortality, as they may cause fishing mortality to continue to increase. In a fishery without a hard harvest limit (where a bag limit may be present but the number of tags is not capped), harvest may increase to unsustainable levels as effort increases with more anglers acquiring tags (Johnston et al. 2007). In a fishery with a hard harvest limit (where a bag limit is present and the number of tags is capped), increased effort by catch-and-release anglers (those without tags) could increase release mortality and thereby cause fishing mortality to exceed target levels (Cox et al. 2002; Sullivan 2003; Johnston et al. 2007). Furthermore, designing a harvest tag program to adequately limit harvest mortality requires investment into stock assessments, and studies of target species catchability, that will inform the level of allowable harvest. A separate consideration is that tag allocation processes may not achieve goals of equitable access across demographic groups. Assigning a price to tags may disproportionately restrict anglers with less disposable income (Johnston et al. 2007). In contrast, allocating tags via a lottery can mitigate (or eliminate) economic welfare considerations in the process but does not weigh preference for anglers for whom the tags would be of higher value (Johnston et al. 2007; Abbott 2014).

Limiting entry via a license cap may not provide the intended benefits to target stocks and fishing quality when management is applied at an overly broad spatial scale or when redistribution of displaced effort occurs. Limiting entry only at the regional level can fail to prevent widespread collapse at the local level if anglers successively concentrate effort into and overfish individual fisheries within a region (Hunt et al. 2011). In contrast, when limiting entry at the local level, the displacement of effort from limited entry fisheries (which increases their fishing quality) may reduce the total satisfaction of anglers summed across a region if enough of that effort is redistributed into open access fisheries (which decreases their fishing quality). For example, a regional-scale model of dynamic fishing effort found that limiting entry in 30% of the lakes in a region to 40% of the effort occurring under open access could increase total regional satisfaction by nearly 200% if no effort redistribution occurred (Cox et al. 2003). However, if 90% of anglers displaced by limited entry redistributed their effort to open access lakes, the aforementioned scenario could lead to $> 400\%$ decreases in total regional satisfaction; with this level of effort redistribution, $> 60\%$ of lakes would need to limit entry to 40% of open access effort to increase total regional satisfaction at all (Cox et al. 2003).

Angler perceptions

Most harvest tag programs have been well received by anglers, but others have experienced resistance to their cost or inconvenience (Johnston et al. 2007) and been less preferred than many other management strategies (Ditton and Hunt 1996; Loomis and Holland 1997; Hunt and Ditton 1998). The degree of angler support for potential harvest tag programs may be related to both target stock status and the relative restrictiveness of regulations prior to implementation. In Alberta, Canada, a local fisheries advisory group disagreed with a proposal to institute a limited number of harvest tags in a recovering walleye fishery because less restrictive harvest regulations had been in place prior to the fishery's decline and, now that the fishing quality had improved as a result of a catch-and-release policy, it argued that less restrictive regulations than harvest tags should be put back in place (Sullivan 2003). In contrast, $\sim 50\%$ of Florida, USA, anglers surveyed in 2012 agreed that goliath grouper (*Epinephelus itajara*), a critically endangered species closed to all harvest since 1990, should be reopened for harvest and exhibited a mean willingness-to-pay of \$34–\$79 for a harvest tag allowing the take of one goliath grouper per year (Shideler et al. 2015). In the former case with walleye, the proposed harvest tag program would not have provided the same freedom to harvest as anglers had enjoyed in the recent past, whereas in the latter case with goliath grouper, anglers had not been able to harvest them at all for over 20 years and wanted to regain the limited ability to do so afforded by a harvest tag program.

Anglers typically express vehement opposition to implementing limited entry in local fisheries (Walters and Cox 1999; Sullivan 2003). Some anglers are only interested or capable of participating in a single fishery and may not have the means of fishing elsewhere if displaced by a limited entry program (Sullivan 2003); the potentially complete loss of recreational opportunity in such cases contributes to angler disapproval of this regulatory strategy. In contrast, some support for limited entry programs comes from anglers who believe that quality fishing experiences for a subset of anglers may be better than poor fishing experiences for all (Walters and Cox 1999; Lester et al. 2003), consistent with the ability of this regulation to improve fishing quality for those anglers still permitted entry.

Gear restrictions

Gear restrictions limit the type or quantity of gear that anglers can use in a particular fishery. These restrictions are primarily meant to reduce release mortality but may also be implemented to reduce catchability of target species.

Gear type

Gear type restrictions mandate the use of particular fishing tackle and are intended to reduce the release mortality rate. There are many stages of a recreational angling event that influence the overall likelihood of an individual fish experiencing release mortality (including hooking, retrieval, landing, handling, unhooking, and release), thus, there is a great diversity of gear type restrictions that interact with one or more of these stages and can contribute to reducing release mortality (Brownscombe et al. 2017). For example, placing restrictions on bait type (e.g., natural vs artificial), hook shape (e.g., circle vs J), and hook type (e.g., barbed vs barbless) can all decrease release mortality of target species by reducing the likelihood of deep hooking in the gills or gut, extent of tissue damage, and/or duration of hook retrieval (reviewed in Muoneke and Childress 1994; Bartholomew and Bohnsack 2005; Davie and Kopf 2006).

Having an estimate of the release mortality rate of a target species captured with a particular gear set can enable more accurate assessments of fishing mortality and permit sustainable management of more imperiled stocks (e.g., Stokesbury et al. 2011; Phyne et al. 2013). Decreasing release mortalities increases the effectiveness of most other management strategies, particularly those that aim to reduce fishing mortality by reducing harvest mortalities (e.g., Coggins et al. 2007; Henderson 2009; Gwinn and Allen 2010), and is modeled to increase the spawning potential ratio and total angler satisfaction (Johnston et al. 2015). Lastly, in addition to reducing release mortality, certain gear type restrictions may also reduce catchability of target species intentionally, or as a side-effect (e.g., Alós et al. 2008), and even discourage angler effort (Bailey et al. 2019) if the use of a more effective gear type is banned.

Gear quantity

Gear quantity restrictions limit the amount of fishing equipment an individual angler may use per unit effort (e.g., number of rods, hooks-per-line), and therefore are used to reduce the CPUE of anglers. Stricter gear quantity restrictions may decrease fishery attractiveness and reduce angler participation (Dawson and Wilkins 1981; Beardmore et al. 2011). In a European eel fishery in Germany, reducing the rod limit from three to two or from three to one was predicted to decrease eel angling days by 2.7% or 17%, respectively; these effort reductions were comparable to those predicted when the daily bag limit of eel was decreased from three to two (−1.5% of eel angling days) or from three to one (−15% of eel angling days) (Beardmore et al. 2011).

Limitations

The ability of gear type restrictions to improve target species stocks may be undermined by high effort. A meta-analysis of saltwater, freshwater, and diadromous fish species found the mean release mortality rate to be 18% and that rates ranged from as low as 0% to as high as 95% (Bartholomew and Bohnsack 2005). Yet, under high effort, a release mortality rate as low as 5% could result in overfishing in fisheries managed with a minimum size limit (Johnston et al. 2015) or even a year-round catch-and-release regulation (Post and Parkinson 2012). Thus, while gear type restrictions may be able to reduce release mortalities, the magnitude of that reduction may not be enough to make a high effort fishery sustainable. Alternatively, the number and severity of gear type restrictions needed to potentially achieve the desired release mortality rate may result in substantial regulatory complexity. Furthermore, different species exhibit varying levels of vulnerability to release mortality and responsiveness to gear type restrictions (Muoneke and Childress 1994; Bartholomew and Bohnsack 2005; Sass and Shaw 2020); therefore, substantial species-specific work is required to determine the potential reduction of release mortality provided by such restrictions. We were unable to find a study that quantified the reduction of CPUE caused by a per angler gear quantity restriction, so the efficacy of this approach in controlling fishing mortality is unclear beyond potentially lowering effort by dissuading angler participation.

Angler perceptions

Angler receptiveness to gear type restrictions is highly variable based on the aspect of the gear that is being regulated (and its perceived effect on angler catch rate), as well as the specialization of the angler (i.e., the particular type of fishing and gear use practiced). Within a fishery, angler support for mandating the use of a specific gear type is largely associated with the type they typically use; in salmonid fisheries, anglers that regularly use bait oppose bait restrictions whereas anglers that specialize in fly-fishing support bait restrictions (Aas et al. 2000; Hutt and Bettoli 2007). Subsequently, angler preference for gear type restrictions relative to other forms of regulation is dependent on whether anglers (potentially of varying specialization) think the gear type restrictions inhibit their fishing success or provide conservation benefits without reducing the quality of their fishing experience (Hunt and Ditton 1998; Aas et al. 2000; Hutt and Bettoli 2007; Cardona and Morales-Nin 2013; Murphy et al. 2015).

Anglers generally perceive gear quantity restrictions negatively because they require changes in fishing behavior, but not as poorly as regulations that limit fishing opportunity (Dawson and Wilkins 1981; Dorow et al. 2009, 2010). However, there may be substantial variability among anglers in a fishery regarding their attitudes towards gear quantity restrictions (Lawrence 2005). This is potentially the result of anglers using different fishing methodologies; for example, anglers actively casting artificial lures or flies generally only deploy a single rod and would not be affected by a rod limit, whereas anglers fishing with bait or trolling often use multiple rods at once and would be constrained by a rod limit.

Discussion

The challenge of regulating recreational fisheries is balancing stricter regulations that impose progressively more on angler behavior with maintaining or recovering the fishing attributes anglers desire. There are a number of strategies that can contribute to controlling fishing mortality but each has its limitations. The major weaknesses of these regulations are release mortality, heterogeneous catchability, and quality-driven effort response (Table 1). Release mortalities, if extensive, can erode the effectiveness of any management strategy still permitting fishing activity to occur, particularly those that aim to conserve target stocks by limiting fishing mortality via reductions in harvest (i.e., harvest size restrictions, harvest quantity restrictions, temporal harvest closures, and harvest tags). Similarly, heterogeneous catchability in space or time undermines strategies targeting reductions in harvest or release mortality, as anglers can exert effort where/when high catchability occurs and dramatically increase (or attenuate decrease in) fishing mortality. The redistribution of displaced effort and/or influx of new effort, spatially or temporally within a fishery, undermines management strategies that prohibit or hinder effort under conditions of high catchability (i.e., NTZs, ROFAs, temporal fishing closures, accessibility restrictions), as effort and fishing mortality may continue to increase when/where fishing is allowed even under conditions of low catchability. Although angler preferences among alternative management strategies may vary by their orientation or specialization, anglers in general support improving target stocks but strongly prefer approaches that do not limit their opportunity. Temporal fishing closures, NTZs, and limited entry directly restrict the opportunity of anglers, and harvest quantity restrictions reduce or eliminate an important aspect of the fishing experience to harvest-oriented anglers. In contrast, harvest size and gear restrictions do not prevent anglers from fishing and only affect which fish can be harvested or the fishing methodology of anglers.

Management intervention creates a trade-off for anglers in which potential welfare gains from a particular regulation (e.g., the increase in abundance and/or size of the target species as a result of implementation) are weighed against the welfare losses (i.e., the additional behavioral impositions) and determine net benefit or loss. For example, anglers in Virginia, USA exhibit increased willingness-to-pay for additional and larger cobia (*Rachycentron canadum*) caught but are more likely to target other species if more restrictive harvest regulations for cobia are implemented (Scheld et al. 2020). Similarly, socially optimal minimum size limits are higher for target species whose life history type makes them more vulnerable to overfishing, and the magnitude of the net welfare benefit under optimal regulation changes with angler orientation (Johnston et al. 2013). Evaluating these trade-offs for anglers when comparing regulatory alternatives is key to the identification of best management practices that consider both biological and social outcomes. A hindsight assessment of the regulatory options considered to address overfishing of two groundfish species in the Gulf of Maine concluded that the policy that was implemented in 2014 decreased angler welfare the most but did not yield a faster rebuilding time for the stocks (Lee et al. 2017). In contrast, the quantification and incorporation of angler welfare trade-offs into management decision-making enabled identification of regulations that should help meet biological recovery targets for overfished striped bass (*Morone saxatilis*) and minimize welfare costs to anglers in the US Atlantic (Carr-Harris and Steinback 2020).

The heterogeneity in angler preference for the different regulatory strategies poses a difficult problem for fisheries managers, given that they have unequal potential to affect fishing mortality. Harvest and release mortality are post-capture processes, meaning that regulations that lower the number of

Table 1 Summary of the intended biological benefits, potential limitations, and angler perception of each approach to regulating recreational fisheries

Strategy	Regulation	Benefits	Limitations	Angler Perception
Harvest Size Restrictions	Minimum size limit	Reduce harvest, conserve future stock productivity	High release mortality rate, heterogeneous catchability, increase in effort	Highly preferred by all orientations due to minimal behavioral imposition, less so by harvest-oriented anglers due to reduced harvest
	Maximum size limit	Reduce harvest, conserve current stock productivity	High release mortality rate, heterogeneous catchability, increase in effort	Highly preferred by all orientations due to minimal behavioral imposition, less so by harvest-oriented anglers due to reduced harvest
	Slot limit	Reduce harvest, conserve future and current stock productivity	High release mortality rate, heterogeneous catchability, increase in effort	Highly preferred by all orientations due to minimal behavioral imposition, less so by harvest-oriented anglers due to reduced harvest
Harvest Quantity Restrictions	Bag limit	Reduce harvest, possibly limit effort of individual anglers at unit of time defined by limit	Affect only most successful anglers, high release mortality rate, overharvest of species in aggregate limit, heterogeneous catchability, increase in effort	Disliked by harvest-oriented anglers due to reduced fishing day value, more preferred by trophy and general anglers
	Catch-and-Release	Eliminate harvest	High release mortality rate, heterogeneous catchability, increase in effort, ecological imbalance among species	Most disliked by harvest-oriented anglers due to maximal welfare cost, more preferred by trophy and general anglers
Spatial Management	NTZs	Eliminate effort in high catchability areas	Spatial scale mismatch, localized benefits, increase in effort in open areas	Highly disliked by all orientations due to short-term yield loss, potentially permanent restriction of opportunity from areas to which anglers may be bonded
	ROFAs	Eliminate commercial effort in high catchability areas	Increase in effort, economic hardship in commercial sector	Highly preferred by all orientations due to exclusion of commercial fishing
Temporal Restrictions	Fishery closure	Eliminate effort during high catchability periods	Increase in effort during open times	Generally disliked by all orientations due to reduction of available fishing days, less so by general anglers
	Harvest closure	Eliminate harvest during high catchability periods	High release mortality rate, increase in effort	Generally preferred by all orientations, less so by harvest-oriented anglers
Accessibility Restrictions	Transportation constraints	Inhibit effort in high catchability and sensitive habitat areas	Increase in effort	Mixed preferences due to relocation of some anglers into poorer fishing grounds
Rights-Based Management	Harvest tags	Reduce or cap harvest, possibly cap effort if no catch-and-release allowed	High release mortality rate, heterogeneous catchability, possible increase in effort depending on implementation, tag allocation inequity	Generally preferred by all orientations, some resistance to cost or inconvenience
	Limited entry	Reduce and cap effort	Overly broad spatial scale, redistribution of effort	Highly disliked by all orientations due to potential exclusion from favorite or only accessible fishery

Table 1 continued

Strategy	Regulation	Benefits	Limitations	Angler Perception
Gear Restrictions	Type	Reduce release mortality rate, possibly also catchability	Heterogeneous catchability, increase in effort	Mixed preferences depending on the gear specialization of the angler and effect on fishing success
	Quantity	Undocumented beyond possible dissuasion of effort	High release mortality rate, heterogeneous catchability, increase in effort	Generally disliked due to behavioral imposition

fish being caught (and subjected to those processes) have greater potential effect on fishing mortality than those only reducing the number of captured fish that are harvested or the number of captured fish that die incidentally after release. Thus, regulations such as spatial management, temporal fishing closures, accessibility restrictions, and limited entry that directly reduce or influence angler effort, particularly in its interaction with spaces or times of high catchability, have the ability to more substantially influence fishing mortality. In contrast, harvest size restrictions, catch-and-release policies, and gear restrictions affect the post-capture processes of harvest or release mortality and do not directly curb or influence angler effort—although gear restrictions may also affect catchability. Harvest tags and bag limits, depending on their implementation (e.g., whether the number of tags is capped, whether fishing must cease after filling a limit) may or may not constrain or dissuade angler effort in a fishery in addition to reducing the number of captured fish that get harvested. Thus, regulations that aim to modulate effort, catchability, or their interaction, have greater potential (but are not guaranteed) to reduce fishing mortality more than those primarily targeting only the post-capture processes of harvest or release mortality.

However, there are two notable problems. First, anglers largely favor the use of regulations that impose less on their behavior and therefore have less potential to control fishing mortality (Table 1). Some of these strategies may dissuade angler participation and thereby reduce effort but that reduction will be ephemeral if new anglers enter the fishery when fishing quality improves. Second, among the strategies that target effort, catchability, or their interaction, limited entry is the only regulation that can guarantee a substantial fishery-wide reduction and cap to its associated process. Although NTZs, ROFAs, temporal fishing closures, and accessibility restrictions all prohibit or inhibit effort, most effectively in areas or times of high catchability, they do not guarantee a reduction in fishery-wide effort since they do not cap effort in areas or times during which fishing is still allowed. As a result, their biological effectiveness depends on the decrease in fishing mortality in restricted areas or times of high catchability exceeding the potential increase in unrestricted areas or times of low catchability, which is uncertain given responsive effort.

Given the aforementioned strengths and weaknesses of each individual strategy, an appropriate combination of regulations for a recreational fishery can be determined by three metrics; (1) the spatiotemporal heterogeneity of catchability, (2) the mean fraction of the stock caught, and (3) the relationship between catchability and stock abundance. First, as catchability becomes more spatiotemporally heterogeneous, spatial management, temporal restrictions, and/or accessibility restrictions become increasingly applicable because they prevent or reduce effort in spaces or times of high catchability that could greatly scale fishing mortality. Implementing these regulations in a fishery with spatiotemporally homogeneous catchability could restrict angler behavior for comparatively less biological benefit. Second, as the mean fraction of the stock caught increases overall, management generally should shift from using laxer harvest or gear restrictions to stricter versions of those strategies, in conjunction, to reduce the number of mortalities post-capture. This can be further supported by restrictions on more effective gear types (thereby reducing catchability and possibly discouraging effort) to try to reduce the number of fish being caught. Although moderate harvest can yield increased catch of trophy-fish under conditions of strong density-dependence (Ahrens et al. 2020), excessive harvest due to high fishing pressure will necessitate implementation of stricter regulations (if not using habitat enhancement and/or stocking programs). However, we advise caution when combining bag and size limits in a fishery with a high release mortality rate, as restrictive size limits could cause harvest-oriented anglers to increase their effort to achieve the bag limit as they are forced to release many fish not of legal size – a process that may actually increase fishing mortality due to release mortality (Woodward and Griffin 2003). Third, if the relationship between catchability and stock abundance is negative, the use of harvest tags and/or limited entry should be considered to reduce or cap effort due to the increased susceptibility of such stocks to collapse. In some fisheries, catchability increases as stock abundance decreases, leading to hyperstability in CPUE that can mask declines in abundance until the stock collapses and the fishery is forced to close (Peterman and Steer 1981; Shuter et al. 1998; Hansen et al. 2005). Other fisheries exhibit no relationship between catchability and abundance, or a positive one (Wilberg et al. 2010), permitting more accurate or conservative monitoring that makes them more likely to be adequately regulated without resorting to effort limitations (Newby et al. 2000). By considering the three aforementioned metrics in tandem, managers can hone in on an appropriate combination of regulations that is likely to achieve the requisite biological outcomes without undue social costs. Regionally, managers can implement combinations of regulations that all achieve biological goals but offer different angling experiences in each fishery, thereby providing opportunities tailored to each specialized angler group (van Poorten and Camp 2019). It is important to note that the least socially acceptable option of limiting entry may be required to salvage a fishery (Cox et al. 2002; Cahill et al. 2018) if pervasive effort continues to maintain fishing mortality at an unsustainable level even after implementation of particularly restrictive regulations and/or aggressive habitat enhancement and stocking programs. Ultimately, managers must decide whether to take a more proactive approach, in which stricter regulations are implemented early to prevent or mitigate future stock decline, or a more reactive approach, in which progressively stricter regulations are implemented in response to ongoing stock decline; in fisheries where anglers have minimal ability to select among species, the reactive approach may incur substantially higher costs if persistent bycatch of an imperiled species eventually necessitates a fishing closure inclusive of highly-valued target species (Anderson et al. 2013).

The most biologically effective regulations in commercial fisheries, those establishing a total allowable catch (Anderson et al. 2019), are largely absent in recreational fisheries (see exceptions in Hansen et al. 1991; Tsehaye et al. 2016). Although limited entry is increasingly suggested as a solution to excessive effort in recreational fisheries (e.g., Cox et al. 2003; Schueller et al. 2012; Post & Parkinson 2012; Cahill et al. 2018), this strategy often fails to meet biological goals in commercial fisheries because economic motivations induce increases in individual effort and investments in gear enabling higher catchability of target species (Eigaard et al. 2014; Anderson et al. 2019). A recreational limited entry program could overcome the issue of increases in individual effort by not only limiting the number of anglers but also the number of fishing days per angler; however, this would likely face strong opposition due to further reduction in fishing opportunity. Particular advances in recreational fishing technology, such as braided line and electric reels that enable anglers to more effectively and efficiently target benthic and demersal fishes in deeper waters, or electronics permitting more targeted ice fishing (Feiner et al. 2020), suggest that there is potential for technology to increase catchability even in recreational fisheries. This additional issue could be addressed with gear type restrictions but would also likely face strong opposition due to reduction in fishing success. Another potential source of increasing catchability is the segregation of anglers by experience, as catchability can vary by an order of magnitude among anglers of different skill levels (Ward et al. 2013; van Poorten et al. 2016). In fisheries with decreasing fish densities, less skilled anglers with low individual catchability are unable to achieve satisfactory catch rates and cease participating, whereas highly experienced anglers with high catchability are able to achieve sufficient catch rates despite the decreased fishing quality and continue to participate – a process that yields a higher average catchability (i.e., skill level) of the remaining anglers (Ward et al. 2013; van Poorten et al. 2016). However, this is unlikely to occur in a limited entry fishery where reduced effort would increase fishing quality and attract experienced and general anglers alike. Thus, while there are ways to implement limited entry and combine it with other regulations to avoid the failures documented in commercial fisheries, such restrictive programs are likely to create tension among recreational fisheries managers and anglers and potentially lead to noncompliance.

The potential benefits provided by regulations to biological and angler outcomes are mitigated in fisheries experiencing noncompliance (Gigliotti and Taylor 1990; Post et al. 2003; Kritzer 2004; Johnston et al. 2015). For example, most rockfish (*Sebastes* spp.) NTZs in British Columbia, Canada continued to experience fishing effort after their establishment (Haggarty et al. 2016). Noncompliance may arise from intentional violations of regulations, which increases as fishing quality declines (Sullivan 2002), or unintentional violations, which may be caused by a lack of awareness or confusion over regulatory complexity (Schill & Kline 1995; Page and Radomski 2006). Unlike mechanisms of management failure that undermine certain regulations but are overcome by other approaches (e.g., heterogeneous catchability is a weakness of bag limits but may be addressed with NTZs), noncompliance can attenuate or negate the benefits of any regulation or combination thereof—making it a universal issue regardless of the regulation(s) employed. Managing agencies are unlikely to have the funding for complete enforcement coverage, and punishing anglers who intend to comply with complex regulations, but accidentally fail to do so, can erode trust in the managing agency (Schill and Kline 1995). Thus, it is paramount that fisheries managers implement regulations in a fashion that minimizes the likelihood of noncompliance (Potts et al. 2019). This can potentially be achieved by including anglers in the decision-making process, which increases their understanding of, support for, and perceived legitimacy of implemented regulations (Daigle et al. 1996; Sutton and Tobin 2009). In addition, a ‘nudge’ approach promoting resource stewardship (Mackay et al. 2018) could improve compliance to formal regulations (Bova et al. 2017) and/or increase angler practice of voluntary, conservation-minded behaviors (Cooke et al. 2013). Lastly, carefully designed signage, brochures, or other educational materials can be used to increase angler awareness of regulations and the rationale for their implementation (Martin et al. 2015).

Regardless of the regulations used, an obstacle to successful management of recreational fisheries is uncertainty in the dynamics of fishing mortality. This stems from unquantified parameters and the unknown functional forms of the relationships among them, particularly catchability as a function of stock abundance (Post 2013). For example, if a regulation is successful in improving the abundance and/or average size of the target stock in the short-term, it may increase angler satisfaction and attract more effort to the fishery in the long-term, potentially until it collapses (sensu Cox and Walters 2002). Additionally, although release mortality has been studied for a number of species (reviewed in Muoneke and Childress 1994; Bartholomew and Bohnsack 2005; Sass and Shaw 2020), such estimates are still lacking for the overwhelming majority of recreationally-targeted species globally. Furthermore, the rate of depredation, which occurs when a predator consumes a hooked fish during the fight with the angler and precludes its capture, is unknown in most recreational fisheries even though it may represent a substantial source of incidental mortality (Mitchell et al. 2018). For example, catch-and-release fisheries for permit (*Trachinotus falcatus*) in the Florida Keys, USA have documented depredation rates up to 90% on shipwrecks where these fish form spawning aggregations (Holder et al. 2020). Managers should strive to use existing methods (e.g., McCluskey & Lewison 2008; Ward et al. 2013) to reduce uncertainty in the parameters contributing to fishing mortality (i.e., effort, catchability, harvest, and release mortality) and, thereby, better inform their management strategies, as well as anglers of the need for particular regulations.

Thus, to reduce uncertainty and identify appropriate regulations, recreational fisheries managers need information on both angler behavior and target species characteristics. First, understanding the composition of anglers in a fishery, their catch and harvest rates, fishing methodologies, effort levels, and responses to different management approaches, including how and to what degree displaced effort will be redistributed, will aid in determining the potential biological and social outcomes of a given regulation (Attwood and Bennett 1995a; Johnston et al. 2010; Beardmore et al. 2015). Second, knowledge of target species abundance, life history, demographics, and biology, including size- and age-at maturity, spawning phenology, population productivity, home-range size, physiological tolerance, and susceptibility to depredation, will assist in identifying the regulatory strictness needed to achieve the desired biological goals (Attwood and Bennett 1995b; Post et al. 2003; Gwinn and Allen 2010). Additionally, combining information on angler behavior with target species characteristics will facilitate estimation of the release mortality rate as well as identification of the stage(s) during the recreational angling event contributing most to that rate.

Recreational fisheries managers must realize that they are not just managing target stocks for sustainability, but also the experiences of anglers for their pleasure, subsistence, or livelihood. While biological sustainability is a key consideration of recreational fisheries management (and the top priority in fisheries for wild stocks), some managers do not appreciate the importance of the social considerations of their mandate (Radomski et al. 2001). This is a misleading perspective that fails to recognize the social-ecological feedbacks inherent to recreational fisheries (Arlinghaus et al. 2013; Ward et al. 2016; Pitman et al. 2019) and the importance of these fisheries to their participants and stakeholders. Similarly, some anglers argue that the impact of recreational fishing on target stocks is small (especially relative to commercial fishing) because individually they harvest few fish and cause few incidental mortalities (Tobin and Sutton 2011; Gallagher et al. 2015). This fails to recognize that the aggregate of anglers has population-level impacts that can contribute to stock collapse (reviewed in Cooke & Cowx 2004, 2006; Lewin et al. 2006). Recreational fisheries management is a fine balance of target stock health and angler satisfaction, and the full diversity of regulatory approaches should be assessed when determining how best to combine them and simultaneously maintain sustainability and angler welfare.

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Declarations

Conflict of interest MCA is a member and unpaid representative of the International Game Fish Association (IGFA) but the views expressed in this manuscript do not necessarily represent those of the IGFA. Furthermore, neither the IGFA nor the funder had any involvement in study design, manuscript preparation, or the decision to publish. CMA, RFB, CD, EAF, and ARJ declare no conflict of interest.

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