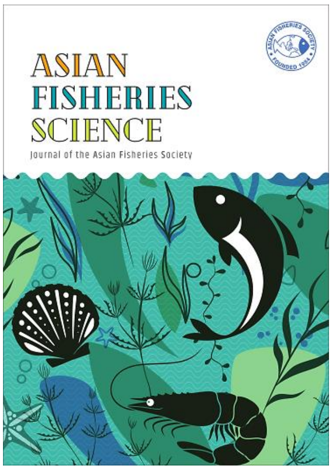

Intensive Fishing Effort and Market Controls as Management Tools for Invasive Aquatic Species: A Review

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Abstract

Invasive aquatic species may disrupt ecosystems and cause socioeconomic damage. Biosecurity protocols were developed to prevent transport and unintended introductions of invasive species, but less attention has been paid to management once they become established. The use of classical fisheries stock assessment to determine levels at which selectively targeted fisheries elicit recruitment overfishing is discussed. Case studies of several species of invasive aquatic organisms, including lionfish *Pterois* spp. two species of mytilids and three species of crayfish, including *Faxonius rusticus* (Girard, 1852), are discussed as examples. Fecundity as measured by egg production rate (EPR) is a key factor determining how the various species react to fishing pressure. Ecosystem modelling of predator-prey relations between indigenous and invasive aquatic species suggests that restricting fishing effort on indigenous predators of invasive prey may be as effective in managing invasive species in lieu of directly increasing fishing effort on the targeted species itself. Invasive mytilids *Dreissena polymorpha* (Pallas, 1771) and *Mytella strigata* (Hanley, 1843) may not be effectively controlled by intensive fishing effort due to high EPR values. However, crayfish that brood offspring and exhibit much lower EPR values may be ideal candidates for stock assessment and setting fishing effort targets to promote recruitment overfishing. Recommendations for managing invasive aquatic species include: collecting data on population dynamics of the invasive species; assessing predator populations; developing fisheries that target the invasive species; and collecting socioeconomic data to understand the human dimensions of the impacts of the invasive species and inform subsequent policy development.

Keywords: invasive aquatic species, recruitment overfishing, invasive species management, *Pterois*, lionfish

Introduction

In a review of economic and ecological impacts of various invasive species in the United States, Lodge et al. (2006) provided a framework for understanding the time course of biological invasions and the types of interventions required to control invasive species based upon stage within their specific invasion time course. The identified stages of biological invasions included: i) invasive species entering the invasion pathway; ii) transport and live release; iii) population establishment; iv) spread; and finally, v) ecological, human health and economic impacts. At each stage, they provided general recommendations to address the five respective invasion stages: i) risk screening of potentially invasive species; ii) prevention by reduction of species in the invasion transport pathways; iii) early detection, rapid response and eradication; iv) controlling and slowing the spread; and finally, v) human adaptation, including behaviour change and bearing the costs and mitigating benefits.

Blackburn et al. (2011) and Marbuah et al. (2014) reviewed the considerably growing biological invasion literature focusing on the wide discrepancies of documented economic impacts by various invasion events in different locations worldwide and the frequency of studies at each of the five stages at which possible intervention can occur to eliminate, control, manage or mitigate potential damage. They concluded that most of the effort in controlling invasive species focused on policies for mitigating dispersal by trade and shipping, which is regarded as one of the most important vectors for the spread of invasive species. The precautionary principle has been applied as a foundational basis for the importation of aquatic species, thus proving to be a somewhat effective tool for controlling transport and live release of invasive species prior to population establishment (e.g. FAO, 1996; Tang et al., 2013; Sampaio et al., 2015). Likewise, the costs and benefits of early detection and mitigation of invasive species compared to later interventions after their establishment have been studied extensively. For example, prevention, early detection, and rapid response are the least expensive options for managing invasive species (Simberloff, 2009). However, the literature on how to best control or mitigate already established invasive species within the framework of the precautionary principle is much more scant. A few studies have suggested that harvesting and consuming invasive species may be a means for controlling their populations (e.g. Thresher, 1997; Franke, 2007).

In response to efforts to harvest and market invasive species, it has been suggested that the creation of new markets for invasive species might lead to economic conditions that could exacerbate their spread (Nuñez et al. 2012). In addition to creating markets for a problematic species that, with time, would need to be maintained if they proved to become conspicuously lucrative (Lambertucci and Speziale, 2011), there is also the added risk of promoting further invasions into adjacent areas by illegal or unregulated stocking (Johnson et al., 2009).

The aim of this review is to explore the application and limitations of fisheries stock assessment protocols and modified fisheries management techniques to control invasive aquatic species, particularly when invasive species may have economic value in seafood markets. An economically viable fishery may be developed for some invasive aquatic species, but considerable care must be taken to avoid economic incentives to expand markets beyond officially agreed upon fishery landing targets. These precautionary actions would be aimed at preventing the creation of incentives for entrepreneurs to proactively facilitate their spread and possibly engage in increased production through aquaculture or other means to meet growing market demand.

Strategic Overfishing as a Management Strategy for Aquatic Invasive Species

In a landmark study of factors influencing the collapse of marine ecosystems, Jackson et al. (2001), using a retrospective data analysis approach, observed that overfishing was the single major factor preceding all other anthropogenic stressors in time, including ecosystem stress by invasive species, as the key driver leading to the collapse of several marine ecosystems that they studied. They showed that economically important species would tend to be overfished over time and the niche occupied by that species would be replaced by a species with lesser niche specialisation, until that newly prominent species, in turn, developed a larger market and became overfished as well. This phenomenon of 'fishing down the food chain' was described for marine fisheries by Pauly et al. (1998), who analysed worldwide fishery catch data between 1950 and 1994 maintained by the United Nations-Food and Agriculture Organization (UN-FAO). They deduced that chronic recruitment overfishing was occurring among more valuable fishery target species that typically occupy higher trophic levels in aquatic food chains. These studies suggest that deliberate selective overfishing of introduced nuisance aquatic species could potentially result in reverse niche replacement by more desirable indigenous species as well if the invasive species were effectively removed, especially in cases of higher trophic level species. At the very least, in theory, heavy fishing upon the introduced species could keep their populations under control and mitigate adverse ecological, economic and social impacts.

Fishery stocks grow as a result of 'recruitment' (R) of young individuals into the fishable stock, and the 'growth' (G) of these recruits, thus contributing to stock biomass. Likewise, fishery stocks decline either by 'natural mortality' (M) or by 'fishing mortality' (F), the rate at which they are caught by fishers (e.g. Hoggarth et al., 2006). Fisheries management plans by the fishery management agency will derive information from a stock assessment that will include determinations of stock recruitment, growth, natural mortality and fishing mortality rates, as well as estimates of the fisheries yield in both biomass and monetary value, the level of fishing effort, the effort costs, and finally, standing biomass of the targeted fishery stock. From all the information derived from the stock assessment, models of the stock status can be constructed to inform policies designed to adjust levels of fishing effort to achieve management goals (Fig. 1).

Benchmark effort management targets include maximum economic yield (MEY and maximum sustainable yield (MSY) as measures of maximum economic return and maximum catch biomass sustainably landed, respectively. The economic break-even point, the point at which fishing effort costs exceed the value of the catch, often corresponds to some reduced percentage of egg production rate (EPR) of spawning stock that affects rate of stock recruitment. Most frequently, an egg production rate of 10 % of those from unfished stocks (10 % EPR) is recognised as a benchmark level likely to induce recruitment overfishing (Fig. 1). Beyond this species-specific critical EPR, stocks are prone to

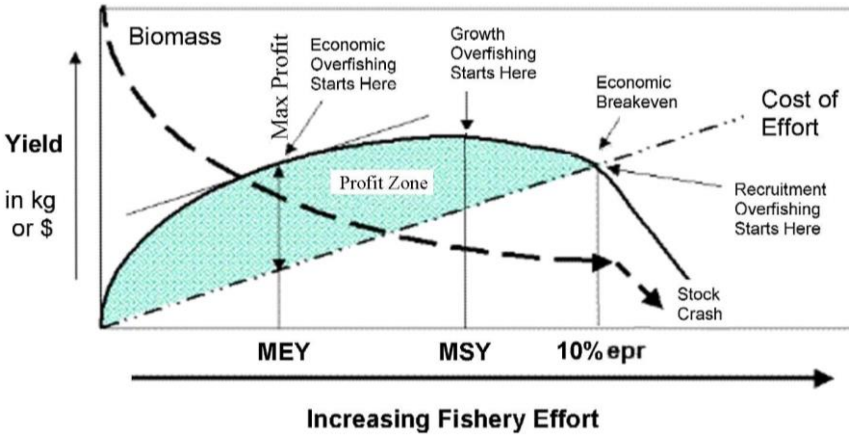

Fig. 1. A conceptual bioeconomic model of a hypothetical fishery based on the static Gordon-Schaefer model showing relative fishery biomass and yields in response to increasing fishing effort, with cost of fishing effort increasing proportionally to the amount of fishing effort exerted. Stock biomass decreases in response to the level of fishing effort. Benchmark fishery effort levels include maximum economic yield (MEY), maximum sustainable yield (MSY) and 10 % egg production rate (EPR). Figure is modified after Parven et al. (n.d.).

catastrophic collapse due to recruitment failure. Typically, management goals employed by fisheries management authorities may be to maximise the sustainable catch over time, so regulations would be to manage total fishing catch or effort near the level of MSY. Alternatively, if the management authority were more interested in the economic efficiency of the fishery, catch or effort might be set at the lower MEY level that has been favoured by fishery managers in Australia and New Zealand (Pascoe et al., 2016). However, one study suggests that if the revenue generated by post-harvest fishery market chains is taken into consideration, this may actually shift MEY toward equivalence with MSY (Christensen, 2010). Finally, if the management goal were to deliberately overfish a stock in a selective manner, such as targeting an aquatic invasive species, no catch limits might be recommended, and perhaps, subsidy payments for gear or other incentives to fishers that lower their cost of fishing might even further the goal of extirpation or eradication.

Fisheries for Invasive Indo-Pacific Lionfish *Pterois* spp. in the Northwest Atlantic

Invasive reef-dwelling lionfish exemplify the type of aquatic organisms that might be controlled by a directed fishing effort that would be informed by ongoing stock assessments. Two species of the invasive Indo-Pacific lionfish, *Pterois miles* (Bennett, 1828) and *Pterois volitans* (Linnaeus, 1758) have become problematic invasive species in the Northwestern Atlantic Region, including the Southeastern United States and parts of the Caribbean since their first discovery in south Florida in the 1980s. These two lionfish species are very similar morphologically and can be best distinguished by genetic analysis (Hamner et al., 2007). The introduction of these lionfish species was likely due to the aquarium trade (Semmens et al. 2004). Population analysis and studies of the rate of spread of the lionfish has led to predictions by Hare and Whitfield (2003) of ecosystem impacts resulting from predation by the lionfish and that would require active management. They predicted that without management action, lionfish densities along the Southeastern USA coast would continue to increase and that ecosystem effects of this increase would become more noticeable as time progressed. These predictions were fulfilled within a decade. The lionfish progressed from being locally abundant in South Florida in the 1980s & 1900s to appear in North Carolina and seasonally in Long Island Sound, New York, by 2000. By 2009, the lionfish were distributed among these locations, as well as throughout the entire Greater and the Lesser Antilles, Bermuda, the along mainland Caribbean coast from the Yucatan Peninsula to Venezuela, and seasonally as far north as southern New England, including Rhode Island's Narragansett Bay (Schofield, 2009).

The implementation of active control measures for lionfish became mildly controversial as suggestions that populations of Caribbean groupers *Epinephelus stiatus* (Bloch, 1792) and *Mycteroperca tigris* (Valenciennes, 1833) might serve as natural predators for the invasive lionfish (Maljkovic et al., 2008). Mumby et al. (2011) studied lionfish predators in a marine reserve area in Exuma Cays in the Bahamas that had been closed to fishing for 20 years and grouper populations were unusually high. They showed that the groupers at this site could effectively act as predators of lionfish and potentially control invasive lionfish populations, but unfortunately, throughout most of the invasive range of the lionfish, Caribbean grouper populations have been overfished to the point that top predator populations could not effectively serve as a practical means to control the lionfish. Sadly, this is yet another example of overfishing as a driver of loss of aquatic ecosystem resiliency, similar to other examples presented earlier by Jackson et al. (2001). In fisheries management terms, the lionfish stock experiences reduced natural mortality rates by reason of fewer available predators such as the groupers. As a result, within some areas of the new range of lionfish, their population densities appear to be orders of magnitude higher than observed in their native range (Green and Côté 2009; Grubich et al. 2009).

In an extensive review of lionfish biology and the exponential expansion of lionfish populations in the Southeastern United States and the Caribbean, Morris and Whitfield (2009) concluded that import limitations on potentially invasive species and early detection and rapid response to invasive species such as the lionfish are the most cost-effective means for preventing future invasions. They also recommended developing a fishery for lionfish as a means for control and management once they had become established, and recommending research into the lionfish population dynamics, socioeconomic impacts on communities, and means to control the invasive species. Recommended research into lionfish control measures included: development of collection/harvest techniques, identifying lionfish refuges; assessing removal strategies, and assessing all other management options.

The use of intensive fishing as a means to control lionfish throughout its new range was proposed by Barbour et al. (2011), who noted that there were localised efforts were beginning to remove lionfish throughout their new range. They used an age-structured population model to evaluate the potential efficacy of lionfish removal programs and identified some critical data gaps. In the model, they used high and low estimates for uncertain parameters, and given these uncertainties, the model predicted an annual exploitation rate between 35 and 65 % would be required to cause recruitment overfishing on lionfish populations given reasonable estimates of their natural mortality and size-related catchability coefficients. In the model, at the end of selective fishing, lionfish rapidly recovered from high removal rates, reaching 90 % of unfished biomass in 6 years after a 50-year simulated fishery removal program. Based on the apparent resiliency of the species, they concluded that complete eradication of lionfish through fishing would be highly unlikely and that substantial reduction of adult populations will require a long-term commitment to maintaining the fishery to keep populations in check. Indeed, Aguilar-Perera (2013) discussed the implementation of long-term unrestricted fisheries for lionfish in Mexico provided that there are training programs for fishers and processors given the venomous nature of lionfish spines and the risks involved.

Although there have been few direct studies of lionfish as a fisheries stock per se in which the various fishing effort benchmarks have been determined, there is a recent ecological modelling study. Chagaris et al. (2017) used a modified version of the Ecopath/Ecosim software specific for the West Florida Shelf in the eastern Gulf of Mexico (Christensen and Walters, 2004) to test various fisheries management protocols that might be used to control lionfish populations. Using known population parameters and some reasonable estimates of others, they studied community effects over a range of harvest scenarios for both lionfish and native predators such as the Caribbean groupers. Results indicated that even modest increases in lionfish harvest (F~0.1) can reduce peak equilibrium biomass by up to 25%, and much higher levels of fishing effort (F~2.0) could lower lionfish equilibrium biomass 15-fold. Reduction in fishing effort upon native reef fish predators such as the groupers could also contribute to lower lionfish densities and contribute overall to greater species diversity within the system.

This ecosystem modelling approach using Ecopath may assist managers in determining target harvest levels of lionfish depending on management goals and simultaneously inform the assessment and overall management of other valuable reef fish fisheries. However, this ecosystem modelling approach is very data-intensive, often beyond the capability of many fisheries management and conservation agencies, particularly in developing countries where the impacts of the invasive species might be most acute. It may be simpler for these fisheries management agencies to engage in classic catch and effort data collection and estimates of stock biomass of fish size/age classes as previously outlined, yielding recommendations for levels of fishing effort. Direct studies of lionfish fishery effort and stock status using targeted stock assessment methodologies throughout their invasive range should validate and refine this important ecological modelling study over much wider geographic areas. Indeed, a recent study by Malpica-Cruz et al. (2021) demonstrated the utility of fishery stock assessments and market analyses of the attempts to control lionfish populations in the Yucatan Peninsula area of Mexico by building up artisanal fisheries and promoting recreational fishing tournaments to control lionfish populations locally. Their population surveys showed a ~ 60 % reduction in lionfish density on Cozumel reefs over a 2 year period (2013–2015). But as the fish populations declined, the fishery's apparent success as a control tool was apparently the source of its own demise. A reduction in landings was followed by evaporating market interest and loss of economic viability. This suggests that if fisheries are to be established and used as management strategies to control future invasions, managers must collect fishery stock assessment data, including catch and effort data and enter into strategic collaboration with commercial fishing partners to maintain the economic viability of the enterprise in some way.

Potential Control of Invasive Crayfish by Directed Fisheries

Invasive freshwater crayfish are becoming problematic worldwide, but once harvested, they are easily marketed in many countries, suggesting that directed fisheries could be developed and sustained. A growing body of literature suggests that habitat change through global climate change (global warming) could be a major factor in influencing habitat suitability for aquatic invasive species, thus influencing their spread and resiliency in new habitats and having both ecological and socioeconomic ramifications. In a review of the mechanisms likely to contribute to the enhancement of invasions by exotic aquatic organisms, Rahel and Olden (2008) identified five potential mechanisms that could be exploited by potentially invasive species, including: altered thermal regimes, reduction of ice cover in polar regions, altered streamflow or marine current patterns, changes in salinity, and increased water development and utilisation. In a meta-analysis of 71 previous studies of climate change and invasive alien species geography, Bellard et al. (2018) found that the ranges of aquatic organisms, especially aquatic vertebrates and pathogens, were more likely to increase following climate change in comparison to terrestrial vertebrates or plants. For example, changing thermal regimes were particularly implicated in exacerbating the already existing spread of the North American signal crayfish, *Pacifastacus leniusculus* (Stimpson, 1857), that are known to be resistant to the crayfish pathogen *Aphanomyces astaci*, causing stress on indigenous European crayfish, *Astacus astacus* (Linnaeus, 1758) (Makkonen et al., 2012). This spread of *P. leniusculus* has been occurring in Great Britain (Rodriguez-Valido et al., 2020) and elsewhere around the world, where fisheries for the crayfish have developed (Zhang et al., 2019).

Faxonius rusticus (Girard, 1852) (=*Orconectes rusticus*) is a crayfish native to the lower Ohio River watershed in Indiana and Western Ohio that has spread as an invasive species within North America well beyond its native range, mostly into locations in Wisconsin, Michigan and Minnesota, but into at least 17 other U.S. states as well (Hobbs et al., 1989). At least at a localised level, *F. rusticus* can be controlled by a combination of intense trapping efforts and harvest restrictions on known predatory species, as shown in a study in Sparkling Lake in northern Wisconsin (Hein et al, 2007). During a 5-year trapping study, catch rates of crayfish declined in the lake by approximately 95 %, from 11 crayfish per trap per day in 2002 to 0.65 in 2004. Although the crayfish were not completely extirpated from the lake, the catch rate in 2005 remained low at 0.5 crayfish per trap. The ability of *F. rusticus* to be controlled by trapping and predator control appears to correspond to its relatively low fecundity as measured by EPR (Table 1).

Table 1. Relative fecundity (EPR) of selected species and estimated likelihood of control by application of high-effort fishing and market restrictions.

Species	EPR (eggs. female^{-1} yr^{-1})	Reference	Likelihood of reaching 10 % EPR	Relative market demand	Potential for spread
Pterois miles (Bennett, 1828)	2,900,000	Gardner et al. (2015)	Low	Moderate	High
Pterois volitans (Linnaeus, 1758)	2,330,000	Fogg et al. (2017)	Low	Moderate	High
Cherax quadricarinatus (von Martens 1868)	750	King (1993)	High	Very high	High
Procambarus clarkii (Girard, 1852)	450	Jin et al. (2019)	High	High	Moderate
Faxonius rusticus (Girard, 1852)	101	Houp (1981)	Very high	Low	Moderate
Dreissena polymorpha (Pallas, 1771)	300,000	Stoeckel et al. (2004)	Low	Very low	High
Mytella strigata (Hanley, 1843)	Assumed >1 million	No published estimate	Low	Moderate	High
Mytilus edulis Linnaeus, 1758	1.6 to 5.0 million	Pronker et al. (2008)	n/a	High	High

n/a = not available.

Two species of exotic crayfish have become established in the Zambezi River watershed of Zambia (Douthwaite et al., 2018). The North American red swamp crayfish *Procambarus clarkii* (Girard, 1852) was introduced into Zambia in 1979, and has become naturalised. Still, without any attempts at market development, it has not spread much beyond the environs of its initial introduction. The other species of crayfish, the Australian red claw, *Cherax quadricarinatus* (von Martens, 1868), was introduced later in 1992, but unlike *P. clarkii* they have become much more widespread within the Zambezi River watershed primarily by unauthorised and illegal stocking largely incented by developing lucrative crayfish export markets to China (Douthwaite et al., 2018). If the management goal is to use intensive fishing effort to control crayfish populations, the result of that intensive fishing effort at the very least would be growth overfishing of the stocks that would run counter to the commercial purpose of marketing larger high-value size classes. Unlike the case of relatively weak markets for lionfish in the Caribbean, mature global markets for crayfish appear to be a complicating factor driving redclaw crayfish production in Zambia. Control of the trade in invasive crayfish species that are high in market value is proving to be a particularly difficult problem to solve worldwide (Gherardi et al., 2011).

Limitations of Fishery Control of Highly Fecund Species: Invasive Mussels and Others

High species fecundity as measured as egg production rate (EPR) has been identified as a particularly strong predictor of invasiveness for aquatic species (Howeth et al., 2015). From this, it follows that the critical fishery effort benchmark of 10 % EPR required to induce recruitment overfishing (Fig. 1) may be difficult to attain if the reproductive output of the invasive species is high enough to render efforts for physical removal by fisheries and other means is inadequate. This was certainly the case with the *Dreissena* spp. introductions into North America in the 1990s that caused considerable damage to built infrastructure through extensive biofouling mats (Nalepa and Schloesser, 1993) and changes in the trophic dynamics of the Laurentian Great Lakes ecosystem (e.g. Nalepa et al., 2001; Pothoven et al., 2001). This pattern is also being repeated in the more recent case of the introduction of charru mussels, *Mytella strigata* (Hanley, 1843) (=*Mytella charruana*) into Southeast Asia.

Beginning in 2014, invasive estuarine charru mussels originating from the Columbian coast of the Caribbean Sea began appearing in Manila Bay, Philippines, near an international shipping port. Within 2 years, the mussels had spread to the Lingayen Gulf Region about 200 km to the north. The earliest studies of the mussels focused on their identification and salinity tolerance as a predictor of their potential for spread (Rice, Rawson, Salinas, Rosario, 2016; Vallejo et al., 2017). The charru mussels in the Philippines were found to be extremely euryhaline, tolerating wide fluctuations in salinity and having the ability to slowly adapt to hypersaline conditions up to 60 ppt. These salinity tolerance characteristics indicated that the mussels might adapt to coastal water conditions throughout the archipelago and most likely inhabit estuarine waters between 5 ppt and 25 ppt, salinities. Since 2017 charru mussels have been found to have rapidly spread well beyond the Philippines to Singapore (Lim et al., 2018), Thailand (Sanpanich and Wells, 2019), India (Jayachandran et al., 2019), and Taiwan (Huang et al., 2021).

Shortly after, the charru mussels became established in the Philippine Province of Pangasinan in 2015. The local fisheries researchers and officers of the Philippine Bureau of Fisheries and Aquatic Resources (BFAR), recognised the infestation of charru mussels as a serious issue since they form extensive biofouling mats in locations not generally accustomed to extensive biofouling, similar to the zebra mussel experience in the North America. First on the list of research activities was to begin investigating if the rapid harvest of the mussels could be a means to control mussel populations and if there could be uses for the harvested mussel biomass (Rice, Rawson, Rosario, 2016). BFAR researchers working with fishers assessed the timing of mussel spawning and recruitment (spatfall), and determined the relationship between mussel spatfall density and the growth rates of mussels. Key findings of these early studies were that high density charru mussel spatfall events (>5000 mussels.m^{-2}) resulted in stunted growth with mussels attaining only valve lengths of <1 cm in 4 to 6 months, while mussels held at low densities (<100 m^{-2}) reached over 4 cm in length in the same time, which is a marketable size at local seafood outlets (Rice, Rawson, Rosario, 2016). Despite the rapid development of this new fishery on an invasive species with ready consumer acceptance, the spread of the mussels continues unabated. Similarly, in its native range, long-standing charru mussel fisheries are managed by targeted fishing solely on the largest individuals (Freitas et al., 2012). Based on these experiences, it is doubtful that fisheries alone will be sufficient to control highly fecund species such as charru mussels.

Fuertes et al. (2021) interviewed a wide variety of coastal stakeholders and found that despite the rapid development of a commercial fishery for charru mussels, particularly those setting at low densities and attaining larger market sizes, the vast bulk of charru mussels that set in extensive mats are not as easy to market. These fouling organisms act to overset and smother indigenous mesohaline mangrove oysters and act to foul aquaculture gear, boats, and coastal infrastructure, in patterns very reminiscent of the zebra mussel infestations in North

America three decades earlier. The only interviewees with positive regard for the charru mussels were the charru mussel fishers themselves and their associates who market them locally. A post-harvest utilisation analysis showed that charru mussels were being consumed directly by households of fishers, sold for cash, used directly as an aquaculture feed, and as a poultry feed ingredient (Fuertes et al., 2021). If the mussels were sold, prices received ranged from 2 to 120 PHP.kg^{-1} (PHP50 = USD1) in local markets depending upon the location and size of the mussels sold. Of particular note is that unlike the high-value international markets for the invasive crayfish in Zambia, charru mussel markets in the Philippines have not grown beyond local consumption, occurring within a few km of the harvest sites, and there has been no post-harvest product development other than drying and grinding mussels as low-cost aquaculture or poultry feed additives. Despite current efforts to increase post-harvest mussel utilisation, the very high fecundity of charru mussels and their nature as high-density biofouling organisms will confound efforts to apply the fishery stock assessment protocols. Reaching a benchmark fishery effort rate exceeding the 10 % EPR benchmark (Fig. 1) would be exceedingly difficult for this highly fecund species.

Recommended Strategies for the Overall Management of Established Invasive Aquatic Species

Strategy 1: Collection of data useful for determination of population dynamics of the invasive species (e.g. fecundity (EPR), growth, natural mortality rate, age structure) to establish if fishing would be a viable option for population control,

Strategy 2: Determine the numbers of natural predators and determine if their populations could be enhanced,

Strategy 3: If appropriate through the assessment of EPR, develop appropriate protocols for establishing a selective fishery targeting established invasive species with a goal of achieving recruitment overfishing,

Strategy 4: Develop the harvest and handling workforce by trainings, extension workshops, and multimedia technologies as appropriate for fishers and other partners,

Strategy 5: Develop a permitting system for issuance of selective fish collection permits to facilitate removal of invasive species from protected or no-take fishery management areas, especially if predator species are being promoted as a biological control mechanism,

Strategy 6: Collection of socioeconomic data on the impacts of the invasive species,

Strategy 7: Engage in extension or outreach educational activities with relevant stakeholders to educate, build awareness and prevent further invasions, and engage in activities aimed at protection of indigenous aquatic resources,

Strategy 8: Engage in post-harvest market analysis to determine if the economic value of the harvested species might be providing market incentives for their protection or enhancement.

Strategy 9: Establish appropriate market controls for the invasive species based upon the balance between environmental impacts and overall economic impacts, including impacts on important peripheral industries such as ecotourism.

In addition to the establishment of targeted fisheries (Strategy 3), there is the need for official management and oversight. Staff members associated with traditional governmental fisheries management agencies frequently have the training and skills to gather catch and effort data through stock assessments and manage fishing efforts by recommending appropriate fishing effort levels to achieve management objectives (Strategy 1). In many developing countries where quantitative fisheries management expertise may be lacking, this may be a good topic for international cooperation and capacity building. Some of the official goals for invasive aquatic species management may be aimed at mitigation of socioeconomic disruption caused by the invasion. The socioeconomic data collected (Strategy 6) can be of considerable value in informing the formation of effective mitigation policies for invasive species. Human dimensions are a sustainability element within any natural resource management decision making as exemplified by the Cozumel lionfish management protocols of Malpica-Cruz et al. (2021). In line with Strategies 8 and 9, efforts should be made to avoid unintended market-driven incentives for greater production of the invasive species beyond the officially authorised fishery harvest and utilisation activities as per the caveat of Lambertucci and Speziale (2011), and the market-driven protection of invasive crayfish in Zambia as reported by Douthwaite et al. (2018). Disincentives for market development of economically valuable invasive species may include export controls, taxation and other economic policy tools aimed at controlling the level of market demand.

Conclusion

The decision whether or not to apply catch and effort stock assessment as a means to establish fishing effort goals should take into consideration the fecundity (EPR) of the target species. Among the various species discussed here, there is considerable variation in their fecundity, as indicated by their estimated EPR for median-sized specimens (Table 1). In the cases of lionfish and the mytilids, their reproductive modes are as broadcast spawners with relatively high fecundity, and the survivability of their numerous offspring is a major factor in their invasiveness. The crayfish species, on the other hand, have fewer eggs per spawn but engage in egg brooding that often result in higher offspring survivability than the broadcast spawners. There are no available data on the EPR of *Mytella strigata*, but a closely related mytilid of similar size, *Mytilus edulis* is known to have EPR values ranging from 1.6 to 5 million eggs.spawn^{-1} (Pronker et al, 2008), suggesting that they would be difficult to eradicate by intensive fishing pressure alone. All of the invading species reviewed herein have proven to be successful as invasive species by becoming rapidly established and difficult to eradicate, however those with lower fecundity such as the crayfish may be better prospects for eradication, extirpation or control by directly employing intensive fishing methods targeting the invasive species, or by reducing fishing effort on their known predators.

Over time, naturally occurring potential predators may adapt to the newly established food source, but this adaptation is rarely immediate. Strong measures to control invasive aquatic species should be considered carefully as an option for reducing the impacts of newly established invasive species, especially if their fecundity as measured by EPR is relatively high. Invasive crayfish that brood relatively few eggs per spawn may be controlled by fishing, as suggested by Hein et al. (2007) in their study of *F. rusticus* in Wisconsin. Any efforts to control already established species by intensive fishing would be in addition to more frequently recommended measures to prevent invasive species from arriving in the first place, as well as frequently recommended surveillance measures, and creating means for rapid response to eradicate invasive species when they first arrive (e.g. ICES, 2005).

Harvest and utilisation of established invasive aquatic species have become a legitimate option for natural resource managers, and many of those recommend-dations provided by Morris and Whitfield (2009) used in response to the lionfish invasion can be easily expanded to become adaptable for the management of other aquatic invasive species. The recent ecological modelling studies by Chagaris et al. (2017) and Malpica-Cruz et al. (2021) suggest that high effort fishing directly on lionfish can control their populations to some extent, as would lowering the fishing effort on proven predator species. However, if invasive aquatic species are to be managed as a fishery with the goal of extirpation or population control, fisheries catch and effort data collection may aid in informing policy formation such as establishing future fishing effort targets. The key weakness of the practice of intensive fishing to control invasive aquatic species is that species with exceptionally high fecundity as measured by EPR, may far exceed the ability for fishing to reduce the overall size of the stock.

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