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Perspective

Conservation aquaculture: Shifting the narrative and paradigm of aquaculture's role in resource management

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ABSTRACT

In the 21st century, aquaculture is generally characterized as a foe to conservation efforts. Yet, much has changed in the two seemingly disparate practices over the last two decades, motivating an updated evaluation of the scientific evidence for how aquaculture currently impacts conservation, as well as prospects for further alignment and research. Here we present a new perspective on *conservation aquaculture*, which we redefine as "the use of human cultivation of an aquatic organism for the planned management and protection of a natural resource." Looking across scales of conservation aquaculture that include single species to ecosystem level benefits (and limitations), we highlight ways aquaculture has historically, and is currently being integrated into conservation (e.g., habitat restoration of oyster beds) and areas that could be improved for the protection of critical species and habitats (e.g., aquarium trade of coral reef species). With a more strategic focus, there appears to be notable conservation aquaculture potential via the cultivation of species for harvest that could provide wild harvest alleviation through replacement or supplement – particularly for over-exploited species – and/or ecosystem services, such as improved water quality and reduction in greenhouse gas emissions. Given that aquaculture is the fastest growing food industry on the planet, aligning farming practices with conservation objectives is particularly pressing to ensure that growth happens in the service of conservation in the most effective and sustainable way possible. The sheer potential of conservation aquaculture suggests a tale of redemption for aquaculture and opportunity for conservationists to bring in a new age of collaborative practices to address global issues.

1. Introduction

For most modern-day conservationists, aquaculture is something to avoid. Shrimp farms destroy coastal mangrove habitats (Silva, 2012), salmon farms can release genetic anomalies into local populations (Naylor et al., 2005, 2001), farms of high-value (often higher-trophic level) species tax wild-caught forage fish stocks for feed inputs (Naylor and Burke, 2005; Naylor et al., 2009), and farms of fed species can pollute local waters (Islam, 2005; Sarà, 2007), among other impacts on native species and natural ecosystems. While some of this reputation is understandably deserved, much has changed in the last 20 years and needs to be revisited in a systematic way. Advances in the technology, practices, and siting of aquaculture have allowed significant mitigation of these environmental risks and harms (Bostock et al., 2010; Edwards, 2015), and expanding uses of aquaculture in resource management have changed the role that aquaculture can, and does, play in conservation. In this paper, we argue that aquaculture has the potential to play a significant, global role in achieving conservation objectives; realizing that potential requires a shift in the way we think about aquaculture, and scaling the way aquaculture is used to be part of the solution, instead of the problem.

Conservation aquaculture is not a hypothetical idea. Nearly all possible ways aquaculture can be used to improve the status and condition of species and ecosystems is already in practice somewhere on the planet, generally at a local level, but occasionally at larger scales (e.g., hatcheries supplying wild salmon stocks). Drawing attention to such approaches helps highlight aquaculture's potential to aid conservation, guide how to appropriately scale the practices, and ultimately offer conservationists a new tool. Changing the narrative around what aquaculture is (and is not) will enable and clarify efforts to use

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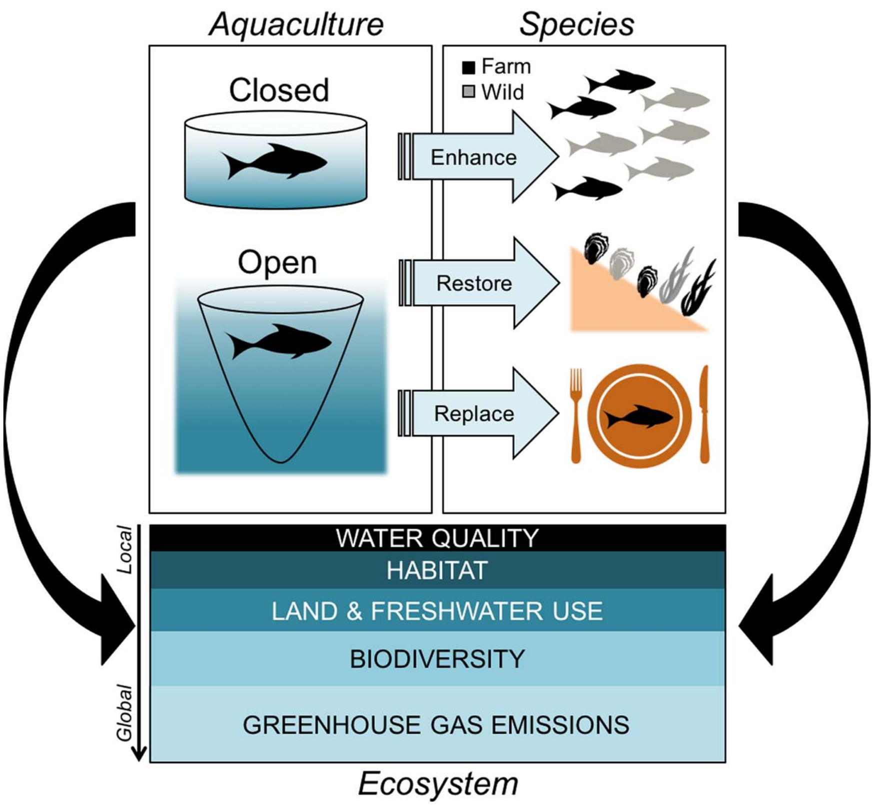

Fig. 1. Conceptual framework of how aquaculture is or can be used for conservation at a species and ecosystem scale. *Large arrows* indicate conservation links. At the species level, *enhance* refers to supplementing a wild population (hatchery), *restore* indicates biogenic restoration, and *replace* signifies farmed species replacing wild species – particularly overexploited or threatened – on the market (food or ornamental). Each component can apply to numerous taxonomic groups (finfish, bivalves, crustaceans, and seaweeds). Connections to ecosystem-level objectives can occur relative to the aquaculture type (*left panel*) and species (*right panel*). *Closed* versus *open* aquaculture denotes the generalized farming practices with differing resource requirements and impacts (e.g., freshwater use). Broad categorization of local to global ecosystem scale is reflected in the size of each box. Note, not all aquaculture practices for conservation result in every ecosystem component depicted.

this tool. Furthermore, aquaculture has been, and is expected to continue to be, one of the fastest growing food sectors in the world (FAO, 2016). Conservationists have the opportunity (and really, the necessity) to steer that growth in the industry toward sustainable practices that can benefit conservation objectives.

Any human use of the natural environment has a level of impact, at least to some species and/or habitats. Since aquaculture is no exception, any aquaculture practice will have some environmental consequences of varying degrees based on the initial objectives. Conservation aquaculture is therefore not a net-zero environmental pursuit, but instead can be used to explore how to use aquaculture in the service of conservation objectives, while still allowing and acknowledging a level of (ideally minimized) environmental impact.

Anders (1998) first coined ‘conservation aquaculture’ as the “*use of aquaculture for conservation and recovery of endangered fish populations*.” This definition is somewhat narrow in scope and reflects the perception of aquaculture and conservation nearly two decades ago. Although a useful starting point, it does not echo the evolving conservation approaches. In redefining conservation aquaculture, we draw on (but do not limit ourselves to) the definitions of each term: conservation represents “*a careful preservation and protection of something; planned management of a natural resource to prevent exploitation, destruction, or neglect*” (Merriam-Webster, 2017), while aquaculture is defined as “*the cultivation of aquatic organisms, especially for food*” (Merriam-Webster, 2017; NOAA Fisheries, 2017). The definition of aquaculture is particularly important; the primary intent tends to be for consumption. Yet, aquaculture is widely used for other purposes, including cultivating certain life-stages of aquatic organisms for wild populations (i.e., hatcheries) or species for the aquarium trade (FAO, 2016). To that end, we focus on aquaculture as any human intended interference in the cultivation of aquatic organisms and define ‘conservation aquaculture’ more broadly as “*the use of human cultivation of an aquatic organism for the planned management and protection of a natural resource*.”

Although the idea of combining aquaculture and conservation objectives through hatchery practices dates back over a century (Costa-Pierce, 2008), we focus on the formal documentation of the joined words for several reasons. First, while Anders' definition of conservation aquaculture nicely reflects the historical connotation, it is already captured by the term ‘conservation hatchery’ (Flagg and Nash, 1999). Second, the definition was published at one of the largest growth periods of aquaculture (FAO, 2016), during which many of the environmental wrongs occurred. It was around this time aquaculture was identified globally as a conservation concern (e.g., Clay, 1997; Flaherty and Karnjanakesorn, 1995; Goldburg et al., 1997). The purpose of our paper is to demonstrate the term ‘conservation aquaculture’ can encompass much more, matching the changes and progress in both fields since its inception.

Strategies for conservation of aquatic species and systems generally include federal or state protection, habitat restoration, and harvest-control rules. For example, large areas of the oceans are being set aside as marine protected areas (MPAs) to buffer the direct impact of human disturbance on critical habitats and/or species (Halpern, 2014). Listing of endangered or threatened species offers focused attention and resources for conservation planning (Harris et al., 2012). Once-degraded habitat, such as oyster beds or seagrass meadows, is restored with the aim to provide natural ecosystem services (Bayraktarov et al., 2016; Costanza et al., 2014). Simultaneously, catch-limits, gear restrictions, and/or seasonal bounds are incorporated into exploited species management to conserve species of economic or cultural significance (Kvamsdal et al., 2016). All of these interrelated approaches have ties to aquaculture that are typically overshadowed by aquatic farming's checkered past. Here we expound on the many ways aquaculture can work with, instead of against, conservation.

Conservation aquaculture ultimately needs to support the sustainable use (or recovery) of natural resources, whether through mitigation, prevention, or restoration measures. How best to achieve this goal requires explicit consideration of the scale at which conservation aquaculture is being pursued. In particular, we explore how conservation aquaculture can protect and manage (1) specific wild species/stocks through commodity production and direct (i.e., hatcheries) and indirect (i.e., habitat restoration) wild population improvement and (2) larger system-level implications through aquaculture-based ecosystem services and reduction in overall environmental footprint (e.g., greenhouse gas (GHG) emissions); Fig. 1 illustrates the conceptual framework of conservation aquaculture redefined in these terms. We first describe the current state and understanding of aquaculture uses relative to conservation, and then provide key aspects that should be considered for future use of aquaculture as a conservation tool. Our intent is to highlight the ways in which aquaculture can help certain conservation actions by providing a succinct snapshot and thought-piece, not an exhaustive review. In doing so, we hope to spur others in the conservation community to dive deeper into the respective conservation benefits, as well as costs, of aquaculture.

2. Scales of conservation aquaculture

2.1. Species-level conservation

Conservation aquaculture for single species can take the form of reducing pressure on wild stocks, enhancing at-risk populations, and/or restoring critical habitat. Aquaculture has been suggested as a possible solution to relieve fishing pressure on wild stocks (Anderson, 1985; Pomeroy et al., 2006), and some wild populations (e.g., oyster and carp species) have increased due to harvest replacement (Diana, 2009; Jiang, 2010) – with some presumed limit of the effect due to natural population dynamics (i.e., density dependence) (Fig. 2a). However, in recent years perceived competition with existing fisheries has often been viewed as a source of contention for aquaculture development (Froehlich et al., 2017; Tiller et al., 2013). Minimizing any negative market effects of aquaculture on fishing has been the focus of more research (e.g., Valderrama and Anderson, 2010) than the alternative goal of aquaculture targeting market-based competition so that it reduces fishing and conserves the wild stock. Increases in human population, wealth, and consumption of seafood has mainly resulted in simultaneous increased exploitation and harvest of wild and farmed species for food (FAO, 2016). For most species, it seems likely we will continue to both fish and increase farming for the foreseeable future (FAO, 2016), such that conservation of the majority of wild stocks through aquaculture harvest alleviation seems unlikely, at least in the near-term.

However, we suggest a need for renewed focus on the potential for aquaculture to reduce pressure on certain highly threatened, over-exploited species. Targeted production of endangered/black-market wild species (e.g., sturgeon for their caviar) may be a tractable approach - both from a consumptive and aquarium trade perspective (Bronzi et al., 2011; Tlusty, 2002). While we can hypothesize simple relationships between aquaculture products improving the status of wild species through harvest replacement (Fig. 2a), the confounding drivers and framework to achieve such a response are poorly understood. In particular, additional research is needed around consumer preference, market dynamics, and management strategies to truly enable – and potentially maximize – aquaculture to ease market-driven pressure of at-risk stocks. While these types of analyses have been studied extensively for endangered terrestrial species (Tensen, 2016), there is a lack of literature focused on aquaculture-based conservation farming, especially for consumptive products. Unintended consequences of aquaculture on the health of wild fisheries could negatively impact the conservation potential of aquaculture (Tisdell, 2003), and would need to be carefully considered and avoided.

There has been growing momentum to develop aquaculture to relieve pressure on aquarium species, particularly those harvested from vulnerable coral reef environments (Domínguez and Botella, 2014; Holt, 2003; Rhyne et al., 2012, 2017). Freshwater ornamental species are nearly exclusively farmed (ca. 90%), and there are several examples of successful conservation-motivated interventions of culturing replacing the wild demand (Fig. 2a), including Asian arowana (*Scleropages formosus*), bala shark (*Balantiocheilos melanopterus*), dwarf loach (*Ambastaia sidthimunki*), and tiger barb (*Puntigrus tetrazona*) (Ng and Tan, 1997). In contrast, wild animals (ca. 95%) are the predominant marine source for both deceased (e.g., invertebrate shells) and living aquarium specimens (Calado et al., 2017; Cohen et al., 2013; Green, 2003; Tlusty, 2002). In particular, the majority of marine species sold in the multi-million dollar industry (USD) originate from coral reef systems (Monticini, 2010; Tlusty, 2002; Wood, 2001), which are some of the most biodiverse but threatened ecosystems on the planet (Bridge et al., 2013; Hughes et al., 2015). Currently, captive breeding of clown and damsel fishes, and corals themselves, is actively being pursued (Domínguez and Botella, 2014; Kumar et al., 2015; Rhyne et al., 2012). Yet, comparatively higher technological constraints (Olivotto et al., 2016) and costs (Kolding et al., 2015) appear to be limiting aquaculture's role in the marine aquarium industry. Importantly, in situ farming of ornamental marine species could be more viable for conservation if promoted by a sustainable trade market that considers socioeconomic and environmental trade-offs (Rhyne et al., 2014, 2017; Tlusty et al., 2013).

One of the most common examples of possible conservation aquaculture is hatcheries - also referred to as stock enhancement (Fig. 2a) (Costa-Pierce, 2008). Hatcheries have been used for several species (e.g., salmonids, sturgeon spp., European lobster) (Klinger et al., 2013; Taylor et al., 2017; Waples, 1999), with 'success' dependent on initial management objectives (i.e., bolster harvest and/or recover wild populations). There is certainly a threshold to supplementing a population, a limit that can even result in undesired management outcomes, such as overcompensation (e.g., in salmonids) (Foss-Grant et al., 2016) (Fig. 2a). With respect to goals of improving population and ecological outcomes of a species, hatcheries can indeed have either negative or positive outcomes, and key information gaps remain (Araki and Schmid, 2010; Naish et al., 2007). Undoubtedly, hatcheries alone are not sufficient if management of fishing effort and habitat for wild populations are ignored. Indeed, new research suggests when combined

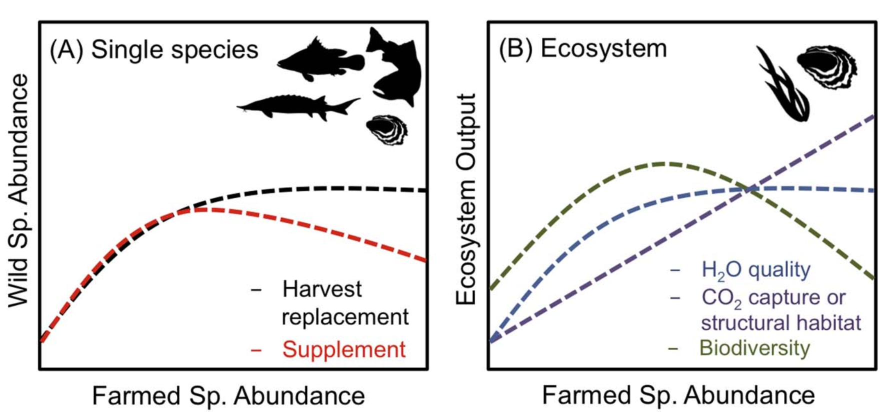

Fig. 2. Conceptualization of idealized conservation aquaculture potential at the (A) species and (B) ecosystem level. Regardless of scale, we suggest the existence of an optimal benefit to nature is some function of a farmed species abundance and practice. In panel (A), *harvest replacement* (black) refers to non-release aquaculture substituting the harvest for wild species (food or ornamental) and *supplement* (red) refers to direct species input to wild populations (i.e., hatcheries). Both practices are potentially more applicable for over-exploited species. In panel (B), improved *H_2O quality* (blue), *CO_2 capture* (purple) and *structural habitat* (purple) depict the farming (for harvest or restoration) of non-fed species (e.g., seaweed), while *biodiversity* (green) could apply to various taxonomic groups. Silhouettes of species indicate examples from primary literature (described further in the main text). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with habitat restoration, hatcheries may play a key role in stock-enhancement (Taylor et al., 2017). Thus, hatcheries used in a management portfolio are probably most representative of a conservation-based approach. In fact, the initial motivation for the term 'conservation aquaculture' (Anders, 1998) stemmed from the management and eventual persistence of the endangered Kootenai River white sturgeon *Acipenser transmontanus*, which involved a combination of harvest, environment, and hatchery managing components (Schreier et al., 2012).

Biogenic habitat restoration in aquatic environments is also, fundamentally, conservation aquaculture, intended to directly increase the habitat-forming species or indirectly benefit other species and/or ecosystem attributes that depend on that habitat. Many biogenic habitats have suffered declines due to anthropogenic pressures (e.g., overfishing, coastal development, commodity aquaculture), including oyster beds (Baggett et al., 2015), seagrass meadows (Waycott et al., 2009), mangrove forests (Spalding, 2010) and corals (Kennedy et al., 2013). Whether the restoration efforts are motivated by harvest of the restored species of interest or not, the practice of cultivating a specific aquatic species through off-site rearing and/or transplantation of wild stock falls within the spectrum of conservation aquaculture. Critically, habitat restoration can have far-reaching conservation effects well beyond the single species being cultivated, as we discuss in the next section.

2.2. Ecosystem-level conservation

Conservation-focused cultivation to restore native biogenic habitat is increasingly being used to help provide ecosystem-level benefits. Although quantification of ecosystem services from restoration is challenging and somewhat limited, several studies have found evidence of direct and indirect benefits of habitat restoration (Baggett et al., 2015; Boulton et al., 2016; Suding, 2011; Wortley et al., 2013). Cultivation and growth of certain species of oysters, seaweeds, seagrasses, and mangroves can improve water quality (Humphries et al., 2016), coastal defense (Narayan et al., 2016), carbon sequestration (Greiner et al., 2013), and essential habitat for wild species (Seitz et al., 2014) (Fig. 2b). In addition, fundamental ecological and biological principles support the potential benefits associated with such planting and growing of certain species – with increases in abundance of farmed species resulting in varying ecosystem outcomes depending on the system and metric of interest (Fig. 2b) (Beck et al., 2011). For example, improvements in water quality of a body of water from filter-feeders (e.g., oysters) is, in-part, a function of nutrient inputs (rate and concentration) and has a maximum filtration-extraction limit or equilibrium (Fig. 2b) (Ermgassen et al., 2013). Although goals and measures of success vary, policy is increasingly adopting such approaches as a conservation tool (Suding, 2011) and aquaculture is inherently tied to that process.

While habitat restoration often has conservation as the primary objective, consideration of ecosystem benefits and commodity production simultaneously is an important, somewhat convoluted next step in conservation aquaculture. At a local or regional ecosystem scale, strategic siting and cultivation of harvestable species has potential for net-benefits to the surrounding environment. Food-based bivalve and seaweed aquaculture in particular are noted for the potential to provide some of the same ecosystem services associated with their wild counterparts, such as increased water quality, coastal structure, and habitat (Dumbauld et al., 2009; Humphries et al., 2016; Kim et al., 2015; Newell, 2003) (Fig. 2b). Both seaweed and bivalve farms also have the capacity to sequester carbon dioxide from the ocean (Jiang et al., 2015), with an assumed increasing extraction capacity with increased abundance of cultivated biomass (Fig. 2b). For example, Tang et al. (2011) estimate that marine culture of harvested molluscs and seaweed in China remove 0.34–0.88 million tonnes of carbon per year. Such services are promising, however there is uncertainty and a level of variability surrounding the role of wider coastal ecosystem processes governing such benefits (Filgueira et al., 2015; Humphries et al., 2016). Farms placed in open-systems may also provide structure and nutrients within the environment, creating habitat and additional energy sources utilized by commercially-important wild species (Akyol and Ertosluk, 2010; Bacher et al., 2015; Dempster et al., 2009; Fernandez-Jover et al., 2011; Hehre and Meeuwig, 2016; Pitta et al., 2009). Yet, it remains unclear whether the fish aggregating function or nutrient inputs of farms actually result in a net increase of fish productivity. In addition, it is important to acknowledge that the effects of aquaculture on wild species can vary depending on the environment and other impacts on the system (Hehre and Meeuwig, 2016), having positive effects on some organisms and negative effects on others – suggesting some optimum level of aquaculture may exist for overall biodiversity of a system (Fig. 2b). Overall, more measurable evidence of comparative and spatiotemporal trends of ecosystems services provided by commodity production aquaculture is needed to better understand and plan for such intended conservation outcomes.

At a country and global food-production level, life-cycle analyses (LCAs) are revealing aquaculture's possible role in lower greenhouse gas emissions, reduced land-use (for open, non-recirculating systems) (Clark and Tilman, 2017; Tilman and Clark, 2014) and freshwater use (for marine production) (Gephart et al., 2014) compared to other animal protein production. Yet, there is much more to compare and understand regarding the various food systems and ecological impact trade-offs (e.g., aquatic pollution); especially as the human population continues to expand (Diana, 2009). An ecosystem approach for aquaculture (EAA) has been proposed (Aguilar-Manjarrez et al., 2017; Soto et al., 2008), but is not nearly as prominent as in wild fisheries and agricultural management or research. These larger ecosystem-level considerations must be at the forefront of Blue Growth goals to be classified in the conservation aquaculture arena. Notably, consideration of conservation issues across terrestrial and aquatic landscapes in a global context is atypical from a management perspective due to the international collaborations and initiatives that would be required, lack of information or access to data, and ability to implement and track such outcomes. That said, larger scale conservation food system objectives are not an impossible endeavor given multinational agreements (such as the 2015 Paris Agreement on climate change) are emerging to combat global level issues. Ultimately, philosophically squaring the various production systems in a conservation framework is undoubtedly challenging, but a necessary frontier that scientists, managers, and consumers need to consider more earnestly in this ever expanding globalized society.

3. Considerations for the future

Much like fisheries (e.g., Quinn and Collie, 2005), aquaculture appears to be progressing from single-species to ecosystem-level considerations, promoting a more holistic approach that may foster better alignment with conservation. Aquaculture is certainly not a remedy for all environmental issues, but with smart planning alongside sustainable measures and regulations, aquaculture could play a larger role in the future of conservation. Other aspects not explicitly discussed, but imbedded in the above sections, such as feed ingredients (Tacon and Metian, 2015), global trade patterns (Rhyne et al., 2017; Watson et al., 2017), and certification/eco-labeling (Tlusty, 2012), are key facets of sustainability that can certainly be captured by conservation aquaculture objectives. Yet, many important aspects of sustainable resource management (e.g., socio-economic implications) may not always be captured by conservation initiatives (Bodin et al., 2014). To ensure sustainability alongside conservation, ecosystem-based management will increasingly need to be pursued through collaborations at local and global scales, where tradeoffs of objectives are carefully considered.

We focused mainly on the environmental and ecological implications of conservation aquaculture, but whenever resources are used or protected, it is important to recognize the social and economic impacts of such practices. In general, accounting for the socioeconomics of conservation appears to be relatively rare (Bodin et al., 2014). However, we recognize actions such as flooding the market to protect a species could have negative consequences on the livelihoods of those that depend on the harvest of the wild species (Rhyne et al., 2014). This concern speaks to the need and benefit of an ecosystem-based approach to conservation aquaculture and the involvement of stakeholders in the process (Bennett and Dearden, 2014; Broitman et al., 2017; Job, 2005; Krause et al., 2015). Local knowledge and collaboration is a key part of resource management and sustainability, and can help foster community involvement and positive conservation outcomes (Charnley et al., 2017).

Monitoring and measuring ecological outcomes can provide much needed information for further understanding aquaculture's role in conservation, as well as offer data for stronger evidence-based adaptive management (Costa-Pierce, 2008). Quantifiable measures of success – a frequently described, but seemingly underutilized aspect of conservation (Bodin et al., 2014; Pullin et al., 2013) – are going to be a must for conservation aquaculture, particularly for practices linked to commodity production. Given divisive public perceptions (Froehlich et al., 2017), aquaculture will most likely not receive the benefit of the doubt when it comes to mitigating, instead of causing, impacts on the environment. Long term, stronger connections to conservation objectives may ease some distrust around aquaculture. More importantly, use of comparative metrics and some level of tracking over time allows for management to change or adjust actions if the measures of interest are, or are not, meeting the desired goals (Westgate et al., 2013). Ultimately, what metrics are monitored and assessed (e.g., biodiversity, species abundances, sedimentation, etc.) will depend upon the system, scale, and original objectives set by the stakeholders.

Just as in any other conservation and resource management context, development of clear objectives among stakeholders is paramount. We cannot overstate the importance of clearly defining the level and role of aquaculture for conservation outcomes. Opportunistic use or retroactive classification of 'conservation aquaculture' not only could limit the possible effectiveness of such practices, but minimize the perceived utility of aligning aquaculture and conservation. Collaboration between scientists, farmers (or fishers), and managers is at the center of more effective development and implementation of management and conservation objectives - particularly at the ecosystem level (Aguilar-Manjarrez et al., 2017; Bodin et al., 2014; Boulton et al., 2016; Jennings et al., 2014; Krause et al., 2015). Concerted efforts within and between stakeholder groups to work in concert to construct conservation goals linked to aquaculture can help identify key trade-offs, articulate the desired or necessary scale (time and space), and allow for further qualitative (e.g., expert opinion) and/or quantitative (e.g., management strategy evaluation) considerations of the possible outcomes. In turn, scale influences the level of collaboration (e.g., number of agencies or governments) and time necessary to meet objectives.

Conservation aquaculture necessitates an ongoing focus on good management that aims to maximize the economic, social, and ecological benefits that can be associated with development while avoiding the unnecessary risks of destructive practices. Unsustainable farming can extol a major disservice on our ecosystems through water pollution, habitat destruction, and impacts on wild species through disease exportation and genetic pollution. Thus, the importance of matching species, farm scale, and locations cannot be overemphasized. Through collaboration, strategic planning, and monitoring practices, aquaculture can be used in the service of conservation, so we can have our aquatic resources and protect the planet too.

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