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Responsible Approach to Marine Stock Enhancement: An Update

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*Marine stock enhancement is a set of management approaches involving the release of cultured organisms to enhance or restore fisheries. Such practices, including sea ranching, stock enhancement, and restocking, are widespread, of variable success, and often controversial. A set of principles aimed at promoting responsible development of restocking, stock enhancement, and sea ranching has been proposed by Blankenship and Leber [American Fisheries Society Symposia **15:** 167–175 (1995)], and has gained widespread acceptance as the 'Responsible Approach'. Fisheries science and management, in general, and many aspects of fisheries enhancement have developed rapidly since the responsible approach was first formulated. Here we provide an update to the Responsible Approach in light of these developments. The updated approach emphasizes the need for taking a broad and integrated view of the role of enhancements within fisheries management systems; using a stakeholder participatory and scientifically informed, accountable planning process; and assessing the potential contribution of enhancement and alternative or additional measures to fisheries management goals early on in the development or reform process. Progress in fisheries assessment methods applicable to enhancements and in fisheries governance provides the means for practical implementation of the updated approach.*

Keywords fisheries enhancement, stock enhancement, sea ranching, restocking, responsible approach, planning, assessment, population dynamics, models

INTRODUCTION

Many of the world's fisheries are fully exploited or overexploited, as well as suffering from the effects of aquatic habitat degradation. Global capture fisheries production is stagnant, while seafood demand is steadily increasing (FAO, 2009); a number of formerly productive stocks have collapsed with only limited evidence of recovery, and ecosystem-level impacts of biomass removal and fishing gear disturbance have become increasingly evident (Hutchings, 2000; Pauly et al., 2002; Hilborn et al., 2003; Hilborn, 2007b).

Besides control of fishing effort and habitat protection or restoration, aquaculture-based enhancement is a third principal means by which fisheries can be sustained and improved (Munro and Bell, 1997; Welcomme and Bartley, 1998; Blaxter, 2000; Bell et al., 2005). Aquaculture-based fisheries enhancement is a set of management approaches involving the release of cultured organisms to enhance, conserve, or restore fisheries. This definition covers a great diversity of enhancement fisheries systems including 'Sea ranching', 'Stock enhancement', and 'Restocking' (Bell et al., 2006; Lorenzen, 2008). Here we focus on fundamental attributes shared by most enhancement systems but also emphasize how different objectives and situations give rise to different system designs. For simplicity, we refer to all forms of aquaculture-based fisheries enhancements as 'enhancements' and to the target organisms as 'fish'.

Aquaculture-based enhancements can, at least in principle, generate a range of benefits (Howell et al., 1999; Leber et al., 2004, Bell et al., 2008, Lorenzen, 2008). In biological terms, enhancement can (1) increase yield through manipulation of population and/or food web structure, thus raising fisheries production at low external inputs and degree of habitat modification;

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(2) aid the conservation and rebuilding of depleted, threatened, and endangered populations; and (3) provide partial mitigation for habitat loss and ecosystem effects of fishing. This may give rise to economic and social benefits, including new opportunities for fisheries-related livelihoods (Smith et al., 2005; Garaway, 2006). Enhancements can also provide incentives for active management and better governance of common pool resources (Arbuckle, 2000; Garaway et al., 2006, Tomiyama et al., 2008). However, many enhancements have failed to deliver significant increases in yield or economic benefits, and/or have had deleterious effects on the naturally recruited components of the target stocks (Hilborn, 1998; Levin et al., 2001; Arnason, 2001; Naish et al., 2007). Sometimes enhancements have contributed to management failure by encouraging or compensating for counterproductive changes in fishing patterns or for habitat degradation (Meffe, 1992; Taylor, 1999).

While some enhancement initiatives have increased yields, generated economic and social benefits, and helped create better fisheries management institutions, only a few such 'success stories' have been documented in the scientific literature (Pinkerton, 1994; Lorenzen et al., 1998; Drummond, 2004; Uki, 2006; Garaway, 2006; Becker et al., 2008). Overall, the contribution of enhancements to global fisheries production has remained small, at below 2% of the global total (Lorenzen et al., 2001). It is, thus, pertinent to ask why enhancements have not made a greater contribution to fisheries. We believe there are several contributing factors. Success in fisheries management is measured against an increasingly broad set of criteria: biological (yield, ecosystem indicators), economic, social, and institutional attributes (Charles, 2001; Garcia and Charles, 2007). Enhancements can score well on a range of criteria, but only under certain conditions. These include existing ecological, economic, and social conditions; and technologies and institutional arrangements that are well adapted to those conditions. Moreover, enhancements need to add value to, or outperform alternative management measures, such as fisheries regulation or habitat restoration, which may be either cheaper or provide a wider range of benefits. These considerations suggest that enhancement initiatives need to be assessed, if not positively driven, from a fisheries management perspective rather than the aquaculture production perspective that has been traditionally dominant.

The effectiveness of stocking cultured organisms, though, has been hampered by lack of a scientific, institutional, and fisheries-management perspective in planning, design, implementation, and evaluation of enhancement programs (Cowx, 1994; Blankenship and Leber, 1995; Munro and Bell, 1997; Leber, 1999; Hilborn, 1998, 1999; Lorenzen et al., 2001; Bell et al., 2005, 2006, 2008; Bartley and Bell, 2008; Lorenzen, 2008). Although fishery managers began to stock cultured fishes into the sea in the 1880's, no scientific publications appeared about effectiveness of releases until empirical studies of anadromous salmonids began to be published in the 1970's (Hager and Noble, 1976) followed by the first studies of marine fishes in 1989 and 1990 (Tsukamoto et al., 1989; Svåsand and Kristiansen, 1990a, 1990b; Svåsand et al., 1990; Kristiansen and Svåsand, 1990). Thus, lacking a foundation of quantitative information for evaluating stocking's real potential as a tool in the fishery management toolbox, by the 1990's the marine enhancement field had largely floundered for over a century (Leber, 1999).

In response to a clear need for change, Cowx (1994, for enhancements in freshwater systems) and Blankenship and Leber (1995, for marine systems) published early platform papers calling for a responsible approach to stock enhancement. Those early papers presented a set of principles aimed at promoting the responsible development of culture-based fisheries/ranching, stock enhancement and restocking. Since then, there have been concerted efforts to apply responsible approaches to the development of new enhancements and to reform existing, operational enhancements in this light (e.g., Mobrand et al., 2005; Zohar et al., 2008).

The ten principles for developing, evaluating, and managing marine stock enhancement programs set out in Blankenship and Leber (1995) have gained widespread acceptance as the 'Responsible Approach' to stocking (Table 1). The 'Responsible Approach' has been widely cited and has provided a key conceptual framework for several subsequent publications (e.g., Munro and Bell, 1997; Hilborn, 1999, Bell et al., 2005, 2006, 2008; Taylor et al., 2005; Zohar et al., 2008). More importantly, it has been used to guide hatchery development and reform processes in Australia (Taylor et al., 2005; Gardner and Van Putten, 2008; Potter et al., 2008; Taylor and Suthers, 2008), Denmark (Støttrup et al., 2008), Japan (Kitada, 1999; Kuwada et al.,

Table 1 Elements of a responsible approach outlined in Blankenship and Leber (1995)

1. Prioritize and select target species for enhancement by ranking and applying criteria for species selection; once selected, assess reasons for decline of the wild population.
2. Develop a management plan that identifies how stock enhancement fits with the regional plan for managing stocks.
3. Define quantitative measures of success.
4. Use genetic resource management to avoid deleterious genetic effects on wild stocks.
5. Implement a disease and health management plan.
6. Consider ecological, biological, and life-history patterns in forming enhancement objectives and tactics; seek to understand behavioral, biological, and ecological requirements of released and wild fish.
7. Identify released hatchery fish and assess stocking effects on fishery and on wild stock abundance.
8. Use an empirical process for defining optimal release strategies.
9. Identify economic objectives and policy guidelines, and educate stakeholders about the need for a responsible approach and the time frame required to develop a successful enhancement program.
10. Use adaptive management to refine production and stocking plans and to control the effectiveness of stocking.

2000, 2004), New Caledonia (Purcell and Simutoga, 2008), Phillipines (Le Vay et al., 2008), and the USA (e.g., Leber, 2004), particularly in California (Bartley et al., 1995), Florida (Willis et al., 1995; Leber, 2004; Tringali et al., 2008), Georgia (Woodward, 2003), Hawaii (Leber et al., 1996, 1997, 1998; Friedlander and Ziemann, 2003), Maryland (Zohar et al., 2008), Mississippi (Blaylock et al., 2000), New Hampshire (Fairchild et al., 2005), North Carolina (Eggleston et al., 2008), South Carolina (Smith et al., 2003; Jenkins et al., 2004), Texas (Karlsson et al., 2008), and Washington (Mobrand et al., 2005). At the same time, there has been a rapid increase in peer-reviewed literature on effects and effectiveness of stocking.

KEY DEVELOPMENTS SINCE THE RESPONSIBLE APPROACH WAS FIRST FORMULATED

Fisheries science and management in general, and many aspects of fisheries enhancement have developed rapidly since the responsible approach was first formulated. Governance in many fisheries has changed from open access and/or government-regulation to alternative, market- and community-based approaches (Hilborn et al., 2005). This has created stronger and more effective governance, creating conditions that may also be conducive to developing and sustaining enhancements. In some cases, enhancement initiatives have been instrumental in bringing about change in governance with wider benefits (Drummond, 2004; Lorenzen, 2008). At the same time, ecological and social impacts of fisheries and their management have come to the forefront of management decision making and public debate. Management goals have become increasingly multi-dimensional (Hilborn, 2007a). Spatial heterogeneity and dynamics in marine ecosystems and social systems, scientific recognition of smaller-scale connectivity, and movements to set aside marine areas for conservation have given rise to marine spatial planning (Lorenzen et al., 2010).

In parallel, and often in interaction with the aforementioned developments in fisheries, significant changes have occurred in the science and practice of fisheries enhancement. Perhaps the most significant of these has been a drive towards fully integrating enhancements into fisheries management frameworks and decision making. This has progressed furthest in the Japanese and New Zealand scallop enhancements and in US Pacific salmon hatchery programs (Drummond, 2004; Mobrand et al., 2005; Uki, 2006; HSRG, 2009). The shift towards looking at enhancements from a fisheries management perspective is facilitated by the emergence of stock assessment models and tools that allow evaluation of the contribution of enhancements to management goals and tradeoffs with other harvest and habitat management (Walters and Martell, 2004; Lorenzen, 2005; Mobrand, Jones, and Stokes Associates, 2006). A broader view of the role of enhancement in fishery systems has also emerged (Lorenzen, 2008).

Many other areas of enhancement science and practice have seen substantial, incremental development. Domestication processes and their management are increasingly well understood (Gross, 1998; Thorpe, 2004; Araki et al., 2008; Frankham, 2008). Many studies have been conducted to evaluate ecological differences between wild and released hatchery fish and their implications for population dynamics (Fleming and Petersson, 2001; Lorenzen, 2005). Rapid methodological and conceptual development has occurred in population genetics. This has shown widespread occurrence of adaptive genetic variation at relatively small spatial scales and fitness effects of hybridization between wild and hatchery fish (Conover et al., 2006; Araki et al., 2008; Fraser, 2008). Methodological advances now also allow marking of fish at any life stage (e.g., Tringali, 2006).

These developments make it necessary to revise the 'responsible approach' to take into account, in particular, the paradigm shift towards analyzing and managing enhancements from a fisheries management perspective. The developments also provide the tools for implementing the shift.

Most enhancements remain weak in four particular areas: (1) fishery stock assessments and modelling are integral to exploring the potential contribution of stocking to fisheries management goals; yet both are found lacking in most stock enhancement efforts in coastal systems; (2) establishing a governance framework for enhancements is largely ignored in stocking programs, thus, diminishing opportunities for integrating enhancement into fishery management; (3) involvement of stakeholders in planning and execution of stocking programs is key from the start, but they are rarely made an integral part of program development; and (4) adaptive management of stocking is not well integrated into enhancement plans, yet is critical to achieving goals, improving efficiencies, and understanding and controlling the effects of stocking on fisheries and on wild stocks. We expand on these points here and emphasize the importance of their inclusion in the responsible approach.

OUTLINE OF AN UPDATED RESPONSIBLE APPROACH TO DEVELOPMENT AND REFORM OF ENHANCEMENTS

We propose an updated Responsible Approach to developing and reforming enhancements, comprising 15 elements (Table 2) arranged in three stages as follows:

Stage I: Initial appraisal and goal setting
Stage II: Research and technology development including pilot studies
Stage III: Operational implementation and adaptive management

Our updated approach is staged in order to ensure that key elements are implemented in the appropriate phases of development or reform processes. In particular, it is important to conduct broad-based and rigorous appraisal of enhancement contributions to fisheries management goals prior to more

Table 2 The updated responsible approach

Stage I: Initial appraisal and goal setting
(1) Understand the role of enhancement within the fishery system.
(2) Engage stakeholders and develop a rigorous and accountable decision making process.
(3) Quantitatively assess contributions of enhancement to fisheries management goals.
(4) Prioritize and select target species and stocks for enhancement.
(5) Assess economic and social benefits and costs of enhancement.
Stage II: Research and technology development including pilot studies
(6) Define enhancement system designs suitable for the fishery and management objectives.
(7) Develop appropriate aquaculture systems and rearing practices.
(8) Use genetic resource management to maximize effectiveness of enhancement and avoid deleterious effects on wild populations.
(9) Use disease and health management.
(10) Ensure that released hatchery fish can be identified.
(11) Use an empirical process for defining optimal release strategies.
Stage III: Operational implementation and adaptive management
(12) Devise effective governance arrangements.
(13) Define a fisheries management plan with clear goals, measures of success, and decision rules.
(14) Assess and manage ecological impacts.
(15) Use adaptive management.

detailed research and technology development and operational implementation. This basic requirement applies to both development of new and/or reform of existing enhancements.

Stage I: Initial Appraisal and Goal Setting

Stage I is focused on a broad-based appraisal of potential enhancement contributions to fisheries management goals and the design of a planning process. Elements of Stage I may be re-iterated in later stages as appropriate.

(1) *Understand the role of enhancement within the fishery system*

Premise: Enhancements enter into complex fishery systems. It is crucial to consider the fishery system, broad objectives for management, and the full range of management options when assessing potential for, developing, and using enhancements.

Enhancements enter into complex fisheries and their role within them must be considered clearly from the outset. Outcomes of enhancement are determined by interacting, biological, and human dimensions of the fishery system into which they enter and are evaluated against a broad set of criteria. Enhancement 'success stories' often show how positive outcomes are dependent on matching enhancements to fisheries characteristics, transforming governance arrangements, and seeking ways in which enhancement can add value to other management approaches (Pinkerton, 1994; Lorenzen et al., 1998; Drummond, 2004; Uki, 2006; Garaway, 2006; Becker et al., 2008). Conversely, many enhancements have failed not or not only for technical reasons, but because they did not address management issues in the fishery (e.g., sometimes enhancements are developed for lightly exploited stocks or stocks of little fisheries interest), or inadvertently caused problematic responses (such as an increase in fishing effort on already overfished stocks).

Therefore, it is of utmost importance to gain a good understanding of the fisheries system at the start of any initiative aimed at developing or reforming fisheries enhancements. The initial fisheries system analysis has the multiple aims of summarizing relevant characteristics of the fishery system, understanding current management outcomes and their causes, and exploring ways in which outcomes may be improved. A broad framework for analyzing enhancement fishery systems is given in Lorenzen (2008). The framework sets out how in operational interactions, situational variables (attributes of the resource, fishing, aquaculture production, habitat and environment, stakeholders, markets and governance arrangements) influence outcomes of enhancement initiatives through physical-biological pathways and through those mediated by stakeholder action (Figure 1). It may also help in understanding how in longer-term, dynamic interactions, situational variables are modified in response to the outcomes of operational interactions. While not a fully specified model, the framework provides an aid for thinking through the logic of enhancement fisheries systems, and exploring options for their development or reform. This is best done in three steps: (1) establishing how situational variables affect current outcomes of the fishery or enhancement; (2) setting explicit goals for development or reform; and (3) assessing how goals might be achieved through modifications in situational variables. Criteria that should be used to evaluate outcomes include biological production, resource conservation, economic benefits and costs, contribution to livelihoods, and sustainability of governance arrangements. The analysis thus involves a preliminary appraisal of virtually all elements of the Responsible Approach. The analysis is best carried out by a multi-disciplinary team and in cooperation with stakeholders. This may require an iterative process, with an initial analysis identifying relevant team members and stakeholders and a subsequent, more in-depth analysis once these have been brought on board.

Setting or clarifying goals of fisheries management in general and of the enhancement initiative in particular is an important aspect of analysis. Only if wider management goals are defined and appreciated is it possible to set specific and appropriate goals for the enhancement. Many fundamental arguments about the role of enhancements concern congruence (or lack thereof) between wider, particularly conservation-oriented goals and more immediate, often fisheries production-centered goals (e.g., Meffe, 1992; Taylor, 1999). Goals at different levels must be made explicit and areas of congruence or conflict identified and addressed constructively in the decision process (Element (2)).

The enhancement fishery system analysis should inform implementation of subsequent steps and other elements of the Responsible Approach, in particular those of Stage I. By the

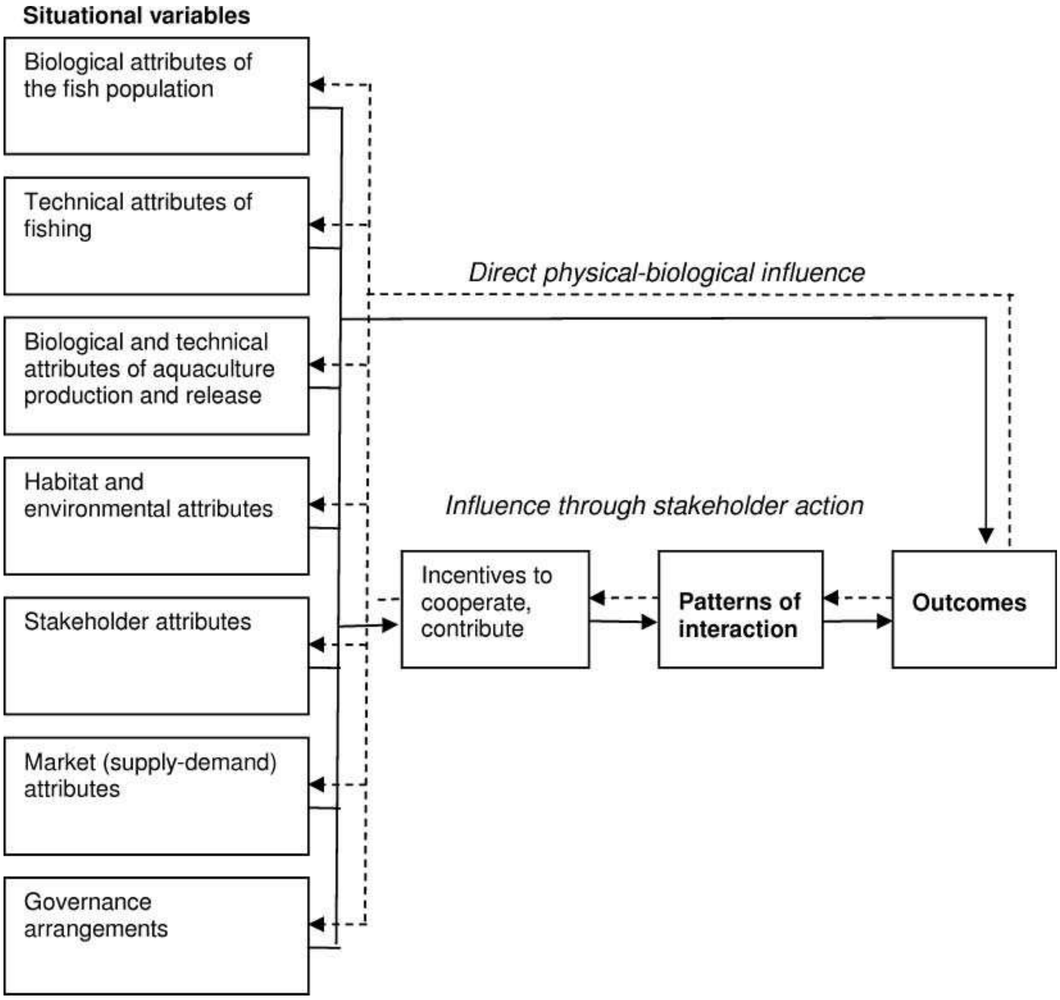

Figure 1 Framework for analyzing enhancement fisheries systems (modified from Lorenzen, 2008). Operational interactions between elements are shown as solid lines and determine outcomes in the short term when the situational variables are fixed. In dynamic interactions, shown as dashed lines, situational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

end of the analysis, the basic features of the fishery and its management outcomes should be well documented, stakeholders identified, and the ground prepared for establishing a decision making process for development or reform.

(2) *Engage stakeholders and develop a rigorous and accountable decision-making process*
Premise: Constructive engagement with stakeholders through a decision making process that is participatory, structured, and makes good use of science is crucial to the successful development or reform of enhancements.

Many successful enhancements owe much to decision making arrangements that involved both stakeholder participation and rigorous use of science (Lorenzen, 2008). Stakeholder engagement is crucial because it brings stakeholder's intimate knowledge of the fishery system into the decision process, builds trust, and encourages commitment to decision outcomes. Rigorous use of science promotes effectiveness and accountability. At the same time, it must be accepted that real decision processes are always a compromise and that the goal of reaching a balanced decision acceptable to stakeholders may take precedence over adherence to the letter of process.

Good examples of decision processes that have the desired features can be found in particular in the hatchery reform movement in the Pacific Northwest of North America (Blankenship and Daniels, 2004; Mobrand et al., 2005; HSRG, 2009). On a smaller scale and in a developing country context, such a process has been documented by Garaway et al. (2006) and Lorenzen (2008).

Key principles for designing such processes include the following. All relevant and interested stakeholders should be engaged: both primary (those, like fishers and aquaculture producers, whose actions directly impact on the enhancement outcomes) and secondary (those who have a legitimate interest but no direct impact). Usually this will involve, at a minimum, individuals or organizations involved in fisheries, aquaculture, and conservation, as well as regulatory agencies and scientists. Stakeholder analysis may be used to identify stakeholders and establish the nature and strength of their interests and interactions (Grimble and Chan, 1995). Scientific expertise will be required from multiple disciplines including fisheries science, aquaculture, genetics, ecology, and economics. For larger initiatives, a multi-disciplinary scientific advisory team should be constituted to include broadly experienced 'integrators' as well as disciplinary experts. Appraisal of enhancements involves considerations that 'general' scientific experts may not be familiar with. Hence, at least some of the scientists involved should have specialist knowledge and experience of enhancements. For smaller initiatives, advice may be provided by broadly trained and experienced professionals (sometimes referred to as 'barefoot scientists', Prince, 2010).

There are three core functions in the process: facilitation of the process itself, stakeholder input, and scientific assessment. Organization of these functions and emphasis may vary, from a stakeholder-driven process with access to scientific advice to a science-driven process with stakeholder consultation (Blankenship and Daniels, 2004; Garaway et al., 2006; Tringali et al., 2008). The facilitation role may be taken on by government, a stakeholder group, scientists, or a separate organization, such as a time-limited initiative. Ground rules for engagement in the process should be established jointly and typically will include trust building, respect for divergent views, developing a shared understanding, and collaborative problem solving (Ansell and Gash, 2008).

The process itself should also be agreed upon collaboratively. Typically, it will include a collaborative fisheries systems analysis (cf. Element 1 above), goal setting, and identification of management options including enhancement, fishing regulations, and habitat restoration. This would be followed by quantitative assessment of potential contributions of options to the management goals identified (Element 3), prioritization of species or stocks where relevant (Element 4), and assessment of economic and social benefits and costs (Element 5). Outputs from these analyses provide the basis for collaborative decision making. A structured decision process using some form of tradeoff or decision analysis is important to make assumptions and values explicit, to promote a focus on key issues, and to address potential inequalities in stakeholder influence (e.g., Janssen, 1994). The initiative may develop into a longer-term, iterative process and possibly lead to the establishment of more permanent governance arrangements (see also Element 12).

(3) Quantitatively assess contributions of enhancement to fisheries management goals
Premise: The ultimate aim of enhancements is to contribute to the achievement of fisheries management goals. This is possible only where enhancements are technically effective and outperform or add value to alternative management measures, such as fishing regulations or habitat management. The potential contribution of enhancement to management goals can and should be assessed early on in the development or reform process.

Quantitative assessment of enhancement contributions to fisheries management goals is important for several reasons (Lorenzen, 2005). First, quantitative benefits, such as increased target population abundance, yield, or economic rent, are often the motivation for enhancements, and thus crucial indicators of success. Secondly, quantitative tradeoffs between enhancement, harvest, and habitat management determine whether enhancements add value to other forms of management. Thirdly, quantitative analysis, even if carried out under conditions of large uncertainty, provides a 'reality check' for often exaggerated expectations by, or promises to, stakeholders. Quantitative assessment early on in the development or reform process is crucial to preventing large investment in, and subsequent maintenance of ill-conceived enhancement programs.

Quantitative assessment should explore the likely outcomes of fishing regulations, releases of cultured fish and, where relevant, habitat restoration on fisheries catches and the population abundance and structure of cultured, wild, and hybrid (cultured-wild) fish. Then assessment should include quantification of uncertainties in the form of a risk assessment. Due to recent progress in the development of population dynamics models and assessment methods for enhancements, such assessments can now be carried out (Walters and Martell, 2004; Lorenzen, 2005; Sharma et al., 2005). An assessment tool based on a general population model for enhancements (Lorenzen, 2005) is now available in the freeware package *EnhanceFish* (Medley and Lorenzen, 2006). There are also a number of more fishery-specific models, such as the AHA model now used to assess many Pacific salmon hatchery operations in USA (Mobrand, Jones, and Stokes Associates, 2006). Such models provide powerful and general tools for evaluation of enhancement programs, from early planning to full-scale operation. Comparative empirical studies and meta-analyses now provide prior information on virtually all required parameters, so that it is possible to conduct exploratory analyses even when there are virtually no stock specific data (see Lorenzen, 2005, 2006 for references). Where available, model parameters may be estimated from quantitative assessments of the wild stock and from release experiments with marked hatchery fish. The most comprehensive applications of quantitative assessment in improving enhancement programs can be found in Hatchery Reform processes (Mobrand et al., 2005; HSRG, 2009). Examples of prognostic evaluations include Lorenzen (2005), Loneragan et al. (2006), and Rogers et al. (2010).

(4) *Prioritize and select target species and stocks for enhancement*
Premise: When multiple species or stocks are being targeted for hatchery releases, criteria need to be developed to remove bias from the selection process so that species

and stocks can be prioritized based on an array of decisive factors.

Sometimes enhancements are being considered for a particular stock only, but often, initiatives have a broader remit and involve choice of species or stocks. Species and stocks considered for enhancement should be subjected to a suitability analysis that can help filter poor candidates from good ones. Just as stakeholder demand, alone, for more fish is not adequate justification for conducting enhancements, model prediction that enhancement would be useful in restoring a fishery, albeit the most significant, is only one of several primary factors that need to be considered before implementing hatchery production for releases.

Selection should be based on a process that scores species on enhancement potential, based on criteria, such as stock assessments and fishery management needs; preliminary enhancement modeling results; extent of habitat and recruitment limitations; likely impact on resident biota; aquaculture capability, or potential, for mass production of juveniles; cost-benefit considerations; life-history and dispersal patterns, etc. Unless attention is focused on the full spectrum of criteria used to prioritize species and stocks, consideration of an immediate need by an advocacy group and simply the availability of aquaculture technology have throughout much of the history of enhancements become the driving factors in species selection.

To reduce the bias inherent in selecting species, a semi-quantitative approach was developed in Hawaii to identify selection criteria and prioritize species for stock enhancement research (Leber, 1994). This approach involved four phases: (1) an initial workshop, where selection criteria were defined and ranked in order of importance; (2) a community survey, which was used to solicit opinions on the selection criteria and generate a list of possible species for stock enhancement research; (3) interviews with local experts to rank each candidate species with regard to each selection criterion; and (4) a second workshop, in which the results of the quantitative species selection process were discussed and a consensus was sought. This decision-making process focused discussions, stimulated questions, and quantified participants' responses. Panelists' strong endorsement of the ranking results and selection process used in Hawaii demonstrate the potential for applying formal decision-making to species selection in other regions.

(5) *Assess economic and social benefits and costs of enhancement*

Premise: Economic and social benefits and costs of enhancement and of alternatives should be assessed at all stages of program development.

Consideration of economic and social benefits and costs is critical to decision making on whether enhancement initiatives should proceed or continue, and how they should be operated. The first step should be a bio-economic analysis of the fishery, considering situations with and without enhancement (Arnason, 2001; Whitmarsh, 2001; Lorenzen, 2005). This analysis can build on the quantitative biological assessment (Element 3) and is fairly straightforward in commercial fisheries where market values for inputs and outputs are readily determined. Both, equilibrium analyses and non-equilibrium analyses considering the discounted flow of costs and benefits when enhancements are started up or modified should be conducted (see e.g., Lorenzen, 2005). The *EnhanceFish* package includes such bio-economic modelling capabilities (Medley and Lorenzen, 2006). In principle, economic analyses should account for externalities and non-market costs and benefits but in practice these are often omitted at least initially (Whitmarsh, 2001). We strongly recommend conducting at least a basic bio-economic analysis to assess whether an enhancement initiative is at all likely to be economically beneficial, given results from the quantitative biological assessment and approximate monetary values.

Recreational fisheries produce an unpriced product (the recreation experience), which can be valued by contingent valuation. Abundance of catchable fish is only one of many factors that affect the demand for, and value of, the recreational experience. Hence, the relationship between fish abundance and recreational demand may be weak and it should not be assumed that an increase in fish abundance due to stocking will create a proportionate increase in demand or value (Loomis and Fix, 1998).

Wider social benefits and costs of enhancements may be analyzed using the sustainable livelihoods framework (Allison and Ellis, 2001; Smith et al., 2005). This framework is particularly useful where livelihoods involve large elements of subsistence activities or non-market exchanges, for example in coastal areas of the developing world. Enhancement initiatives can bring about far-reaching changes in key assets, such as human capital (new knowledge and skills that may also be transferred to other activities), financial capital (individual, corporate or group income), and social capital (new opportunities to engage in networks and exchanges) (Garaway, 2006). The distribution of enhancement costs and benefits is sometimes inequitable among stakeholders, potentially leading to conflict. This may be the case, for example, where access arrangements to resources change (Garaway, 2006; Garaway et al., 2006). The social distribution of benefits and potential for conflict should also be considered and assessed in detail where concerns emerge. Finally, impacts of enhancements on wider ecosystem services may be considered (see Holmlund and Hammer (2004) for a very broad assessment framework and case study).

Stage II: Research and Technology Development Including Pilot Studies

Stage II is focused on elements of research and technology development that can be conducted at experimental or pilot scale, prior to or in parallel with operational-scale enhancements.

(6) Define enhancement system designs suitable for the fishery and management objectives

Premise: Enhancements may be developed in a variety of fisheries situations with a view to achieving different goals. Different situations and goals give rise to very different biological-technical enhancement system designs (combinations of hatchery practices, release, and fishing regimes). Objectives and potential system designs should be clarified early on in the development process because different designs may require very different technologies and governance arrangements.

Enhancement approaches can be used in different situations and for different purposes, which in turn lead to very different design criteria for the biological-technical components of enhancement systems: aquaculture production, release strategies, fishing practices, and auxiliary (e.g., habitat) manipulations (Cowx, 1994; Utter and Epifanio, 2002; Bell et al., 2006; Lorenzen, 2008). Designs for the alternative systems are at least partially incompatible; hence, it is important to clarify the situation and goals of the enhancement program, and decide on appropriate system design criteria before embarking on detailed technology development for components. The most fundamentally important question that must be answered in system design is whether the purpose of the program is primarily production or conservation-oriented.

Five main types of marine fisheries enhancement systems may be distinguished, in a sequence ranging from the most production-oriented to the most conservation-oriented type: sea ranching, stock enhancement, restocking, supplementation, and re-introduction (Utter and Epifanio, 2002; Lorenzen, 2008). Outline design criteria for the different system types are given in Table 3.

Sea Ranching

Ranching systems operate for species that do not recruit naturally or for which natural recruitment is considered unimportant. Ranching systems are stocked and harvested to maximize somatic production (commercial fisheries) or the abundance of catchable-sized fish (recreational fisheries), often manipulating populations in ways that could not be achieved in naturally recruiting populations (Lorenzen, 1995). Because direct genetic interactions with wild stocks are absent, post-release fitness of cultured fish is primarily an economic rather than a conservation issue. Selective breeding may be used to improve performance (Jonasson et al., 1997). Sterile fish may be used where reproduction in the natural ecosystem is possible but undesirable.

Stock Enhancement

Stock enhancement involves the continued release of hatchery fish into a self-recruiting wild population, with the aim of sustaining and improving fisheries in the face of intensive exploitation and/or habitat degradation. Stock enhancements can increase overall abundance of catchable fish and fisheries yield, while allowing for higher exploitation rates than could be sustained by the natural stock alone (Lorenzen, 2005). Aquaculture practices and genetic management are focused on maintaining wild population characteristics in cultured fish. Stocking and harvesting rates are strongly constrained by stock conservation considerations where stocked and wild population components interact ecologically and genetically and are harvested jointly (integrated enhancement programs). Impacts on the wild population component can be reduced by separating the cultured/stocked and wild population components as far as possible (Utter, 2004; Lorenzen, 2005). Where both components can be fully separated, management considerations for the enhanced fishery are similar to those of sea ranching. However, full separation is difficult to achieve in practice and, in general, wild stock conservation will remain an important consideration in enhancement programs (Lorenzen, 2005).

Re-Stocking

Re-stocking involves time-limited releases of hatchery fish, aimed at rebuilding depleted populations more quickly than would be achieved by natural recovery. In re-stocking, the release number must be substantial relative to the abundance of the remaining wild stock if rebuilding is to be significantly accelerated. Fishing intensity should be low in order to maximize the contribution of wild and released cultured fish to population growth (Lorenzen, 2005). Re-stocking calls for close ecological and genetic integration of wild and cultured stocks, combined with very restricted harvesting. Genetic management is clearly focused on maintaining the characteristics of the wild population.

Supplementation

Supplementation is defined here as the release of cultured fish into very small and declining populations, with the aim of reducing extinction risk and conserving genetic diversity (Hedrick et al., 2000; Hildebrand, 2002). Supplementation serves primarily conservation aims, and specifically addresses threat processes in small and declining populations: demographic stochasticity, loss of genetic diversity, and Allee effects (Caughley, 1994). Supplementation typically involves only moderate releases in order not to depress the wild population component further and stringent restrictions on harvesting. Genetic management is clearly focused on maintaining the structure and adaptations of the wild stock, with particular attention being paid to maximizing effective population size in the hatchery through full factorial or minimum kinship mating designs.

Table 3 Design criteria for biological-technical components of enhancement systems serving different objectives (modified and expanded from Lorenzen, 2008)

	Sea ranching	Stock enhancement	Re-stocking	Supplementation	Re-introduction
Aim of enhancement	Increase fisheries catch	Increase fisheries catch while conserving or increasing naturally recruiting stock	Rebuild depleted wild stock to higher abundance	Reduce extinction risk and conserve genetic diversity in small populations	Re-establish populations in historical range
Wild population status	Absent or insignificant	Numerically large Possibly depleted relative to carrying capacity	Numerically large or small Depleted relative to carrying capacity	Numerically small Possibly declining At risk of extinction	Locally extinct
Aquaculture management	Production-oriented Partial domestication Conditioning for release Possibly induced sterility	Integrated programs: as for re-stocking Separated programs: as for sea ranching	Conservation-oriented Minimize domestication Conditioning for release	Conservation-oriented Minimize domestication Conditioning for release	Conservation-oriented Minimize domestication Conditioning for release
Genetic management	Maintain genetic diversity Selection for high return	Integrated programs: as for re-stocking Separated programs: as for sea ranching; also selection to promote separation	Preserve all wild population genetic characteristics	Preserve all wild population genetic characteristics, Maximize effective population size in hatchery	Assemble diversity of adaptations or use stocks adapted to similar habitats
Population management	Stocking and harvesting to create desired population structure	Integrated programs: Restricted stocking and harvesting to increase catch while conserving naturally recruiting stock Separated programs: as for sea ranching; also measures to promote separation	High stocking density over short period; temporarily restricted harvesting or moratorium	Moderate stocking density relative to wild population, no or very restricted harvesting	Low stocking density but sufficient for establishment, minimal harvesting

Re-Introduction

Re-introduction and translocation involve temporary releases of cultured or captured fish with the aim of re-establishing a locally extinct population (Reisenbichler et al., 2003). A founding population may be assembled from multiple locations to maximize genetic diversity and potential for rapid adaptation. Continued releases should be avoided so as not to interfere with evolutionary processes in the newly established population. Fishing, likewise, should be restricted to allow rapid build-up of the population.

(7) *Develop appropriate aquaculture systems and rearing practices*
Premise: The design of aquaculture systems and rearing practices influences production efficiency and the fitness of released fish. Typically there is a tradeoff between these aspects that must be considered in system design and rearing protocols.

Aquaculture systems and rearing practices greatly influence the success of any enhancement through their impacts on both, production efficiency in the culture system and stocking effectiveness in the natural system. Considerable efforts may be required just to develop the basics of culture systems and rearing practices suitable for maintaining new species and closing their life cycle. Once these basics are known, attention must be paid to culture efficiency, post-release performance, and tradeoffs between the two. Culture systems that are efficient at producing juveniles also tend to subject fish to an inadvertent or intentional process of domestication, promoting traits that are associated with low post-release fitness (Fleming and Petersson, 2001; Thorpe, 2004; Araki et al., 2008). The optimal balance between culture efficiency and post-release fitness may vary between enhancement system designs (Element 6): efficient mass-production of moderately fit juveniles may well be economically optimal in marine ranching, while fitness is at a premium in conservation-oriented programs.

Domestication involves plastic developmental responses to the culture environment and an altered selection regime and has strong, almost always negative impacts on the capacity of fish to survive, grow, and reproduce in the wild (Olla et al., 1998; Fleming and Petersson, 2001). While it is virtually impossible to completely avert responses to captivity without also losing the advantage of culture in terms of survival and reproductive success, management approaches have been developed to produce wild-like types that maintain or re-establish certain characteristics of the wild types.

The production of wild-like types in culture requires attention to both the sampling of fish for the founder population and its subsequent management in captivity. Founders should be representative of the wild population, and encompass sufficient diversity of genotypes and life history phenotypes to allow re-establishment of viable populations in the wild (Miller and Kapuscinski, 2003). Once the captive population is established, both genetic and environmental management are important to promote maintenance of wild characteristics. The holistic solution of providing a near-natural environment for fish to live in and possibly reproduce can maintain natural selection and developmental cues. However, this approach is often impractical and, in addition, may negate the survival advantage of culture, which after all is the rationale for instituting enhancement programs in the first place. Far more interventionist genetic resource management and developmental manipulations are usually required.

Developmental manipulations to promote wild traits are important to raise performance after release, and some such manipulations may also reduce selection for culture traits. Typical manipulations include physical environmental features (e.g., temperature, water currents), nutrition, and feeding practices (Tanaka et al., 1998). Environmental enrichment (Berejikian et al. 1999), life skills training (Brown and Laland, 2001) and soft release strategies (Brown and Day, 2002) can successfully promote behavioral skills that may increase survival of released fish. The fact that cultured fish respond readily to habitat enrichment and life skills training by displaying "wild" behavioral patterns (Brown and Laland, 2001) attests to the maintenance of their enormous developmental plasticity. Exposure to variable spatial and foraging cues in the hatchery environment provides fish with enhanced behavioral traits that may be associated with improved survival in the wild (Braithwaite and Salvanes, 2005). While many such manipulations have been shown to promote wild-like traits in laboratory tests, their effectiveness at achieving the ultimate goal, increased lifetime fitness in the wild, has not been widely tested. Results so far have not shown very large effects on long-term survival (e.g., Fuss and Byrne, 2002). Evaluation of impacts of culture practices on survival in the wild (rather than on proxy indicators) should receive a high priority in technology development, despite the associated costs and timescales.

(8) *Use genetic resource management to maximize effectiveness of enhancement and avoid deleterious effects on wild populations*
Premise: Genetic resource management is important to both enhancement effectiveness and conservation of wild population genetic structure, fitness, and evolutionary potential. Attention to genetic resource management is required both in the hatchery operation and in managing the mixed wild/hatchery stock.

Genetic attributes affect fitness and evolutionary potential of stocked and wild fish. There are three areas of direct genetic impacts to consider: (1) potential disruption of neutral and adaptive spatial population structure; (2) effects of hatchery spawning and rearing on genetic diversity and fitness of stocked fish; and (3) genetic consequences for wild stocks of interactions with released hatchery fish. In addition, there may be indirect genetic effects of enhancement on wild stocks (Utter and Epifanio, 2002). Genetic issues and management approaches vary considerably between enhancement system designs (see Element 6).

Wild fish populations show spatial structure in selectively neutral markers where isolation has been sufficiently strong and long-term, and adaptive genetic variation that may be maintained by natural selection even at more moderate levels of isolation (Utter, 2004; Conover et al., 2006). Where no specific studies have been conducted, the default assumption should be that local adaption exists at scales of tens of kilometers in marine systems, and possibly at smaller scales in estuarine and freshwater systems (Reisenbichler, 1988; Palumbi, 2004; Conover et al., 2006). Hatchery practices should reflect and maintain this structure by using brood stock of local origin where possible. Not doing so is likely to carry substantial penalties in terms of post-release fitness, with implications for both enhancement effectiveness and risks to the wild population (Reisenbichler, 1988; Araki et al., 2008). In the case of re-introduction where the local population has been lost, it may be best to assemble a founder population from diverse locations and let natural selection take its course.

Hatchery populations often experience loss of genetic diversity (heterozygosity, allelic diversity) due to low effective population size and consequent genetic drift and inbreeding, though this can be averted relatively easily through appropriate brood stock management (Verspoor, 1988; Kincaid, 1995; Norris et al., 1999). Certain breeding schemes, such as full factorial or minimum kinship designs, allow maintaining a very high effective population size relative to census size in hatchery populations (Miller and Kapuscinski 2003; Fraser, 2008).

Hatchery populations also tend to show rapid loss of fitness in the wild due to genetic adaptation to the hatchery environment, which may be further exacerbated by artificial selection (Berejikian and Ford, 2004; Araki et al., 2008). Loss of fitness is more difficult to avert than loss of diversity. Measures aimed at minimizing fitness loss include rearing in near-natural environments, minimizing time in captivity, partially replenishing brood stock with wild fish in regular intervals, equalizing family size, or fragmentation of brood stock to reduce potential for adaptation (Araki et al., 2008; Frankham, 2008).

Genetic mixing of released hatchery with wild fish can have consequences for diversity and fitness of wild stocks. Consequences depend on the genetic characteristics of both stock segments and their admixture proportions and are managed by implementing sound genetic management of hatchery stocks (see above) and controlling admixture proportions through stocking and fishing practices. Provided that care is taken to maintain spatial genetic variation, the main risks to genetic diversity arise when wild populations of large effective population size are 'swamped' by hatchery fish derived from comparatively small numbers of breeders (Ryman and Laikre, 1991; Duchesne and Bernatchez, 2002). This situation can arise relatively easily in stock enhancement and restocking programs because high fecundity of fish combined with high survival of early life stages in culture makes it possible to produce very large numbers of offspring from very few parents. Where the effective population size of hatchery fish is much lower than that of wild fish, the admixture proportion of hatchery fish needs to be limited by restricting the magnitude of releases or selective harvesting of hatchery fish. Relatively high admixture proportions, however, may be acceptable in time-limited releases, such as those carried out for restocking (Duchesne and Bernatchez, 2002). Of course, the reverse effect (the hatchery population having a higher effective population size than the wild population) can occur, and is desired in supplementation programs (Hedrick et al., 2000).

Reduced fitness of cultured fish can depress the productivity of mixed, naturally recruiting populations while at the same time, reducing the risk of displacement of wild by cultured fish compared to a situation where both components are of equal fitness. The effect of reduced fitness on the productivity of a mixed wild and cultured population, however, is greatest at intermediate levels of maladaptation: well adapted cultured populations have a greater impact on wild fish but do not affect mixed population productivity, while poorly adapted cultured populations contribute little to the mixed population and have little impact on its wild component (Lorenzen, 2005). The magnitude of impacts on wild population abundance and productivity of course also depends on the relative abundance of the populations: even poorly adapted fish can have large impacts if released in great numbers and over long periods of time (Ford, 2002; McGinnity et al., 2003). Empirical studies have found evidence for reduced productivity in some mixed wild-cultured salmonid populations, but not in others (Chilcote, 2003; Sharma et al., 2006; Araki et al., 2007a, 2007b).

Where direct genetic interactions between stocked hatchery and wild fish are absent, i.e., in sea ranching or in stock enhancement programs where both populations components are separated, selective breeding may be used to improve the post-release performance of hatchery fish (Jonasson, 1997). Selection may also be used to promote separation of the population components, for example by selecting for differences in spawning seasonality (Mackey et al., 2001).

Several guidelines and policies have been developed for genetic management of enhancements, including Miller and Kapuscinski (2003) and Tringali et al. (2007). When setting up a genetic management plan, it is crucially important to consider the particular situation, management goals and system design of the enhancement in question.

(9) Use disease and health management

Premise: Releases of hatchery fish can transfer disease or parasites from the hatchery stock to wild stocks and may also affect epidemiological dynamics through addition of susceptible hosts. Thus a health management process is required that includes at minimum health screening of fish prior to release, but may require further measures where enhancements are carried out on a large enough scale to affect host dynamics significantly.

Disease transfer is a major risk associated with fisheries enhancement programs. Impacts of enhancements on disease status of wild or mixed stocks may occur due to two mechanisms:

(1) introductions of alien pathogens, and (2) changes in host population density and structure (in terms of age, size, and immune status) that affect the dynamics of established pathogens. The most dramatic disease impacts of cultured fish so far documented have been caused by introductions of alien pathogens (Johnsen and Jensen, 1991; Wagner, 2002). Such introductions may result from movements of cultured stocks even within their natural range, because the ranges of hosts and parasites are not necessarily identical (Johnsen and Jensen, 1991). Cultured fish released into the wild can increase the reservoir of susceptible hosts substantially. Because transmission of infections is usually density-dependent, most pathogens can only sustain populations when hosts occur above a certain density, and prevalence may rise with increasing density (Anderson, 1981). Release of cultured fish could, therefore, foster establishment of pathogens where they can not be supported by natural populations, or increases in the prevalence or intensity of infection.

Disease and health management concerns need to be considered from the inception of building a hatchery to the time fish are released into the natural environment. Bartley et al. (2006) describe a comprehensive disease and health risk analysis that encompasses a risk identification, assessment, and management framework to allow wise decisions for release of hatchery-reared juveniles, including species selection, hatchery site selection, hatchery protocols, culture conditions, and monitoring and surveillance. Controlling infectious diseases in culture is crucial to minimizing disease interactions with wild fish, but not always sufficient (Bartley et al., 2006). Changes in disease ecology brought about by releases of cultured fish need to be considered where releases are numerically large. Vaccination of fish for diseases where this option is available has the dual benefit of controlling disease in culture and mitigating against the introduction of a large number of susceptible hosts into natural environments through culture in open systems or release.

Several US states and organizations (e.g., California Department of Fish and Game, Florida Fish and Wildlife Conservation Commission) have developed aggressive and responsible approaches in association with their enhancement projects. Their policies require that all groups of fish cultured for stocking pass a certified inspection for specific bacterial and viral infections and parasites prior to release. The certification must be made by a certified aquatic veterinarian. Maximum acceptable levels of parasites, etc., in the hatchery populations are established based on the results of screening healthy wild populations.

(10) *Ensure that released hatchery fish can be identified*
Premise: Virtually all aspects of enhancement research and management require an ability to identify released hatchery fish. Various traditional and innovative tagging methods are available.

One of the most critical components of any enhancement effort is the ability to quantify success or failure. Without some form of assessment, one has no idea to what degree the enhancement was effective or, more critically, which approaches were totally successful, partially successful, or a downright failure (Blankenship and Leber, 1995). Natural fluctuations in marine stock abundance can mask successes and failures. Maximization of benefits cannot be realized without the proper monitoring and evaluation system. Thus, it is crucial to use a reliable marking technique to identify released hatchery fish and distinguish them from wild fish.

Without an unbiased tag or mark, quantitative assessment of release impact is impossible. All, or a high and known proportion of fish released from hatcheries should be marked in order to allow assessment of hatchery fish performance and contribution to population abundance and catch. In order to assess interactions with wild conspecifics, it is also recommended to mark a sufficient number of wild juveniles in the same sizes/locations as hatchery fish are being released (e.g., Leber et al., 1995). Marking wild fish is critical to determine whether wild survival to recruitment is depressed as hatchery production increases (Walters and Martell, 2004; Brennan et al., 2008).

Today's fishery scientists have tagging tools in their arsenal that now enable research not even feasible in 1995. Tagging systems innovations have resulted in technologies that are smaller, 'smarter', more automated, more reliable, and longer-lasting than ever before. Revolutionary advances in fish tagging and marking technology have been made. With each new innovation, seemingly another monitoring breakthrough or logistical constraint in release-recapture studies is solved.

Most enhancements release small juveniles or fry, which are difficult to mark with many conventional tags. Tagging or marking systems that are benign and satisfy the basic assumption that identified fish are representative of untagged counterparts are essential. Although electronic tags and external tags can be used to mark larger individuals, there remains a limited number of marking systems for small fingerlings and fry. Three marking systems that have proven to be most effective for tracking the small fishes released by hatcheries (typically < 100 mm) are the coded-wire tag (high information content; see applications by Hager and Noble, 1976; Leber et al., 1998; Johnson et al., 2008), genetic fingerprinting (micro-satellite DNA, intermediate information content; e.g., Tringali, 2006; Tringali et al., 2008), and otolith marks (low information content; e.g., Tsukamoto et al., 1989). Although electronic tags are highly desirable for several reasons (remote sensing, high information content, easy information recovery, some last the life of the fish), they have not yet been reduced enough in size for use with small fish.

(11) *Use an empirical process for defining optimal release strategies*
Premise: Enhancement cannot be conducted effectively without pilot release experiments to identify optimal release strategies. The effects that release tactics have on hatchery organisms and on hatchery and wild stock interactions must be taken into account. Interactions of release tactics strongly influence survival of hatchery organisms

and can be identified with pilot releases and accounted for in designing viable release strategies.

Survival of hatchery fish in the wild is highly dependent upon release strategies (Hager and Noble, 1976; Bilton et al., 1982; Tsukamoto et al., 1989; Svåsand et al., 1990). Choices made about release parameters can have dramatic effects on post-release survival—to such a degree that they can account for total mortality of released fish if the wrong choices are made (e.g., Leber and Arce, 1996). Pilot release experiments afford a means of quantifying and controlling the effects of release tactics and their influence on the performance of cultured fish in coastal environments (Blankenship and Leber, 1995; Munro and Bell, 1997; Leber, 1999, 2002).

Key release parameters that affect survival of hatchery fish released into the wild include fish size-at-release (e.g., Hager and Noble, 1976; Tsukamoto et al., 1989; Svåsand and Kristiansen, 1990b; Leber et al., 1996, 1997, 1998, 2005; Lorenzen, 2000), release season (e.g., Bilton et al., 1982; Leber et al., 1997, 1998; Hines et al., 2008), release habitat and microhabitat (e.g., Leber and Arce, 1996; Leber et al., 1998; Gardner and Van Putten, 2008; Hines et al., 2008), release magnitude (Brennan et al., 2008; Hines et al., 2008), transport and release associated stress (Sulikowski et al., 2005; Fairchild et al., 2009), and acclimatization at release sites (Brennan et al., 2006; Fairchild et al., 2008; Hervas et al., in press). These and similar experimental studies have shown that choices made about release parameters can result in significantly different mortality rates of released hatchery fish. In most cases, the greater mortality rates associated with ‘poor’ choices relative to ‘good’ ones was evident shortly after release. In many cases, differences in mortality rates were associated with interactive effects of release tactics (for example, differential effects of size-at-release varied with release season or with release habitat, and sometimes with both (e.g., Leber et al., 1998; Tringali et al., 2008). Some differences were counter intuitive and habitat specific, precluding generalities about, say, size-at-release effects upon survival. Confronting models with data about the short term effects of release tactics based on empirical field comparisons is important for developing successful enhancement release strategies and improving predictive value of the models. Clearly, release strategies cannot be developed successfully without understanding the interactive effects of release tactics.

Density dependent mortality should be a key consideration in enhancements (Hilborn, 1999; Levin et al., 2001; Lorenzen, 2005), but accounting for it in choices about release strategies can be difficult and expensive. Understanding interactions among release magnitude, size at release, release habitat, and the timing of releases can be accomplished via pilot release experiments designed to evaluate release-tactic interactions and surplus productive potential in specific habitats. Such data are then valuable for choosing release tactics that help avoid competitive displacement of hatchery or wild fish (Brennan et al., 2008; Berejikian et al., 2008). Effects of density dependence can be explored in enhancement models (Lorenzen, 2005; Medley and Lorenzen, 2006), and then coupled with field experimentation to optimize release strategy. Brennan et al. (2008), in attempting to double juvenile recruitment in nursery habitats of common snook, showed competitive displacement could be avoided in some habitats, but resulted in loss of a significant portion of hatchery fish at another. Berejikian et al. (2008) showed steelhead releases could increase salmon spawning nests (redds) without interfering with wild redds by controlling size at release and seasonal timing of releases.

Our viewpoint is that quantitative field experiments to develop optimal release strategies should always be conducted in pilot-scale releases prior to launching large enhancement programs (Leber, 1999, 2002). Empirical field experiments are a critical intermediate step in identifying enhancement capabilities and limitations and in determining release strategy. They also provide empirical data needed to plan enhancement objectives, test model assumptions about survival and cost-effectiveness, and refine enhancement models.

Stage III: Operational Implementation and Adaptive Management

Elements in Stage III are those that require attention when an enhancement is implemented at fully operational scale.

(12) *Devise effective governance arrangements*
Premise: Effective governance arrangements are essential for sustaining operational enhancements and minimizing any adverse impacts. Governance arrangements should facilitate effective coordination of the enhancement fishery system and operation of its components. Development or reform of enhancements often requires changes in governance, from small adjustments to radical transformations.

Governance failures are at the heart of many fisheries problems (Hilborn, 2007b). This is perhaps even more so in fisheries enhancements, which entail investments in the resource that can be sustained only under good governance, as well as technical interventions that can cause substantial damage if used inappropriately. Governance failures are evident where beneficial enhancements are not sustained or ineffective or damaging enhancements are not reformed or discontinued.

Effective governance requires a good understanding of stakeholder interests and behavior and of the institutional arrangements that are in place (or could be put into place) to govern stakeholders action. Stakeholder attributes including interests and behavior should already be well understood from Elements (1) and (2) in Stage I. The most critical institutions to understand and manage usually are those that relate to fishing (including access and ownership issues); but those governing aquaculture production, release, and environmental impacts can also have important implications (Pickering, 1999; Hilborn et al., 2005). Institutional arrangements should also, critically, provide a means for coordinating the different parts of the enhancement fisheries system such that each part operates in a way that contributes to a positive net outcome (Lorenzen, 2008). Governance arrangements can be structured into three levels: (1) governmental, (2) collective choice rules which determine how operational rules can be made by stakeholders, and (3) operational rules.

Initial appraisal (Stage I) and technology development (Stage II) in the development or reform of enhancements can usually be conducted within existing governance arrangements, with additional but flexible and temporary consultation processes. Starting new or reforming existing enhancements at operational scale often requires changes in governance. The extent to which governance arrangements pertaining to enhancements can be changed, of course, depends on the wider governance framework. In some jurisdictions, major changes can be made quite easily while in others, even minor adjustments require major efforts.

Governance systems for fisheries typically fall into one of four broad categories: open access, government regulation, community management, or private use rights. Open access typically results in dissipation of economic rent and resource degradation and provides little incentive for enhancement. Enhancements are particularly vulnerable to unsustainable patterns of behavior because they require investment into the resource. Government regulation through total harvest limits and input controls can solve these problems in principle but evidence suggests that community-based or individual use rights combined with some government oversight perform best because they give fishers a stake in management and provide incentives for sustainable behavior. Community-based systems can perform well where boundaries of the resource and those who can use it are clearly defined, fishers are involved in designing rules and in monitoring, and low-cost mechanisms exist for setting sanctions and resolving disputes—attributes most commonly found in local, small-scale fisheries (Ostrom, 1990, 2008). Individual rights-based systems can perform well in situations less suited for community-based approaches, including large-scale commercial fisheries. There are good examples of sustainable, self-governing enhancement fisheries involving both community-based approaches (Pinkerton, 1994; Garaway, 2006) and private use rights (Drummond, 2004).

Rules and regulations regarding aquaculture production may be extensive and cover *inter alia* facility design and operation, stock management and movement, disease control, and welfare. In some cases there are specific rules for enhancements, such as the genetics and health policies implemented in Florida (Tringali et al., 2007, 2008). Often, however, rules have been designed primarily with aquaculture in mind and may conflict with practices that are deemed desirable in enhancements. For example, the practice of replenishing captive broodstock with wild fish on a regular basis to minimize domestication effects may conflict with biosecurity protocols aimed at establishing disease-free broodstock. Rule compliance with respect to aquaculture production and release is variable and, as in the case of the fisheries component, is usually best where stakeholders have been involved in making the rules.

Arrangements for coordination among the various components or enhancement fisheries systems are often inadequate. Such arrangements must integrate multiple organizations, rules and regulations; a feat that may be best achieved through polycentric or network governance (Gibbs, 2008; Lorenzen et al., 2010).

Implementation of enhancements can be greatly facilitated by good governance arrangements that are increasingly adopted in capture fisheries and may also, in turn, facilitate the emergence of such arrangements (Anderson, 2002; Hilborn et al., 2005; Lorenzen, 2008; Lorenzen et al., 2010). Availability of enhancement technologies and investment in the resource can provide the impetus for governance change. The transformed institutional arrangements can be far more effective at regulating resource use than those previously in place. This can be a major, if somewhat indirect, benefit from enhancements (Garaway et al., 2006; Drummond, 2004; Tomiyama et al., 2008). Enhancements also expand the tactical management tool box and provide opportunities for trading off different management interventions. For example, in spatially zoned management systems, enhancement in one zone may be traded against closing the fishery in another etc. (Lorenzen et al., 2010).

(13) *Define a fisheries management plan with clear goals, measures of success and decision rules*
Premise: To increase the likelihood of success and avoid long-term maintenance of enhancements that are unsuccessful, management plans should be devised for enhanced stocks with clear goals, measures of success and decision rules. Stock management goals should reflect wider fisheries management and conservation goals and be associated with specific measures of success (measurable indicators and reference points). Decision rules should set out what actions are to be taken in the light of realized measures of success.

Operational enhancements require the coordinated management of stocking and fishing operations in order to achieve management goals for the enhanced stock. Management plans with clear goals, measures of success, and decision rules are crucially important to the development of successful enhancements where potential exists and (just as important), to ensuring that ineffective or damaging enhancements are phased out. Unfortunately, many enhancement initiatives are marred by unclear or inappropriate goals, lack of evaluation and lack of decision making.

Goals defined for the enhanced stock should reflect wider fisheries management and conservation goals. Goals should be outcome- rather than input-oriented (specifying, for example, a net increase in fisheries catches rather than a number of fish released). Because enhancements tend to involve partial replacement of wild with stocked fish, it is important to specify explicit abundance or catch goals for both segments rather than a relative contribution goal (which could be met without any net increase in abundance or catch if replacement is complete. For each explicit goal, measures of success should be defined. These will involve specific indicators and ways of measuring them as well as reference points. Reference points are values of the indicator that management should achieve (target reference points) or not exceed (limit reference points). Decision rules specify what action should be taken if a target reference point is not achieved or a limit reference point exceeded.

Management goals in most fisheries are multi-dimensional and this should be reflected in the definition of measures of success and decision rules. A set of measures of success might include, for example: 'fisheries catches increased by 20%; any concomitant reduction in the wild population component not to exceed 10%, no reduction in wild population genetic diversity measures, costs per recaptured fish not exceeding fisher's willingness to pay, no persistent conflicts generated between fishing stakeholders'. Corresponding indicators would include catch data, abundance estimates, measures of genetic diversity, estimates of enhancement costs and fisher's willingness to pay, and monitoring of conflicts. The required information would be obtained by a combination of fisheries monitoring, research surveys and possibly stakeholder consultation (about conflicts). Decision rules might specify for example increases in release numbers if catch increases are below 20% but all other criteria are met, reduction in release numbers if the wild population component is reduced by more than 10% or impacts on genetic diversity are apparent, or phasing out the enhancement if costs exceed willingness to pay. Setting appropriate and realistic reference points will always require consultation and judgement, but may be helped greatly by quantitative assessment and modeling. There are well-established reference points for capture fisheries, but enhanced fisheries involve additional and different considerations particularly with respect to cultured-wild fish interactions. The proportionate natural influence (PNI) factor defined in the hatchery reform process is an example of a reference point that has emerged to address such issues (Mobrand et al., 2005; HSRG, 2009). Management strategy evaluation—modeling of the full fisheries management system including assessment and decision making—may be used to test the performance of alternative indicators and reference points, as is commonly done in capture fisheries (Butterworth and Punt, 1999).

Needless to say, the management plan and, in particular, the goals and decision rules should be defined through a participatory and accountable process. This maximizes buy-in and the likelihood that constructive decisions will actually be made and implemented.

(14) *Assess and manage ecological impacts*

Premise: Impacts of operational enhancements on wild populations and ecosystems can be significant, either positive or negative. Such impacts arise from intra- and interspecific, biological and technical interactions. Ecological impact assessment and management needs to form part of any development or reform process.

Potential ecological impacts should be appraised early on in the development or reform of enhancements (Stage I). However, because impacts may become apparent only once enhancements are scaled up to fully operational scale, empirical assessments and where required, remedial management should be conducted in Stage III.

Ecological impacts of enhancements can arise from intra- and interspecific, biological and technical interactions. Intraspecific interactions should be assessed comprehensively through quantitative assessment, genetic resource management and the stock management plan (Elements 3, 8, and 13). Some additional research studies may be required, for example to assess the fitness in the wild of stocked and hybrid stocked-wild fish.

Interspecific biological interactions can arise where cultured fish increase the abundance of existing wild populations or establish new populations where the species was previously absent. In either case, the strongest impacts on other fish species are likely to arise due to predation from stocked fish, or due to biogenic habitat modification by stocked species that may, for example, reduce macrophyte abundance or reduce or increase turbidity (Caddy and Defeo, 2003; Eby et al., 2006). This could lead to trophic cascades, particularly in simple food webs, but such dramatic effects of enhancements appear to be rare. Interspecific competitive interactions tend to be weaker, but may also be significant (e.g., Levin and Williams, 2002).

Technical interactions, which may be intra- or interspecific, arise when the aquaculture or harvesting operations for cultured fish affect wild populations. This may occur through broodstock capture, changes in fishing pressure, or habitat modifications resulting from harvesting or culture operations. Broodstock capture can have significant impacts when wild populations are small, which is typically the case in captive breeding programs for conservation. Broodstock capture for the Mekong giant catfish breeding program, for example, has contributed to a dramatic decline in wild population abundance (Lorenzen et al., 2007). In larger populations, changes in fishing pressure associated with large-scale release programs are the most common technical interactions. Pacific salmon enhancements may have increased fishing pressure on mixed wild-hatchery stocks, though the impact of this on wild stocks remains controversial (Hilborn and Eggers, 2000). Non-target species may be harvested inadvertently or deliberately (e.g., in the case of predator control programs sometimes implemented with enhancements). Conversely, harvest restrictions brought in to protect stocked fish may also reduce pressure on wild stocks (Lorenzen et al., 1998; Lorenzen, 2008). Significant habitat disturbance may also result from harvesting operations, particularly for benthic species. Finally, aquaculture facilities supplying operational-scale enhancements can be large enough to entail significant habitat modifications. These examples, while not exhaustive, show that technical interactions can be significant and should be assessed.

Assessment of ecological impacts is best started by identifying the set of possible impacts (for example, on the basis of the overview provided here) and then scoring the risk of occurrence and potential significance of each. Frameworks developed for ecological risk assessment of fisheries may be adapted for this purpose (e.g., Fletcher, 2005; Hobday et al., 2007). Interspecifc biological impacts may be further quantified by predatory impact or ecosystem modelling (Taylor and Suthers, 2008).

Monitoring and management requirements for environmental impacts are broadly related to the magnitude of the enhancement program. A special case is where there are many similar programs that are individually small, but collectively substantial. In this case, rather than conducting cursory assessments on individual programs, it is preferable to conduct an in-depth assessment on a representative sub-set of systems.

(15) Use adaptive management

Premise: 'Actively adaptive' management needs to be firmly established as part of the operational plan for enhancements. Adaptive management enables evaluation of the performance of hatchery releases and provides the means to resolve critical uncertainties, improve the efficiency of release strategies, refine operational plans and achieve the goals of enhancement.

Development and management of enhancements often proceeds under conditions of uncertainty and may also be affected by change in environmental conditions, fishing pressure, management goals, etc. Management must deal constructively with such challenges, resolving uncertainties and adapting to change.

Assessment of impact is an integral part of 'actively adaptive' management, which entails posing and answering questions about enhancement effectiveness that allow steady adaptation and improvements to be made in operational plans (Walters and Hilborn, 1978; Walters and Martel, 2004). Adaptive management has associated costs beyond those to produce and release fish, and those costs may preclude this essential element of enhancements from being incorporated into operational plans. Without adaptive management, enhancements cannot operate efficiently and potential changes or improvements may not be recognized, which could have been used to meet goals. In the worst case, where no assessment is conducted and are operating blindly with no sense of what is being achieved, negative impacts may be occurring.

The key to effective management of enhancement impact lies in having a process for changing both production and management plans to control enhancement performance and effectiveness. To use adaptive management, a moderate level of ongoing assessment is needed, superimposed over a modest research framework that provides the new information needed to understand the effects of the enhancement system, refine enhancement strategies and tactics and achieve goals and manage uncertainty. New opportunities for refining enhancement are thus constantly generated and integrated into the management process. An important corollary of adaptive management is that change should be anticipated. This implies that aquaculture facilities, for example, should be designed in such a way that operation can be adapted relatively easily when modifications are deemed necessary (Blankenship and Daniels, 2004).

If uncertainties in the outcome of alternative management options are low and courses of action can be identified that will almost certainly lead to the achievement of objectives, these courses of action may be implemented. If uncertainties are high, it is important to assess whether a reduction in these uncertainties is likely to allow substantially improved management regimes to be developed. When this is the case, the reduction of uncertainties becomes an important objective in its own right, and courses of action should be evaluated for their potential to yield the necessary information. Experimental management may be passive, i.e., rely on 'natural' variation in management regimes to generate information, or active when variation is introduced deliberately. Which of the two adaptive strategies is implemented will depend on specific circumstances, including the degree of control that can be exercised over management actions.

Explicitly experimental management actions may be implemented and their outcomes monitored to gain crucial information (McAllister and Peterman, 1992; Walters, 1997; Garaway and Arthur, 2002). Experimental approaches may be the only way of resolving certain fundamental uncertainties. For example, varying stocking numbers over a wide range temporally and spatially may be the only way of disentangling enhancements and environmental change impacts on wild populations (Walters and Martell, 2004). It must be appreciated, however, that the costs of setting up, monitoring, and evaluating management experiments can be considerable. Therefore, experimental management should be implemented only where anticipated benefits warrant this expenditure.

When designing management experiments, careful consideration should be given to experimental design (McAllister and Peterman, 1992; Walters, 1997). Key issues are: (1) replication—ideally, this should be temporal (before and after intervention) as well as spatial (parallel measurements at similar sites where no intervention has been carried out); (2) contrast—the intervention should be substantial in order to have a measurable effect; (3) sampling effort—each replicate unit must be sampled with sufficient intensity to allow detection of an impact of the expected magnitude (MacGregor et al., 2002).

IMPLEMENTING A RESPONSIBLE APPROACH

The responsible approach sets out broad principles that may be implemented under a wide range of different circumstances and in different management settings. Not all elements are relevant under all circumstances, but most will be. No element should be discounted simply because its implementation is difficult. In our experience, integrative elements that require constructive engagement between the fisheries and hatchery constituencies and between science, management and stakeholders are most often ignored or postponed. For example, the elements 'develop a species management plan' and 'identify economic and policy objectives' of the 1995 Responsible Approach have often received only cursory attention compared to elements that are readily addressed by science alone. We urge colleagues and stakeholders to tackle all elements of the new approach and where necessary, to seek new institutional structures and processes for doing so.

The Responsible Approach can be implemented at different levels: individual enhancements, sets of similar enhancements, or at state or national level. A balance must be struck between program size and assessment/management effort. However, where many small enhancements are being developed or operated, cumulative impacts may become an issue. We suggest conducting strategic assessments on a representative sub-set of such enhancements where relevant.

We have provided a set of principles but resisted the temptation to set out a fully specified framework or process, for several reasons. First, any framework or process of sufficient generality to be useful in the diverse situations the principles apply to would be prohibitively complex and quite likely, muddle rather than clarify the key issues. Secondly, designing a locally appropriate framework and process is in itself a key element of implementing a Responsible Approach, promoting interaction among stakeholders and scientists and buy-in to the planning outcomes. Thirdly, relevant assessment and planning frameworks are likely to be in place in many locations and integrating key principles into such existing frameworks is likely to be more effective than bringing in a new framework. Finally, stakeholders and, in particular, decision makers often resist being constrained by overly prescriptive frameworks—we recognize this and encourage them to make inspired and responsible choices by drawing on the principles set out here.

DISCUSSION

We have provided a set of issues that need to be addressed if enhancements are to be developed or reformed responsibly. For each point, we provide a rationale (why the point is important) and refer readers to key publications and tools that will allow them to address the issue raised. Many issues require specialist knowledge and skills and we encourage practitioners to assemble interdisciplinary teams for development or reform processes.

The updated Responsible Approach differs from its predecessor in that it takes a broad systems view of enhancements and accords equal weight to the dynamics of their biological and human components. It requires an integrated, quantitative, and participatory analysis of the contribution enhancement could make to fisheries management goals and should be conducted at the very beginning of any enhancement initiative. Many elements of the updated Responsible Approach have direct equivalents in the earlier version and have simply been updated in the light of new knowledge. Exceptions are Elements 1, 2, and 3 of the updated approach, which provide more explicit and detailed guidance on Element 2 of the old approach. Also, Elements 7 and 14 of the updated approach expand on and clarify issues covered in Element 6 of the old approach. An explicit focus on governance arrangements has been added in the new approach (Element 12).

The updated responsible approach takes account of and can guide implementation of several related policy instruments and guidelines, including the Code of Conduct for Responsible Fisheries (FAO, 1995, 1997) and the IUCN Guidelines for Re-introductions (IUCN, 1998).

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