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Understanding and Managing Enhancement Fisheries Systems

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Aquaculture-based fisheries enhancement is a set of management approaches involving the release of cultured organisms to enhance, conserve, or restore fisheries. Enhancement has a long history, and substantial progress has been made in key areas of science underpinning the activity. Yet the contribution of enhancements to global fisheries production has remained small, and there are few outright "success stories." Enhancements enter into complex fisheries systems and, to be successful, must contribute to a broad set of biological, economic, social, and institutional management objectives. In doing so, enhancements need to add value to, or outperform, alternative measures such as fishing regulation or habitat management. This is possible only under certain conditions and may require transformations in multiple biological-technical as well as market and institutional attributes of the fisheries system. I outline a framework for the integrated analysis of enhancement fisheries systems and a systematic, transparent, and stakeholder-participatory development process.

Keywords fisheries enhancement, systems approach, institutional analysis, population dynamics

INTRODUCTION

Aquaculture-based fisheries enhancement is a set of management approaches involving the release of cultured organisms to enhance, conserve, or restore fisheries. In line with the Food and Agriculture Organization's (FAO) definition, 'cultured' organisms are subject to active husbandry and private ownership. 'Fisheries' is the harvesting (only) of organisms that are held in some form of common property regime. Aquaculture-based fisheries enhancements combine partial use of aquaculture technologies in natural environments with institutional arrangements that are broadly typical of fisheries, but often involve strong access controls or property rights. Enhancements are thus intermediate between aquaculture and fisheries in terms of both technical and human control (Anderson, 2002). This definition covers a great diversity of aquaculture-based enhancement fisheries systems (for overviews, see Munro and Bell, 1997; Petr, 1998; Travis et al., 1998; Welcomme and Bartley, 1998; and Bell et al., 2005). A call has been made to develop definitions for different types of enhancements and the objectives they serve, such as "restocking," "stock enhancement," and "sea ranching" (Bell et al., 2008). In this paper, I focus on fundamental attributes shared by most enhancement fisheries systems before outlining how different objectives and situations give rise to different system design criteria. For simplicity, I refer to all forms of aquaculture-based fisheries enhancements as "enhancements" and to the target organisms as "fish."

Many of the world's fisheries are fully exploited or overexploited, as well as suffering from effects of aquatic habitat degradation. Global capture fisheries production is stagnant, 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 restoration, aquaculture-based enhancement of stocks is the third principal means by which fisheries can be sustained and improved. Aquaculture-based enhancements can, at least in principle, generate a range of benefits. 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; (2) aid the conservation and rebuilding of depleted or threatened populations; and (3) provide partial mitigation for ecosystem effects of fishing (Lorenzen, 2005). This may give rise to economic and social benefits, including new opportunities for

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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).

Aquaculture-based enhancement has been practiced on a large scale since the mid-19th century, and transfers of wild juveniles probably have a much longer history. Systematic research on stock enhancement issues probably started in the late 19th century with Johan Hjort's studies on the early life history of marine fish, which were at least partly motivated by the Norwegian cod stocking program (Schwach, 1998). Since those early days, stock enhancement research has made dramatic progress. A consolidated body of theoretical and empirical knowledge now underpins hatchery production, release strategies, and genetic management (Leber et al., 2004). Understanding of population dynamics, ecological interactions, health management, socioeconomic, and institutional aspects is less mature but developing rapidly.

Despite the impressive development of enhancement science and many, often substantial, release programs, the contribution of enhancements to global fisheries production has remained small. Yields have been stagnant or even declining, at below 2% of the total, over the past decades (Lorenzen et al., 2001). This contrasts with the remarkable growth of aquaculture over the same period. 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). It is thus pertinent to ask why enhancements have not made a greater contribution to fisheries. I 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 are often 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.

Developing successful enhancements involves far more than producing and releasing hatchery fish that survive (though that clearly is important). Enhancements enter into complex fisheries systems comprising, at a minimum, the enhanced population, the habitat and ecosystem it depends on, the hatchery operation, the fishery (harvesting operation), the markets for inputs and outputs, the stakeholders, and the institutions (rules and regulations) that govern stakeholder behavior (Pido et al., 1996; Charles, 2001). Only in certain systems will enhancements have the potential to contribute to management objectives, and, even then, changes in multiple attributes of the system may be required for this contribution to materialize. Indeed, many enhancement "success stories" are characterized by both conducive initial conditions and constructive change in fishing regimes, and marketing and institutional arrangements in conjunction with the release of cultured organisms. Well-documented examples include the Japanese and New Zealand scallop enhancements (Drummond, 2004; Uki, 2006), Alaska salmon enhancement (Pinkerton, 1994; Heard, 2003), and Asian culture-based lake fisheries (Lorenzen et al., 1998; De Silva, 2003; Garaway, 2006; Garaway et al., 2006). On the other hand, enhancement initiatives that are poorly integrated into fisheries systems can contribute to management failure by encouraging or compensating for counterproductive changes in fishing patterns or for habitat degradation (Meffe, 1992; Taylor, 1999). Clearly, the sustainable development of enhancements requires an understanding of how releases of cultured fish enter into and precipitate intentional or unintentional modifications in fisheries systems. Here I outline a framework for the integrated analysis of enhancement fisheries systems, review key aspects of the structure and dynamics of such systems, and propose a systematic, transparent, and stakeholder-participatory process to facilitate their sustainable development.

UNDERSTANDING ENHANCEMENT FISHERIES SYSTEMS: A FRAMEWORK

The core challenge in understanding enhancement fisheries systems is to elucidate how the characteristics of the target population and its environment, fishing and enhancement technologies, and stakeholder behavior interact and lead to particular outcomes. Stakeholders determine the choice and application of fishing and enhancement technologies, and understanding their actions is thus just as important as understanding the biological processes influencing enhancement outcomes. Most fisheries enhancements are developed in common pool resources, where exploitation and replenishment patterns arise from the aggregated behavior of multiple independent resource users. A useful framework for such resource systems has been proposed by Oakerson (1992), based on core ideas of Institutional Analysis and Design (IAD; Ostrom 1990). The framework has been applied to fisheries systems by Pido et al. (1996) and specifically to fisheries enhancements by Lorenzen and Garaway (1998). Here I review, adapt, and expand the framework by synthesizing within it our current knowledge of the structure and dynamics of enhancement fisheries systems. The suggested framework for analyzing aquaculture-based enhancement fisheries systems (Figure 1) has three main types of attributes: outcomes, patterns of interaction, and situational variables. Outcomes are influenced by the situational variables via two pathways: physical-biological processes and the actions of stakeholders.

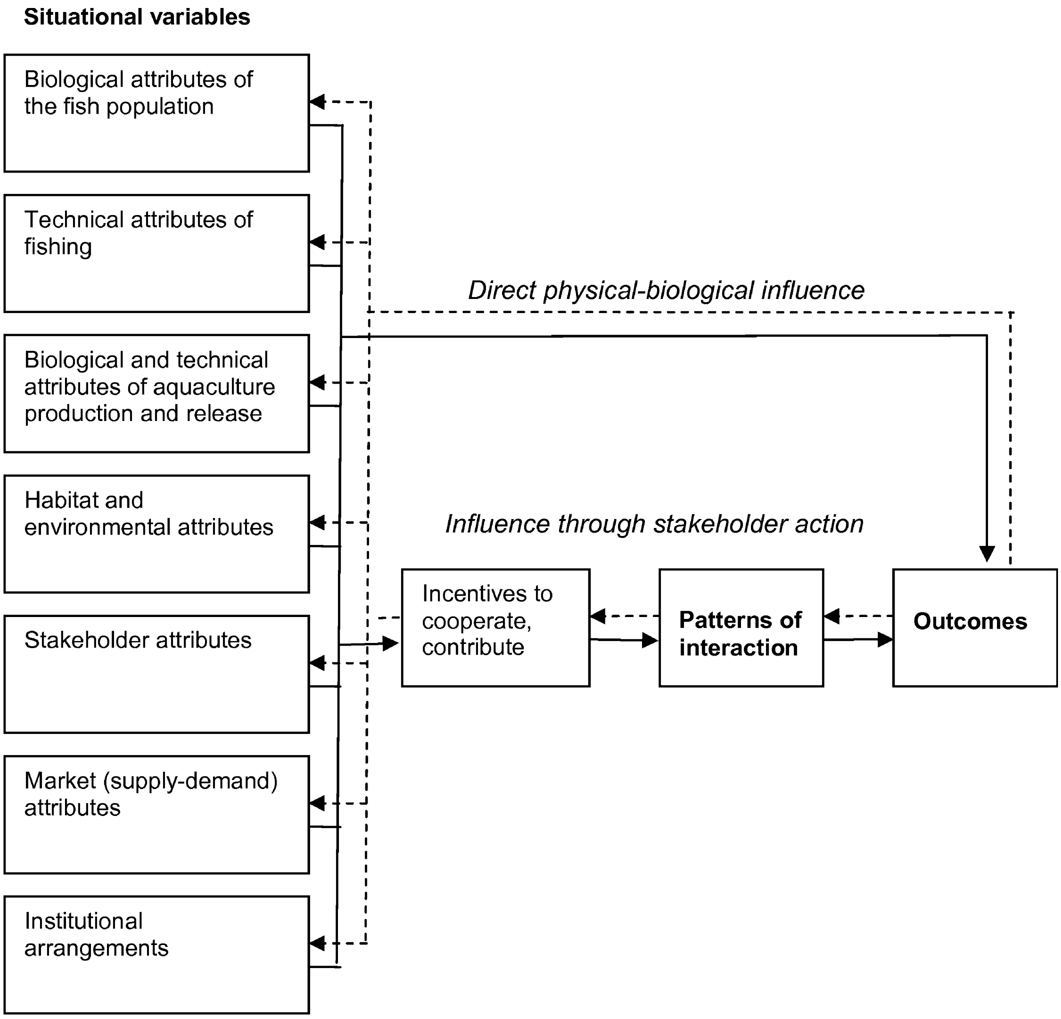

Figure 1 Framework for analyzing fisheries enhancement fisheries systems, adapted from Oakerson (1992) and Pido et al. (1996). Operational interactions between elements are shown as solid lines and determine outcomes in the short term when the situational variables are fixed. In dynamic interactions, shown as dashed lines, situational variables are modified in response to the outcomes of operational interactions.

Outcomes

Outcomes of resource use are biological (e.g., stock abundance or production) at the most basic level. Stakeholders attach values to biological outcomes according to their own objectives and situations, and thereby translate biological outcomes into benefits and costs. In most aquaculture-based fisheries enhancements, there are many stakeholders—from fishers and aquaculture producers to organizations with a general interest in conservation. Different stakeholders may have very different objectives. A broad range of criteria must therefore be considered in analyzing an enhancement fisheries system. An overview of some criteria is given in Table 1. Charles (2001), Holmlund and Hammer (2004), and Hilborn (2007a) discuss such criteria in more detail.

Patterns of Interaction

A key feature of the IAD framework is the recognition that the actions of stakeholders are influenced but not directly determined by the prevailing situational variables. Actions are influenced in a complex way, not only by existing rules but by the stakeholder's perception of benefits to be gained from following the rules, the degree to which others follow rules, the likelihood of getting caught when breaking rules, etc. For example, individual fishers will decide how much effort to expend on fishing in light of the status of stocks (biological attribute), the value they place on fishing compared to alternative activities (stakeholder attributes), the market price of fish (economic attributes), and the rules for resource use as well as the expected penalty for breaking these (institutional attributes). Aggregated over all fishers and a period of time, these decisions define the level of harvesting effort in the fishery. Patterns of interaction are the aggregation of all the actions taken by individual stakeholders.

Situational Variables

The situational variables are the main attributes of the system that influence outcomes in the short term: biological attributes

Table 1 Some criteria and indicators by which outcomes of enhancement may be evaluated

Outcome criteria	Specific indicators (examples)
Biological production	• Total yield of target species • Total yield from fishery • Size distribution of catch
Biological resource conservation	• Abundance of wild target population • Abundance of other wild fish populations • Natural productivity of target population • Genetic integrity of target population • Food web dynamics
Economic benefits and costs	• Economic rent from the enhanced fishery • Income flow • Costs of management (transaction costs) • Costs of benefits from wild fish harvesting foregone • Costs of enhancement research • Value of information gained from enhancement experiments
Contribution to livelihoods	In addition to the above: • Equity of benefits • Health benefits • Skills and knowledge developed • Networks and associations created • Trust • Access to wider institutions • Recreation
Institutional sustainability	• Persistence of management institutions • Rules are followed by stakeholders • Rules adapt to changing conditions
Broader sustainability	• Resilience of ecosystem maintained or increased

of the fish population, technical attributes of fishing, biological and technical attributes of aquaculture production, habitat and environmental characteristics, attributes of stakeholders, market (supply and demand) attributes, and institutional arrangements. Situational variables may themselves be modified by enhancements in the long term.

Interactions

Among the attributes, there are two types of interactions: operational interactions (Figure 1, solid lines) determine outcomes in the short term when the situational variables are fixed. In dynamic interactions (Figure 1, dashed lines), situational variables are modified in response to the outcomes of operational interactions. Both operational and dynamic interactions may involve direct physical-biological effects and effects mediated by stakeholder action. For example, in operational interactions, the release of cultured juveniles may add to the total abundance of catchable fish while partially replacing wild with cultured fish (biological interactions). At the same time, fishers' knowledge of the release may encourage them to increase fishing effort unless institutional arrangements are in place to prevent this (stakeholder behavior). The outcome of these combined effects could be an increase in yield and an overall reduction in spawner biomass and spawning potential. Longer-term, dynamic interactions arising in response to this outcome may involve a reduction in productivity of the natural fish population due to the reduced spawner biomass and reduced average fitness of the mixed stock of cultured and wild fish (biological interactions). However, it is also possible that stakeholders would recognize and respond to the undesired short-term outcome by transforming institutional arrangements so as to limit fishing effort, and modifying culture techniques in order to improve the post-release fitness of cultured fish (stakeholder behavior).

SITUATIONAL VARIABLES, INTERACTIONS, AND OUTCOMES IN FISHERIES ENHANCEMENTS

I now provide a brief overview of the specific situational variables, interactions, and outcomes commonly observed in enhancement fisheries systems. For each situational variable, I describe its main elements and the ways in which these influence outcomes through operational interactions, and in turn may be modified through dynamic interactions. As explained above, interactions in both directions may be directly physical-biological or mediated by stakeholder action (patterns of interaction).

Biological Attributes of the Fish Population

Biological attributes of the fish population include its life cycle, use of space and resources, its population biology, and its exploitation and conservation status.

Operational Interactions

Biological characteristics of the resource influence outcomes directly and through the incentives they provide for resource users. Life history characteristics and exploitation/conservation status of the target population are the primary determinants of biological enhancement potential (Lorenzon, 2005). Regulatory mechanisms at different stages in the life cycle determine the biological potential for increasing yields over and above the level supported by natural recruitment, and the concomitant ecological impacts on the wild population component. As a temporary measure for stock rebuilding, enhancement is likely to be beneficial only if the population has been reduced to a very low proportion of its unexploited biomass. Proposed enhancements can be "screened" using population modeling to assess whether they are likely to add value to other forms of fisheries management (Lorenzen, 2005). The mobility of the target population also influences whether those who undertake enhancement activities will be able to reap the benefits, and thus has a major influence on the incentives provided to stakeholders (Ostrom, 1990; Garaway et al., 2006).

Dynamic Interactions

Effective enhancement by definition entails increasing and thus modifying the target population. Where a wild target population exists, it will almost inevitably be impacted to some extent through ecological and genetic interactions with the released fish (Lorenzen, 2005). This may lead to partial or complete replacement of the "wild"-type fish by "hatchery"-type fish, often concomitant with an overall reduction in fitness and genetic diversity (Ford, 2002; Utter and Epifanio, 2002). However, hatchery supplementation can be instrumental in maintaining genetic diversity in very small wild populations (Hedrick et al., 2000). Impacts of enhancement on the target populations need to be managed through an appropriate combination of fishing, aquaculture production, and release regimes.

Technical Attributes of Fishing

Technical attributes of fishing comprise the efficiency of the gear(s) used in the fishery and their selectivity for species and sizes of fish.

Operational Interactions

Technical attributes of fishing have a major influence on the technical and economic efficiency of enhancements and their impact on wild populations. Where harvesting is unselective for released cultured and wild fish, and enhancement sustains an overall increase in fishing effort, pressure on the wild population is bound to increase (Lorenzen, 2005). Highly selective fishing techniques on the other hand can help to avoid additional fishing pressure on wild populations, and may even reduce biological interactions between wild and released cultured fish by removing the latter before they mature. The scope for selective harvesting of released cultured fish varies greatly between fisheries, but may be expected to improve overall due to new developments in both mass-marking and fishing techniques. It may also be possible to use behavioral conditioning of hatchery fish before release in order to facilitate selective harvesting (Balchen, 2001).

Dynamic Interactions

Modifications in fishing techniques and patterns may occur in response to new operational rules (institutional arrangements) or new fishing opportunities or constraints created by enhancement. Examples are the introduction of more highly selective fishing methods or rotational harvesting in the Lao Lake and New Zealand scallop fisheries enhancements discussed in the case studies below.

Biological and Technical Attributes of Aquaculture Production and Release

Biological and technical attributes of aquaculture production concern the husbandry and genetic management of broodstock, early life stages, and juveniles.

Operational Interactions

Sourcing of broodstock and aquaculture production practices influence both the phenotypic and the genetic quality of seed fish and thus the effectiveness of enhancement and its impact on any wild population component. Plastic developmental responses to the culture environment and an altered selection regime have strong, almost always negative impacts on the capacity of fish to survive, grow, and reproduce in the wild (Fleming and Petersson, 2001). Rearing in semi-natural environments or provision of specific conditions and stimuli can be effective in reducing such impacts (Olla et al., 1998; Brown and Dey, 2002). Genetic management is typically focused on maintaining the genetic characteristics of the wild population where released and wild fish are likely to interbreed (Frankham et al., 2002). However, intentional selection for traits of interest may be applied where the released fish remain reproductively isolated, and may even be used to promote such isolation (Jonasson et al., 1997; Mackey et al., 2001). Release size, density, location, and timing strongly influence post-release performance of fish (Blankenship and Leber, 1995). While some simple generalizations have emerged with respect to release size (Lorenzen, 2000), other aspects of release strategies appear to be quite location specific and need to be evaluated experimentally.

Dynamic Interactions

Aquaculture practices and release strategies may be modified and improved in the light of enhancement outcomes. This is important because impacts of hatchery and release practices on post-release performance are not readily known. Explicitly experimental approaches can be very effective in identifying improvements and should be considered where possible (Blankenship and Leber, 1995; Leber 1999).

Habitat and Environmental Attributes

Enhancement outcomes are strongly influenced by habitat and environmental attributes, and these in turn may be intentionally or inadvertently modified where enhancements are being developed. Habitat and environmental effects are implicit in the biological attributes of the target population (see above), but must be considered explicitly where habitat or environmental modifications occur—whether or not these are linked to the enhancement initiative.

Operational Interactions

Availability of suitable habitat for released fish is a key requirement for successful enhancement (Caddy and Defeo, 1993; Bell et al., 2005). Habitat availability need not extend to all life stages: many ranching systems or culture-based fisheries exist where habitats are suitable for late juvenile and adult fish, but not for early life stages. The biotic environment, in particular predation pressure, may also impact greatly on enhancement outcomes.

Dynamic Interactions

Enhancement initiatives often interact dynamically with habitat and environmental modifications. Direct physical-biological impacts are most often associated with culture facilities and thus localized. Impacts on foodweb structure and functioning can be more significant, for example, in predator stocking or the release of herbivorous fish to control aquatic vegetation (FAO, 1999). In other cases, ecosystem level impacts have been found to be surprisingly limited despite intensive stocking of omnivorous exotic species (Lorenzen et al., 1998; Barthelmes and Braemick, 2003). The most important habitat and environmental effects of enhancements are often those mediated by stakeholder action. This may include allowing habitats to deteriorate while attempting to compensate for fisheries impacts through releases of cultured fish (Taylor, 1999). On the other hand, releases of cultured fish for population restoration or rebuilding may precipitate major investments in habitat improvements, such as pollution control or the building of fish passage facilities (Philippart, 1995; Prignon et al., 1999). Many production-oriented enhancements benefit from intentional manipulations of habitats (e.g., fertilization of reservoirs; De Silva, 2003) or biotic interactions (e.g., predator control; Bell et al., 2005) to improve productivity of the released stock. It is thus important to recognize and manage interactions between aquaculture-based enhancements and habitat and environmental modifications in order to achieve positive outcomes for the fisheries system as a whole.

Stakeholder Attributes

Stakeholders are those persons, groups, and organizations with a valid interest in the enhancement or the pre-existing fishery (Grimble and Chan, 1995). Key attributes of stakeholders include their specific interests in the enhancement, the strength of their influence, and their interrelations. Primary stakeholders are those who interact directly with the biological-technical attributes of the enhancement and typically derive their livelihoods from it, while secondary stakeholders are all others who may influence the system. Livelihoods comprise the assets (natural, physical, human, financial, and social capital), activities, and access to these which together determine the living gained by the stakeholder (Allison and Ellis, 2001; Smith et al., 2005).

Operational Interactions

The configuration of stakeholders, their interests and interactions, have a major influence on whether and how enhancement initiatives can be initiated and sustained. Shared interests and norms, and the presence of entrepreneurial individuals and skillful leaders, are often important (Ostrom, 1990; Garaway et al., 2006). Primary stakeholders (fishers and aquaculture producers) may need substantial human (skills and knowledge), financial, and social (networks and relationships) capital to engage in enhancements. Those engaged in fishing as a "survival" or "semi-subsistence" activity (Smith et al., 2005) are likely to lack both the financial capital to buy fish for stocking, and the skills and knowledge to produce them. They may thus be unable to initiate enhancements even where these may be highly beneficial once operational. The physical, human, and financial assets available to aquaculture producers can greatly constrain their capacity to adopt production methods that optimize post-release performance and minimize genetic problems even where, in principle, this would be possible.

Dynamic Interactions

Enhancement initiatives can bring about far-reaching changes in stakeholder attributes. This concerns the basic configuration of stakeholders (emergence of new organizations and ways of interacting), and 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). However, some stakeholders may be disadvantaged by enhancements, for example, due to new restrictions on access to resources, and this can lead to conflicts. Conflicts are most likely to arise where stakeholders are heterogeneous.

Market (Supply and Demand) Attributes

This concerns the extent to which markets exist for the inputs and outputs of enhancements, and their structure and dynamics.

Operational Interactions

Market structure and dynamics can play a major role in determining the technical attributes of the system and its economic viability, and should be studied carefully. The extent to which inputs and outputs are subject to markets varies greatly. For example, markets for fish for stocking may be nonexistent where no aquaculture industry exists, while in other cases there may be very competitive markets supplying grow-out aquaculture producers or even specifically the enhancement sector. Almost always there are inputs and outputs that are not marketed or valued, such as certain environmental goods and services. There is, however, an increasing tendency towards valuation of such aspects and the creation of markets for them (Arnason, 2001). It is also important to understand exactly what is being marketed: in recreational fisheries, this is often the recreational experience rather than the fish per se, and the relationship between fish abundance and recreational demand may be much weaker than often assumed (Loomis and Fix, 1998). Often enhancement inputs and outputs interact in markets with those of capture fisheries, aquaculture, and other activities, and this may have important implications where the other sectors undergo significant changes (Delgado et al., 2003). For example, the rise of salmon aquaculture and associated decline in salmon prices has greatly reduced the profitability of salmon enhancement programs (Arnason, 2001).

Dynamic Interactions

Development of enhancements could and sometimes does affect markets through changes in demand and supply. In some locations, such as European inland waters, specialist markets for fish for stocking are well established. In general, however, enhancements make only minor contributions to markets dominated by capture fisheries and aquaculture inputs or outputs, so that the influence of enhancement on market characteristics is very limited.

Institutional Arrangements

Institutional arrangements are the rules and regulations pertaining to the enhancement fisheries system. The most critical institutions to understand and manage usually are those that relate to harvesting (including access and ownership issues); but those governing aquaculture production, release, and environmental impacts can also have important implications (Pickering, 1999; Walrut, 2002). Institutional arrangements in common pool resources, such as most fisheries, can be structured into three levels: (1) Operational rules for resource use; (2) Collective choice rules which determine how operational rules can be made by stakeholders; and (3) External arrangements. Institutional arrangements may be formal or informal.

Operational Interactions

Institutional arrangements should 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 overall outcome. Unfortunately, many enhancements operate without arrangements that allow for such coordination, and rules pertaining to individual parts of the operation 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 bio-security protocols aimed at establishing disease-free broodstock. 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 (Pickering, 1999). Rules on fish stocking into natural waters are becoming increasingly restrictive, as are other environmental regulations. Rule compliance is often poor with respect to the aquaculture production, release, and the harvesting side of the operation (i.e., the patterns of interaction are very different from those intended). Particular institutional challenges arise because most fisheries enhancements are developed in common pool resources which are used jointly by multiple users that are difficult to exclude and regulate, and whose joint use involves subtractability (Ostrom, 1990). In such resources, in the absence of regulation and/or the allocation of property or use rights, there tend to be strong incentives for users to behave in ways that lead to unsustainable outcomes for the fishery as a whole. Providing adequate incentives to avoid this outcome is a core problem in fisheries management (Hilborn et al., 2005). Enhancements are particularly vulnerable to unsustainable patterns of behavior because they require investment into the resource. Institutional analysis suggests that the collective choice and external arrangements have a major influence on rule compliance. Compliance is best where operational rules have been made with participation from primary stakeholders and adapted to local conditions; rule monitors are primary stakeholders or are at least accountable to them; there are low-cost mechanisms to resolve disputes, and the rights of stakeholders to devise institutional arrangements are not challenged by external authorities (Ostrom, 1990, 1999).

Dynamic Interactions

Existing institutional arrangements may be transformed dramatically during enhancement initiatives, and indeed such transformations are often essential for sustainable enhancements to develop. Availability of enhancement technologies and investment in the resource can provide the impetus for institutional change that can lead to improved incentive structures and resource user behavior. Such transformations are facilitated where the number of decision makers is small, and their interests are well aligned with those of the key stakeholders and by supportive external arrangements (Ostrom, 1990). The transformed institutional arrangements can be far more effective at regulating resource use than those previously in place, and this may play a greater role in determining outcomes than the release of cultured fish per se (Garaway et al., 2006; Drummond, 2004; Tomiyama et al., 2008).

FISHERIES SYSTEM TRANSFORMATIONS ASSOCIATED WITH SUCCESSFUL ENHANCEMENTS: TWO CASE STUDIES

To illustrate the dynamics of enhancement fisheries systems, I briefly review two examples of systems that have reached a fully operational scale and broadly achieved their objectives. In reviewing the examples, I make use of the framework set out above and describe first the structure of the fisheries system before enhancement, then the transformation process involved in developing the enhancement, and finally the resulting enhancement fisheries system.

Lake Fisheries Enhancement in Laos

Pre-Enhancement Situation

Floodplain lake fisheries in Laos are very heavily exploited, yielding around 100 kg ha^{-1} of mostly small fish. Returns to fishing effort are very low, but sufficient to make fish the dominant source of animal protein. Several factors contribute to this outcome. The lakes are easily accessible, shallow, and discrete bodies of water. A plethora of fishing gear is made locally or cheaply available to buy. Livelihoods are diversified but mostly subsistence oriented, with a great reliance on fish for nutrition (Smith et al., 2005). Opportunity costs of fishing are low and access generally open to local people, so that very high fishing intensities are sustained despite of low returns.

Transformation

Lake fisheries enhancement started in 1994, with transformations that affected most situational variables. Enhancements were established mostly in lakes close to villages, where monitoring of rule compliance is easy. Fishing techniques were changed to focus on the efficient harvesting of large stocked fish. Juveniles of Nile tilapia (*Oreochromis niloticus niloticus*) and Indian and Chinese major carps (*Cirrhinus mrigala*, *Labeo rohita*, *Aristichthys nobilis*, *Hypopthalmichthys molitrix*) were obtained from the aquaculture seed market and released into the selected lakes. The objective of primary stakeholders (the villagers) to engage in enhancements was to raise communal income for infrastructure development, as well as raising fisheries production and strengthening collective action. Costs of stocking were initially shared between villages and government. In most stocked lakes, villages restricted access for individual fishing and instead instigated communal harvesting and marketing systems, or allocated exclusive rights to the fishery to a harvesting group in return for a fee. External help with the improvement of management systems was provided through spatially replicated, participatory experiments supported by international development projects (Garaway et al., 2006). Several factors promoted these transformations, including the ready availability of seed fish from the aquaculture industry, the low number of decision makers and participants and their similarity of interest, presence of skillful leaders (enhancements did not evolve in villages where such leaders were lacking), and a changing economic environment where village income could be used for infrastructure development.

Enhancement Outcome

The outcomes have been an increase in total yield but, in particular, much increased catch rates (CPUE). This is the result of a much reduced fishing intensity and the targeting of large stocked fish in the fishery. This exploitation pattern has created a "size refuge," and led to a dramatic increase in the abundance of native wild fish populations (Lorenzen et al., 1998). Economically, the enhancements have generated substantial income for communal projects and benefited poorer groups disproportionately through reduced contributions to community development (Garaway, 2006). Villages operating enhancement have also been found to strengthen their capacity for further collective action and their ability to access support for other initiatives. There have been no significant conflicts over the changes in management, and the systems have become not only self-sustaining but have spread rapidly to other villages. The enhancements have thus generated a wide range of ecological, economic, and social benefits in addition to an increase in resource productivity. Key reasons for this success include the effective and economically efficient enhancement technology itself, and institutional arrangements that meet virtually all the design criteria described by Ostrom (1990).

The Southern Scallop Fisheries Enhancement in New Zealand

Pre-Enhancement Situation

The Southern Scallop Fishery developed from 1959. A dramatic expansion in fishing effort occurred in the 1970s, with yield peaking at over 1200 t in 1975 and rapidly declining thereafter. The sedentary nature of the resource, its highly variable recruitment, the availability of effective harvesting methods, and high marked demand all contributed to a rapid build-up of fishing effort. Most importantly, although various spatial and gear restrictions had applied, entry to the fishery was unrestricted until 1977 (Drummond, 2004).

Transformation

The fishery was closed in 1981 and re-opened in 1982 with a radically revised management framework of which enhancement formed an important cornerstone. Fishing effort was reduced by about 75%, and rotational harvesting was introduced as the enhancement program developed. The Japanese technology for scallop enhancement was adapted (from on-growing of spat in lantern nets to shorter on-growing in seed collectors) and introduced on an operational scale. Individual transferable quotas (ITQ) were introduced in the 1990s, and at the same time provision was made for a compulsory levy to recover the costs of enhancement from the quota holders. Use of enhancement technology played a key role in institutional development because it exempted the Southern Scallop Fishery from the prescriptive management objective of maximum sustainable yield (Arbuckle, 2000). A dedicated company (the Challenger Scallop Enhancement Company) was set up by ITQ holders to manage the enhancement operation, and this company has since taken a much more wide-ranging role in management. Other stakeholders, including recreational fishers and community groups, have since joined the management process. The enhancement initiative played a major role in facilitating and motivating the innovation in the management system of this fishery. Other contributing factors included a flexible legislative environment, a non-coercive government approach, and the development of a collective and accountable management capacity (Arbuckle, 2000).

Enhancement Outcome

Scallop catches rebounded, and seeded scallops accounted for the dominant share of the catch during the period of recovery in the early-mid 1990s (Drummond, 2004). Economically, the enhancement fishery has been successful. Institutional arrangements have proved sustainable and resilient, and are being continuously developed and adapted. At the time of writing, oceanographic conditions have led to low overall yields, and the economic viability of enhancement is being questioned, but the innovative fisheries system transformations motivated by enhancement are likely to remain (Arbuckle, personal communication).

General Lessons

Both of the above enhancements have been successful in generating a wide range of ecological, economic, social, and institutional benefits. Despite the very different settings, there are striking similarities in the way these enhancements have affected the existing fisheries systems. Both involved major transformations of the fisheries system: development of culture and release techniques, radical changes in harvesting regimes, and new institutional arrangements. Innovation was required in multiple areas, often achieved through interaction between entrepreneurial practitioners and technical experts. Releases of cultured organisms (the defining feature of enhancement) were instrumental in initiating or facilitating system transformations, but not necessarily the most important factor contributing to the ultimate outcomes. Changes in the harvesting regime in the light of enhancement, informed by quantitative fisheries assessments, were important contributing factors to success. Institutional arrangements were modified to allow a high level of control through effective communal governance and/or the allocation of individual access rights. Both initiatives involved constructive engagement of fishers, government, and other stakeholders over extended periods.

ANALYZING ENHANCEMENT FISHERIES SYSTEMS IN PRACTICE

Gaining a Broad Understanding

The framework outlined above, together with the more detailed survey of situational variables and interaction pathways, can be used to structure and guide the integrated analysis of particular enhancement fisheries systems. 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 further development. This is best done in two steps: (1) establishing how situational variables affect current outcomes of the fishery or enhancement, and (2) assessing how modifications in situational variables are likely to influence outcomes. Causes of current outcome are best understood by synthesizing the information on the system attributes within the framework, and then working backwards from the known outcomes to identify how these are determined by situational variables directly and through the patterns of interaction. To predict likely outcomes of future development or modification of situational variables, it is best to work forwards through the framework while drawing on the understanding gained in the first step. This should be done considering both operational and dynamic interactions.

The analysis of particular interactions draws on relevant disciplinary knowledge of resource ecology and population dynamics (Walters and Martell, 2004; Lorenzen, 2005), population genetics (Utter and Epifanio, 2002; Miller and Kapuscinski, 2003), hatchery production and release strategies (Blankenship and Leber, 1995; Olla et al., 1998; Brown and Dey, 2002), fishing practices, human sciences, economics (Arnason, 2001), and institutional analysis (Ostrom, 1990; Garaway et al., 2006). Integrated analysis is thus fundamentally an interdisciplinary task, best conducted by multidisciplinary teams with a strong ethic of combining disciplinary rigor with the integration of perspectives and results across disciplines.

Linking to Quantitative Assessment

Quantitative assessment of outcomes and their responses to changes in situational variables is important for several reasons. 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. Second, quantitative tradeoffs between enhancement, effort, and habitat management determine whether enhancement adds value to other forms of management. Third, quantitative analysis, even if carried out under conditions of large uncertainty, provides a "reality check" for often exaggerated expectations by, or promises to, stakeholders.

There has been considerable development of population dynamics theory and assessment methods for enhancements in the very recent past (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 the U.S. (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. The required model

Table 2 Qualitative design criteria for biological-technical components of enhancement fisheries systems serving different objectives

	Sea ranching or culture-based fisheries	Stock enhancement	Restocking	Re-introduction
Objective of management	Increase yield or opportunity to catch	Increase stock and yield or opportunity to catch	Increase stock and avert loss of genetic diversity	Re-establish populations in historical range
Management release	Early stages/juveniles, high density	Juveniles, high density	Any life stage, low density	Any life stage, low density
Fishing intensity	High	High or low	Low	Low
Genetic management	Possibly selection for high return to fishing gear	Selection for high return or preservation of wild population characteristics	Preserve wild population genetic characteristics	Assemble diversity of adaptations or use stocks adapted to similar habitats
Developmental manipulations in aquaculture	Sterility, conditioning for natural environment and return/recapture	Conditioning for natural environment and return/recapture, possibly sterility	Conditioning for natural environment	Conditioning for natural environment
Auxiliary habitat and environmental modifications	Habitat enhancement	Habitat enhancement or restoration	Habitat restoration, control of non-native species	Habitat restoration, control of non-native species

parameters may be estimated from three principal sources: (1) quantitative assessments of the wild stock, (2) release experiments with marked fish, and (3) comparative empirical studies and meta-analyses. The latter are now available for virtually all parameters of interest, so that it is possible to conduct exploratory analyses even when there are virtually no stock specific data (see Lorenzen, 2005, 2006, for references).

Design Criteria for Successful Enhancement Fisheries Systems

Enhancement fisheries systems are highly diverse, and successful outcomes tend to arise under quite specific circumstances: when conducive pre-existing situational variables combine with appropriate transformations of others. While this makes it difficult to identify general design criteria for successful enhancements, the following two considerations may be helpful in the analysis and design process.

First, the biological-technical components of the enhancement fisheries systems (aquaculture production and release, harvest technology and regulations, habitat manipulations) should be designed, individually and in combination, to meet the specific objectives of the intervention. Different objectives (Bell et al., 2008) call for very different designs. Restocking to restore depleted spawning stock biomass, for example, requires genetic management to preserve wild population characteristics and a low fishing intensity to allow spawning biomass to recover. Sea ranching, on the other hand, can benefit from genetic selection for traits that improve return rates and intensive fishing to maximize recapture of release fish. An outline of design criteria for different objectives is given in Table 2.

Second, effective institutional arrangements are required to control exploitation and promote investment in the resource. These may take a variety of forms, from effective common-pool resource management institutions (Ostrom, 1990) to various forms of property rights, including full private ownership. The key is to provide incentives to individual operators in the fishery to show behavior that contributes to positive outcomes (Hilborn et al., 2005). It should be noted that the way in which decisions about the enhancement fisheries system are made (i.e., the collective choice and external institutional arrangements) is as important as the decisions themselves when it comes to promoting appropriate behavior of stakeholders (Ostrom, 1990, Hilborn et al., 2005).

A PROCESS FOR DEVELOPING ENHANCEMENT FISHERIES SYSTEMS

It is clear from the above considerations that enhancement initiatives are most likely to contribute positively to management goals if their development is guided by a broad-based, integrated, and quantitative analysis of their role in the fisheries system. Even though approaches to integrative analysis (such as the one described here) and tools for quantitative assessment of enhancements (Walters and Martell, 2004; Lorenzen, 2005; Sharma et al., 2005) are becoming available, it will never be possible to design successful enhancements a priori or in an entirely top-down manner. Most successful enhancement initiatives involve leaps of faith as well as technical and institutional innovation, often driven by stakeholders other than scientists. The challenge is to bring rigorous analysis and the best available science into the development process. This section outlines a participatory, integrated process for developing enhancement fisheries systems (Figure 2). The process may be initiated and facilitated by any stakeholder or even an outsider, but it must draw in all key stakeholders to gain legitimacy. The suggested process has five steps:

Step 1: Engage stakeholders. Engagement of stakeholders is critical for several reasons. Stakeholders can make invaluable contributions to the analysis due to their intimate knowledge of

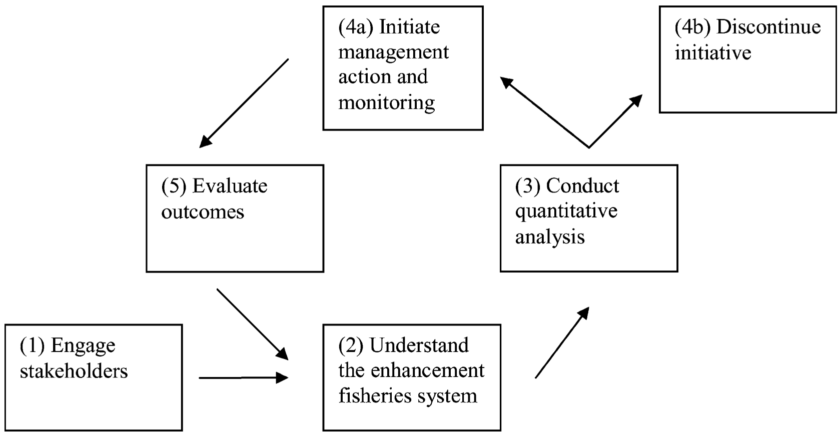

Figure 2 Suggested process for developing or improving enhancement fisheries systems.

the system and, not least, their own motivations and behavior under a variety of circumstances. Stakeholders, not analysts, should make development and management decisions—a democratic imperative and, in itself, a strong incentive for abiding by the decisions made. Finally, it must be remembered that stakeholder actions drive the development of the enhancement fisheries system, and that such actions are informed by perceptions of the system's status and potential. Close involvement of stakeholders in the analysis helps to ensure that perceptions reflect the actual state of the system. In the initial step, stakeholder analysis may be used to identify stakeholders and establish the nature and strength of their interests and interactions (Grimble and Chan, 1995). Stakeholder analysis in itself may kick-start a participatory process, which may be further invigorated by some form of participatory problem analysis such as Participatory Rural Appraisal or Participatory Learning and Action (Chambers, 1992; Pretty, 1995). This will help to create institutional arrangements (formal or informal) that allow effective two-way interaction between various stakeholders and analysts, i.e., co-management arrangements (Pomeroy and Berkes, 1997). Many participatory approaches have their origin in international development, but are easily adapted for use in the developed world.

Step 2: Understand the enhancement fisheries system. A broad, integrated analysis of the enhancement fisheries system is conducted using a suitable framework such as the one outlined above. The information required is obtained from a variety of sources including stakeholders and published information. A key element of this step is to identify development objectives and possible courses of action including, but not limited to, enhancements. The analysis is best done by an interdisciplinary team in direct interaction with stakeholders. It may draw on a variety of disciplinary frameworks such as in Cowx (1994), but the participatory process should not be reduced to working through decision aids.

Step 3: Conduct quantitative analysis. Quantitative analysis draws on the fisheries system attributes, interactions, development options, and objectives identified in Step 2. Key relationships are described and analyzed quantitatively, using models and assessment tools (Walters and Martell, 2004; Lorenzen, 2005; Medley and Lorenzen, 2006). It is particularly important at this stage to evaluate the potential for enhancement technologies relative to and in combination with fishing regulations and habitat management.

Step 4: Initiate management action and monitoring or discontinue the initiative. Clearly, this is the most difficult step in the development process and one that may require years of innovation and negotiation in any real fisheries system. Outcomes of Steps 2 and 3 are communicated to stakeholders. This may involve defining specific communication objectives and means for each group of stakeholders, based on the group's current knowledge and practice, and the desired effect of communication (Norrish et al., 2001). Decision-making by stakeholders about management and development options may be facilitated by techniques of multi-objective decision-making such as trade-off analysis (Janssen, 1994). At this stage, the initiative may be discontinued if Steps 2 and 3 indicate that the benefits of enhancement are likely to be lower than those of alternative options, or very uncertain. Depending on the level of uncertainty in predicted outcomes, 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).

Step 5: Evaluate outcomes. Outcomes are evaluated jointly by analysts and other stakeholders. If outcomes are judged to be unsatisfactory or sub-optimal, the analysis and development cycle may be reiterated. The knowledge gained is incorporated into the understanding of the enhancement fisheries system (Step 2), the quantitative analysis refined (Step 3), and new management actions initiated.

DISCUSSION

The framework and process suggested here are defined in very broad terms to allow application to a wide range of enhancement fisheries systems and promote creativity as well as rigor in development. In practical application, some ambiguity can arise as to where and how particular attributes or interactions "fit" into the framework, but this is not important. The purpose of the framework is to encourage and facilitate rigorous integrated thinking about the enhancement fisheries system, not provide a fully specified model or assessment scheme.

The framework outlined here differs from others that have been proposed and used (e.g., Cowx, 1994; Blankenship and Leber, 1995) in that it takes a broad systems view of enhancements and accords equal weight to the dynamics of their biological and human components. I argue that an integrated, quantitative, and participatory analysis of the contribution enhancement could make to fisheries management goals can and should be conducted at the very beginning of any enhancement initiative. This differs from some previous frameworks that emphasize development of culture and release techniques before engaging with fisheries management issues. Finally, the process suggested here places as much emphasis on stakeholder action and innovation as on rigorous assessment and evaluation; both aspects are important because no successful enhancement, or indeed fisheries management system, is likely to emerge without the former, no matter how well we deal with the latter. Despite some differences in scope, approach, or spirit, by and large the earlier frameworks are easily integrated into the one outlined here and continue to provide essential guidance on specific analyses and procedures. Blankenship and Leber's (1995) responsible approach can guide development of an enhancement initiative following the initial Steps 1 to 3 of the process outlined here. Cowx (1994) provides guidance on ecological assessments that are required to evaluate enhancement potential. Genetic management issues can be evaluated following Miller and Kapuszinski (2003). Where very specific and detailed planning procedures exist, for example, in certain inland enhancement, the broad framework outlined here may be used to conduct an open-minded review of procedures with a view to identifying possible innovations.

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