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REVIEW PAPER

Understanding and managing enhancements: why fisheries scientists should care[§]

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Fisheries enhancements are a set of management approaches involving the use of aquaculture technologies to enhance or restore fisheries in natural ecosystems. Enhancements are widely used in inland and coastal fisheries, but have received limited attention from fisheries scientists. This paper sets out 10 reasons why fisheries scientists should care about understanding and managing enhancements. (1) Enhancements happen, driven mostly by resource users and managers rather than scientists. (2) Enhancements create complex fisheries systems that encompass and integrate everything fisheries stakeholders can practically manage. (3) Enhancements emerge in fisheries where the scope for technical and governance control is high, and they synergistically reinforce both. (4) Successful enhancements expand management options and achievable outcomes. (5) Many enhancements fail or do ecological harm but persist regardless. (6) Effective science engagement is crucial to developing beneficial enhancements and preventing harmful ones. (7) Good scientific guidance is available to aid development or reform of enhancements but is not widely applied. (8) Enhancement research advances, integrates and unifies the fisheries sciences. (9) Enhancements provide unique opportunities for learning about natural fish populations and fisheries. (10) Needs, opportunities and incentives for enhancements are bound to increase.

Key words: aquaculture; enhancement; governance; hatcheries; restoration; stocking.

INTRODUCTION

Fisheries enhancements are a set of management approaches involving the use of aquaculture technologies to enhance or restore fisheries in natural ecosystems. Aquaculture technologies include hatchery rearing and release of aquatic animals (Bell *et al.*, 2008; Lorenzen *et al.*, 2012), provision of artificial habitat (Baine, 2001; Welcomme, 2002), feeding (Halldórsson *et al.*, 2012), fertilization (Hyatt & Stockner, 1985) and predator control (Zimmerman & Ward, 1999). Fisheries refer to the harvesting of aquatic organisms as a common-pool resource, and natural ecosystems are ecosystems not primarily controlled by humans, whether truly natural or modified by human activity. Releases of hatchery-reared aquatic animals are the most common form of enhancement, followed

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by provision of artificial habitat such as artificial reefs, while the other measures are rare and used mostly in connection with the release of hatchery-reared fish. The present paper focuses primarily on enhancements involving hatchery-reared fish, but many of the arguments presented also apply to other forms of enhancements, such as provision of artificial habitat.

Some fisheries enhancements, such as translocations of juveniles or the construction of brush parks to aggregate fish, have been practised for centuries (Welcomme, 1985). The rapid development of aquaculture technologies over the past 150 years, however, changed the nature of fisheries enhancements and greatly expanded their scope. This trend has been further strengthened by the advent of fisheries governance regimes that permit greater control of exploitation and recovery of costs associated with enhancements (Lorenzen *et al.*, 2013).

Despite their long history, widespread use and expanding scope, enhancements have received limited interest from fisheries scientists. Questions about the effectiveness of fish hatcheries played an important role in the early development of fisheries science (Schwach, 1998; Secor, 2002). Subsequently, however, fisheries science split into separate disciplines with divergent concerns and frames of enquiry, including fisheries ecology and aquaculture science. Fisheries ecology has concerned itself principally with protecting natural fish populations and communities by limiting harvests and environmental modifications to levels that maintain biodiversity, ecological and evolutionary processes (Pikitch *et al.*, 2004; Jørgensen *et al.*, 2007). This orientation, together with a widening of the fishing effects being taken into consideration, has led to a progressive lowering of harvest rates considered sustainable and rejection of interventionist approaches including many traditional fisheries management tools, such as selective fishing (Zhou *et al.*, 2010). Meanwhile, aquaculture science has pushed towards ever increasing levels of control over all aspects of the production cycle and separation of culture systems from natural systems in order to reduce environmental effects on and from aquaculture (Bostock *et al.*, 2010). These paradigms are not only different but they are also diametrically opposed and defined, in part, by rejection of the other. Enhancements, interventionist approaches applied in natural aquatic resources where many attributes are beyond management control, run contrary to both dominant paradigms and are largely ignored, if not are regarded as renegade elements by each.

The limited interest afforded to enhancements by scientists has done little to stop practitioners from conceiving and implementing them, but it has limited the effectiveness of many and allowed considerable ecological and economic damage to be done by some. Equally as important, it may have impeded progress in the fisheries and aquaculture sciences by preventing researchers from taking advantage of the rich insights the study of these systems provides.

There are signs that this situation is changing. Over the past two decades, scientists from a wide variety of disciplines have conducted path-breaking research on key issues relevant to enhancements, and slowly this research is galvanizing a coherent scientific field. Leber (2013) chronicles the emergence of marine fisheries enhancement as a scientific field and points to rapid advances but also to indicators such as limited representation in textbooks and curricula, suggesting that the field is still immature and not widely recognized by the mainstream fisheries sciences. It is noteworthy, nonetheless, that recent papers have called for greater recognition of the full range of aquatic resource systems (Klinger *et al.*, 2012) and that enhancement science has been accorded a distinct section in a compilation of seminal papers in fisheries science (Sass & Allen, 2014).

In a visionary perspective, Anderson (2002) admonished fellow fisheries economists for neglecting to engage with the implications of the rise of aquaculture and rights-based governance arrangements in fisheries, instead continuing to focus on open-access problems and other well-honed 'issues of the soon-to-be past'. His perspective remains pertinent and arguably extends beyond the economics discipline into the biological and wider human dimensions of fisheries science. The emergence and proliferation of fisheries enhancements is a direct consequence of the rise of aquaculture, and one that has profound implications for the management and conservation of fisheries. Yet, it has been largely neglected by mainstream fisheries science.

Inspired by Anderson's (2002) perspective, and paraphrasing his title, the present paper sets out why fisheries scientists should care about understanding and managing enhancements. The argument is presented in 10 reasons that relate to the current and future extent of enhancements, their central and integrating position in the realm of aquatic resource systems, the opportunities and risks they pose for sustainable use of aquatic resources, the crucial role of science engagement in promoting sustainability in enhancements and the advances that enhancement research can bring for the fisheries sciences.

TEN REASONS WHY FISHERIES SCIENTISTS SHOULD CARE

I. ENHANCEMENTS HAPPEN

In the U.S.A., state fisheries management agencies release over $1{\cdot}7 \times 10^9$ hatchery-reared fish of over 100 types annually (Halverson, 2008, 2010). On an average, the same agencies expend 21% of their budgets on practical enhancement activities (Ross & Loomis, 1999). Additional stocking is carried out by private entities and individuals, sometimes illegally (Johnson *et al.*, 2009). In China, state and private entities operate fisheries enhancements in over 80% of the country's vast acreage of reservoirs, yielding over 2·5 Mt of fish annually (Li, 1999; Miao, 2009). In the Nordic countries, 126 482 lakes managed mostly by local fishing associations are estimated to contain 52 000 fish stocks manipulated by stocking (Olsson & Folke, 2001; Tammi *et al.*, 2003). In Japan, 76 million juveniles of 37 finfish species and over 3×10^9 juveniles of 46 invertebrate species are released annually into the coastal oceans by partnerships of national and prefectural governments and fishing cooperatives (Imamura, 1999; Kitada & Kishino, 2006). Around one third of the harvest of notionally wild Alaska salmon *Oncorhynchus* spp. is actually of hatchery origin, released by community-based aquaculture associations (Pinkerton, 1994; Knapp *et al.*, 2007). Rural people in the rice-farming landscapes of south-east Asia implement a plethora of fisheries enhancement measures in public, communal or private water bodies (Garaway *et al.*, 2006; Amilhat *et al.*, 2009*a*, *b*). Fish conservation and restoration programmes worldwide make extensive use of supportive and captive breeding in hatcheries (Philippart, 1995; Lintermans, 2013; Anderson *et al.*, 2014). In addition to stocking of hatchery fish, provision of artificial habitat is widely used in the enhancement of freshwater (Tugend *et al.*, 2002; Welcomme, 2002) and marine fisheries (Baine, 2001).

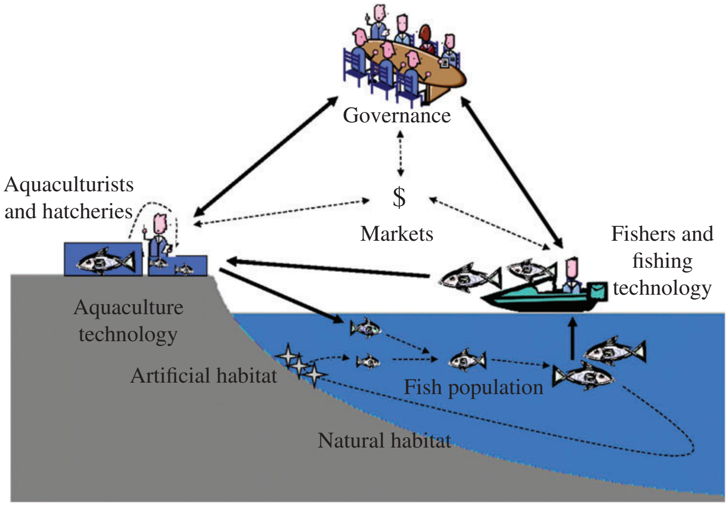

FIG. 1. Components of an enhancement fishery system and their interactions. ⟶, interactions under management control; [--->], interactions outside management control.

Even this casual survey suggests that enhancements are common and are pursued with considerable effort by diverse stakeholders including fishers, fisheries managers and conservationists. It also suggests that many stakeholders do not view capture fisheries and aquaculture as fundamentally separate activities but rather, as complementary activities that can be combined as needed in the quest to achieve desired outcomes. This important facet of management practice appears to have been largely lost to the disciplinary fisheries sciences.

II. ENHANCEMENTS CREATE COMPLEX FISHERIES SYSTEMS THAT ENCOMPASS AND INTEGRATE EVERYTHING FISHERIES STAKEHOLDERS CAN PRACTICALLY MANAGE

Stakeholders such as fishers or fishery managers establish enhancements by making use of supply-side fisheries management measures that are within their power to use, principally production and stocking of cultured fish or provision of artificial habitat on a limited scale. In doing so, they create fisheries systems that encompass and integrate all attributes fisheries stakeholders can practically manage. The resulting enhancement fisheries systems can be considerably more complex than pure capture fisheries or aquaculture systems. An enhancement fisheries system involving the production and release of hatchery-reared fish is visualized in Fig. 1. At a minimum, the system comprises the target fish stock (biological resource), the supporting habitat and ecosystem, the aquaculture operation, stakeholders (including fishers, aquaculture producers and resource managers), markets for inputs and outputs, governance arrangements and the linkages between these components. Note that only some of the linkages are under management control. In practice, enhancement systems are often compartmentalized so that certain aspects (*e.g.* aquaculture production) are carried out without explicitly considering system-level linkages, but that does not mean that such linkages are absent.

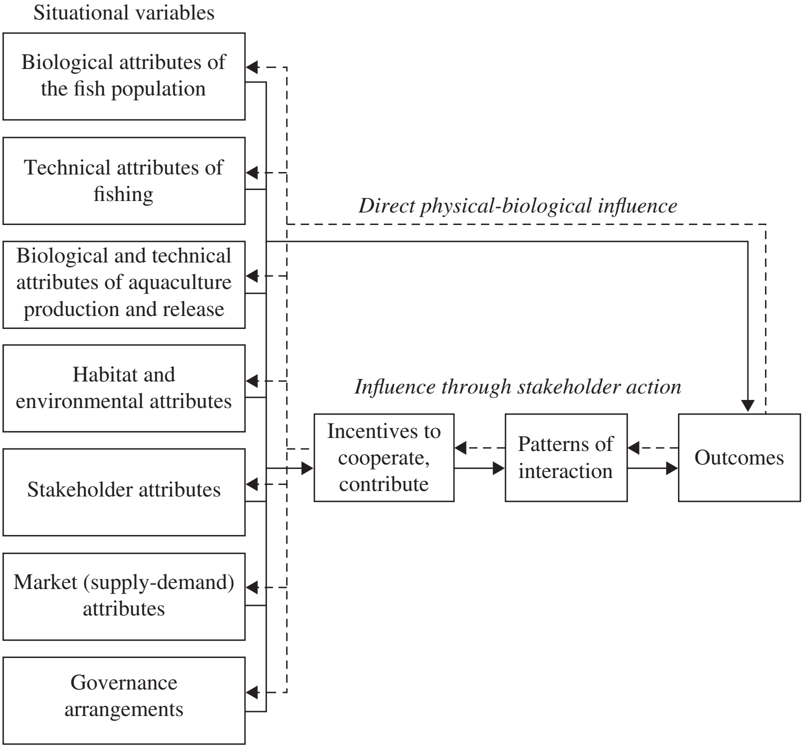

FIG. 2. Framework for analysing enhancement fisheries systems [Lorenzen (2008*a*), modified from Oakerson (1992) and Pido *et al.* (1996)].

In enhancement fisheries systems, outcomes are influenced by multiple system attributes through biological-technical pathways and the actions of stakeholders (Fig. 2; Lorenzen, 2008*a*; modified from Oakerson, 1992 and Pido *et al.*, 1996). In common pool resources such as fisheries, stakeholders influence outcomes through the aggregate of their individual actions ('patterns of interaction' in Fig. 2), which in turn are influenced by the incentives that situational variables provide for individuals to cooperate and contribute towards a positive outcome for the shared resource. Nowhere in fisheries is this pathway as critical as in enhancement systems, which can only be initiated and sustained through investment into the shared resource. The situational variables influence outcomes through direct, operational interactions but may in turn be modified in the light of outcomes through dynamic interaction (essentially feedback loops). Much of the scientific literature on enhancements focuses on exploring operational interactions through the biological-technical pathway (Cowx, 1994; Lorenzen, 2005; Araki& Schmid, 2010). Operational interactions though stakeholder action and dynamic interactions at system level have received far less attention in the literature (Lorenzen, 2008*a*; van Poorten *et al.*, 2011; Hunt *et al.*, 2013), but are likely to be important for understanding the persistence of both successful and unsuccessful enhancements.

The complex and interconnected nature of enhancement fisheries systems implies that understanding and managing them will often require consideration of multiple

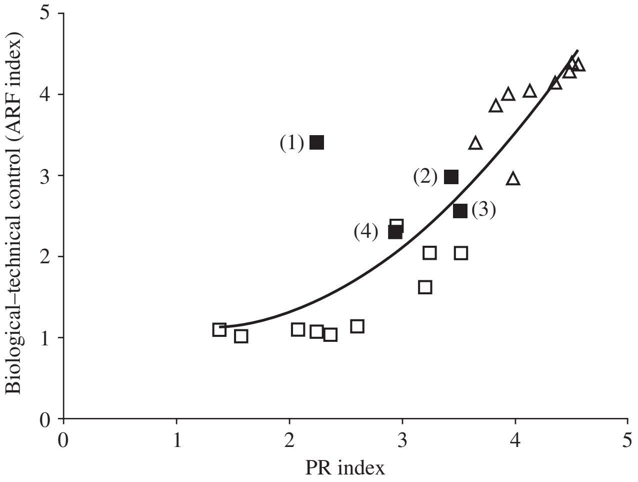

FIG. 3. Relationship between strength of property rights (PR index) and intensity of management in aquatic resource systems: capture fisheries (□), fisheries enhancements (■) and aquaculture (△). The fisheries enhancements shown are (1) stocked (culture-based) recreational trout *Oncorhynchus mykiss* and *Salmo trutta* fisheries, U.S.A., (2) scallop *Patinopecten yessoensis* ranching in Hokkaido, Japan, (3) salmon *Oncorhynchus* spp. ranching in Hokkaido, Japan and (4) salmon *Oncorhynchus* spp. stock enhancement in Alaska, U.S.A. [modified from Anderson (2002)]. PR, property rights; ARF, aquaculture–ranching–fishery.

attributes and linkages, as well as a diverse set of biological, socio-economic and institutional outcome measures (Lorenzen, 2008*a*).

III. ENHANCEMENTS EMERGE IN FISHERIES WHERE THE SCOPE FOR TECHNICAL AND GOVERNANCE CONTROL IS HIGH, AND THEY SYNERGISTICALLY REINFORCE BOTH

Enhancements are likely to emerge in fisheries where available aquaculture technologies and characteristics of the resource are conducive in achieving a high degree of technical control, and where the governance system provides sufficient control over resource use and incentives for investing into the resource. Empirical support for this argument can be found in Anderson (2002) observation that levels of biological-technical control and the strengths of property rights in the resources are closely correlated across aquatic resource systems, and that enhancement systems occupy an intermediate position between capture fisheries and aquaculture (Fig. 3). The influence attributed to property rights in Anderson (2002) study can probably be extended to other forms of strong governance control, including state management of public resources [which would make U.S. recreational trout, principally steelhead trout *Oncorhynchus mykiss* (Walbaum 1792) and brown trout *Salmo trutta* L. 1758, fisheries less of an outlier than they appear to be in Fig. 3]. Further support for this argument is provided by a closer examination of the examples of enhancements discussed in I, all of which involve strong governance arrangements.

Incentives for stakeholders to engage in enhancements exist under all common types of governance arrangements: in government-managed fisheries where agencies need to show their worth through proactive management beyond restricting harvest;

in market-based systems (such as individual transferable quotas, ITQ) where those owning rights to the resource stand to benefit from increased harvest or harvest potential; in communal systems where the same is true but in addition, the opportunity for proactively enhancing the resource may be important for galvanizing collective action. In all cases, engaging in enhancement activities is a rational choice for stakeholders. It should also be noted that this is true regardless of whether a direct biological benefit of enhancement is apparent because the perception of proactive management alone may confer benefits such as approval for governance or increased value of rights to the resource. Enhancements as proactive initiatives also meet stakeholder's psychological needs to be effective and engage in meaningful action (Kaplan & Kaplan, 2009).

Technical and governance control often act synergistically in the emergence of enhancements, with effective governance providing incentives for investment in the shared resources and this investment in turn legitimizing governance control and allocation of property rights (Anderson, 2002; Lorenzen, 2008*a*). Such synergistic effects leading to major fisheries system transformations have been documented, for example, in the development of new management structures in the wake of Alaska *Oncorhynchus* spp. enhancements (Pinkerton, 1994), the transformation of the New Zealand southern scallop fishery (Drummond, 2004) and the emergence of culture-based community fisheries in south-east Asia (Garaway *et al.*, 2006; Lorenzen, 2008*a*).

IV. SUCCESSFUL ENHANCEMENTS EXPAND MANAGEMENT OPTIONS AND ACHIEVABLE OUTCOMES

Enhancements expand the options available to fisheries resource users and managers. Such approaches may simply offer alternative routes to a particular outcome (*e.g.* accelerating recovery of a stock that would also recover naturally), or they may support outcomes that cannot be achieved by other fisheries management measures or through aquaculture (*e.g.* a high-value recreational fishery in a highly modified habitat).

Many of the situational variables that influence outcomes of enhancements (Fig. 2) are set by natural and social conditions outside of management control. Only under certain conditions can enhancements contribute to achieving better fisheries outcomes even in principle and even this is likely to require careful tuning of those variables that can be controlled in relation to those that cannot. With respect to the biological-technical attributes of enhancements, Cowx (1994) sets out a typology of fisheries situations in which enhancements may be effectively used, while Utter & Epifanio (2002), Naish *et al.* (2007) and Lorenzen *et al.* (2012) outline enhancement system designs suitable for achieving desirable outcomes in such different situations. The most recent typology by Lorenzen *et al.* (2012) recognizes five different enhancement system types: culture-based fisheries and ranching, stock enhancement, restocking, supplementation and re-introduction. Each of these systems is geared towards achieving different objectives and crucially involves quite different management practices (Table I). Culture-based fisheries and ranching systems are successfully used in many ecosystems to maintain stocks that do not recruit naturally for purposes ranging from supporting commercial or recreational fisheries to bio-manipulation (Cassani, 1995; Li, 1999; Askey *et al.*, 2013). Because sustaining natural recruitment is not a consideration in culture-based fisheries, aquaculture production, stocking and harvesting regimes can be designed to maximize somatic production or abundance of catchable-sized fish (Lorenzen, 1995; Askey *et al.*, 2013). Stock enhancement involves the continued release of hatchery fish into naturally recruiting populations, a practice that typically leads to trade-offs between overall production enhancement and the productivity and genetic integrity of the wild stock component (Hilborn & Eggers, 2000; Lorenzen, 2005). Such trade-offs can be partially mitigated by separating hatchery and wild components genetically, ecologically and at harvest (Lorenzen, 2005; Mobrand *et al.*, 2005; Naish *et al.*, 2007). Restocking involves temporary releases of hatchery fish aimed at rebuilding depleted populations quickly following overfishing, pollution events or habitat restoration (Philippart, 1995; Richards & Rago, 1999; Lorenzen, 2005). Supplementation can address threat processes in small and declining populations, increasing abundance to counteract demographic stochasticity and Allee effects and employing genetic management to maintain diversity (Hedrick *et al.*, 2000; Hildebrand, 2002). Supplementation may, however, carry short and medium-term fitness costs (Fraser, 2008; McClure *et al.*, 2008). Re-introduction involves temporary releases of cultured fish with the aim of re-establishing a locally extinct population (Philippart, 1995; Harig *et al.*, 2000; Reisenbichler *et al.*, 2003).

Economic and social benefits of enhancements may arise from the biological outcomes described above, *e.g.* increased catches (Arnason, 2001; Askey *et al.*, 2013), the creation or maintenance of fisheries and other ecosystem services in highly modified environments (Cowx & Portocarrero Aya, 2011; Brummett *et al.*, 2013) or the re-establishment of locally extinct stocks following ecosystem restoration (Philippart, 1995). Successful enhancements, however, often have further, more subtle and higher-order benefits. Pinkerton (1994), for example, describes economic benefits of Alaska *Oncorhynchus* spp. enhancements that result from greater consistency and quality of harvests as well as greater volume. Community-based lake fisheries enhancements in Laos led to substantial catch and efficiency gains in the fisheries and to communal cash income that was used to fund infrastructure projects while reducing the level of individual household contributions to such projects (Garaway, 2006). Governance arrangements for fisheries may be strengthened and transformed in the wake of enhancements as discussed in II, and this may have wider benefits for resource conservation as well as social development (Pinkerton, 1994; Garaway *et al.*, 2006; Lorenzen, 2008*a*). 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 (Lorenzen *et al.*, 2010*a*; Sale *et al.*, 2014). Finally, aquaculture-based supplementation or re-introduction programmes may provide the impetus for large-scale habitat restoration initiatives by maintaining or restoring charismatic or legally protected species (Cowx & Portocarrero Aya, 2011).

These examples show that under certain conditions, enhancements can make positive contributions to the management and conservation of natural aquatic resources. There is some life in between the opposing paradigms of fisheries ecology and aquaculture.

V. MANY ENHANCEMENTS FAIL OR DO ECOLOGICAL HARM BUT PERSIST REGARDLESS

Many enhancements fail to meet their objectives and some do considerable ecological or genetic harm, yet such enhancements often persist. Hilborn (1998) and Arnason

TABLE I. Biological-technical typology of enhancement fisheries systems (simplified from Lorenzen *et al.*, 2012)

	Culture-based fisheries, ranching, bio-manipulation	Fisheries stock enhancement (integrated or separated programmes)	Re-stocking or stock rebuilding	Supplementation and captive breeding	Re-introduction and translocation
Aim of management	Increase fisheries catch	Increase fisheries catch and 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
Domestication type	Domesticated, mixed	Mixed, wild-like	Wild-like	Wild-like	Wild-like
Genetic management	Selection for high return to fishing gear	Integrated programmes: as for re-stocking Separated programmes: selection for high return and separation	Preserve wild population genetic characteristics	Preserve wild population genetic characteristics, maximize effective population size	Assemble diversity of adaptations or use stocks adapted to similar habitats
Release	Early stages–juveniles or large catchable fish, high density	Large juveniles, moderate to high density	Any life stage, high density	Any life stage, low density to supplement natural recruitment	Any life stage, low density
Fishing intensity	High	Integrated programmes: moderate Separated programmes: high	Low	Low	Low
Wild population	Usually absent	Present (large, but possibly depleted)	Present (depleted)	Present (small, declining)	Absent (locally extinct)
Biological interactions	Interspecific ecological and technical	Intraspecific ecological, genetic and technical	Intraspecific ecological, genetic and technical	Intraspecific ecological and genetic, possibly technical	Interspecific ecological

(2001) examined the economic viability of marine enhancements using hatchery-reared fish and concluded that only a small proportion was demonstrably viable. For many marine enhancements, the outcomes were not sufficiently quantified to allow an economic assessment. No comparable synthesis has been attempted for freshwater fisheries enhancements but the situation there is likely to be slightly better owing to more confined resources and therefore greater scope for control, and to generally lower production costs for freshwater organisms. Enhancements based on artificial structures have likewise shown mixed effectiveness (Bohnsack, 1989; Baine, 2001). The variable and, on average, moderate success rate of enhancements is also evident from the fact that the overall contributions of these systems to fisheries production have remained limited, most likely accounting for only a few per cent of global capture fisheries production and around 10–20% of freshwater fisheries production in areas where enhancements are well developed (Lorenzen *et al.*, 2001).

Enhancements may fail for many different reasons. Released organisms may perform very poorly in the wild because of domestication effects of hatchery rearing and may essentially vanish without trace (Olla *et al.*, 1998; Lorenzen, 2006; Araki *et al.*, 2008). Where released organisms survive, they may elicit compensatory mortality or growth responses that adversely affect the wild population component and reduce or completely invalidate net production benefits (Hilborn & Eggers, 2000; Lorenzen, 2005). Released hatchery fish can disrupt genetic population structure and diversity of wild stocks unless careful genetic resource management is in place and even then, may adversely affect fitness because of domestication effects (Utter, 2004; Araki *et al.*, 2007, 2008). Interspecific interactions of released hatchery fish may be significant or severe, particularly in the case of predator stocking (Levin & Williams, 2002; Eby *et al.*, 2006), but have been found to be minimal in other cases (Arthur, R. I. *et al.*, 2010).

Failed enhancements carry social and economic costs because returns on investments are not realized and in some cases, significant externalities are imposed through ecological damage (Arnason, 2001). In addition to such fairly direct costs of failed enhancements, there may be indirect and subtle costs. The literature on such indirect costs has focused on two related areas: the role of enhancements in mitigating the effects of habitat loss and degradation and of unsustainable exploitation on fisheries, thereby hiding these effects (Meffe, 1992; Holmlund & Hammer, 2004), and the idea that this has allowed affecting developments to proceed that may otherwise not have occurred (Taylor, 1999).

Given the complexity of enhancements (II), the fact that they are likely to perform well only under certain conditions and with appropriate designs (IV), and often poor knowledge of conditions in the target fishery, it is not surprising that many enhancements fail or do harm. The more intriguing question is why such enhancements tend to persist regardless. There are several possible reasons. First, as discussed in III, incentives for maintaining enhancements are not necessarily dependent on them achieving biological objectives. Secondly, enhancements implemented at small scale need not be expensive, and stakeholder may simply take the chance. Thirdly, stakeholders may rely on mental models of the fishery that are unrealistic but have not been confronted with evidence. For example, anglers may assume that stocked fish simply add to existing wild stocks rather than eliciting compensatory responses that might diminish or completely obliterate a positive effect (von Lindern, 2010).

VI. EFFECTIVE SCIENCE ENGAGEMENT IS CRUCIAL TO DEVELOPING BENEFICIAL ENHANCEMENTS AND PREVENTING HARMFUL ONES

Because enhancements tend to emerge in fisheries where stakeholders are proactive and governance arrangements are strong (III), the prospects for scientists to engage with enhancements and influence their outcomes are excellent (or at least, better than in fisheries that do not share these characteristics). To be effective in this situation, however, science engagement must go beyond research on biological processes or outcomes. It must take account of the motivations, knowledge, attitudes and behaviours of the stakeholders driving the enhancement, and of the governance arrangements that influence their actions. Not only that, scientists must constructively interact with stakeholders and governance systems in order to effect change and often, this will require making stakeholder perspectives explicit before biological research outputs can be constructively used (Sarewitz, 2004). In a nutshell, scientists must engage with the enhancement fisheries system and find ways to steer it towards better outcomes (Lorenzen, 2008*a*).

Several examples show the power of effective science engagement in improving enhancement systems. The hatchery reform process in the Pacific Northwest of the U.S.A. is perhaps the most systematic and large-scale use of science to improve enhancements (Blankenship & Daniels, 2004; Mobrand *et al.*, 2005; Paquet *et al.*, 2011). Working cooperatively with fisheries and hatchery managers, a team of scientists has reviewed hundreds of salmonid hatchery programmes. Modelling was used to determine the best system design for each programme, using an approach based on best available science, goal identification, scientific defensibility and adaptive management to refocus from an aquaculture paradigm to a renewable natural resource paradigm. In a recent application to the Columbia River basin, hatchery reform solutions improved the conservation status of many populations [25% for *O. mykiss* and >70% for Chinook salmon *Oncorhynchus tshawytscha* (Walbaum 1792) and coho salmon *Oncorhynchus kisutch* (Walbaum 1792)] while also providing increased harvest (Paquet *et al.*, 2011). On a much smaller scale and in a developing country context, a programme of science engagement with community-led lake fisheries enhancements in rural Laos has yielded equally impressive results (Garaway *et al.*, 2006; Arthur, R. *et al.*, 2010). Working cooperatively with local communities in research design, execution and analysis, the team used comparative observational studies and adaptive learning experiments to improve management approaches to better meet local community' aims for the enhanced fisheries while safeguarding wild fish stocks (Garaway & Arthur, 2004*a*, *b*). This has resulted in substantial gains of fishery yield, economic and social benefits ranging from fishing efficiency increases to infrastructure development and strengthening the capacity of communities to manage their resources (Garaway, 2006; Garaway *et al.*, 2006; Arthur, R. *et al.*, 2010). At the same time, stocking and harvesting practices of the enhanced fisheries were associated with an increase in natural stock abundance and no loss of wild fish diversity (Lorenzen *et al.*, 1998; Arthur, R. I. *et al.*, 2010).

Science engagement does not necessarily lead to successful enhancements because in many cases, 'no enhancement' may emerge as the best option for a given fishery and available technology. In the science engagement case studies described above, for example, enhancements were downscaled or discontinued in some of the systems examined. In the 1980s and 1990s, Norwegian scientists undertook a large-scale, multidisciplinary study on the performance of cod *Gadus morhua* L. 1758 fisheries enhancements and concluded that although a moderate level of biological production enhancement could be realized, this would not be economically viable (Svåsand *et al.*, 2000). As a result, no further *G. morhua* enhancements are being undertaken. Prevention or discontinuation of ineffective or harmful enhancements is as important an outcome of science engagement as is the development of successful initiatives.

Science engagement with enhancements need not come at a big cost to other science priorities, such as the study of wild fish stocks and natural ecosystems. Many of the questions that need to be answered to assess the potential or actual utility of enhancements are about the dynamics and status of the wild stocks and supporting ecosystems. Moreover, enhancements provide unique opportunities for experimental research in with natural systems.

VII. GOOD SCIENTIFIC GUIDANCE IS AVAILABLE TO AID DEVELOPMENT AND REFORM OF ENHANCEMENTS BUT IS NOT WIDELY APPLIED

Scientific knowledge and assessment tools have matured to the extent that they can be used in an effective and timely manner to improve emerging and established enhancements. The strategic and responsible approaches to enhancements as set out by Cowx (1994) and Blankenship & Leber (1995) provide overall conceptual frameworks as well as substantive and some procedural guidance. This responsible approach has been recently updated and restructured to better guide development and reform of enhancement systems from a fisheries management perspective (Lorenzen *et al.*, 2010*b*); while Cowx's (1994) strategic framework has been further operationalized with a set of more detailed decision rules (Cowx *et al.*, 2012). Synthesis papers, guidelines and tools provide further guidance in specific areas including: broad-based analysis of enhancement systems (Lorenzen, 2008*a*), biological-technical system designs for particular situations and objectives (Utter & Epifanio, 2002; Naish *et al.*, 2007; Lorenzen *et al.*, 2012), domestication processes and their management (Thorpe, 2004; Araki *et al.*, 2008; Fraser, 2008), promoting wild behavioural traits in hatchery fish (Olla *et al.*, 1998; Brown & Dey, 2002), ecological differences and interactions between wild and released hatchery fish (Fleming & Petersson, 2001; Jonsson & Jonsson, 2006), population modelling and assessment (Walters & Martell, 2004; Lorenzen, 2005; Mobrand, Jones and Stokes Associates, 2006), genetic management (Miller & Kapuscinski, 2003; Tringali *et al.*, 2007), bio-economic modelling (Askey *et al.*, 2013; Camp *et al.*, 2014), disease risk assessment and management (Bartley *et al.*, 2006), interspecific interactions and ecosystem effects (FAO, 1999; Eby *et al.*, 2006) and stakeholders engagement (Miller *et al.*, 2010; Gregory *et al.*, 2012).

A crucial development in enhancement science is that, due in particular to the development of population dynamics models for enhancements and meta-analyses of key biological parameters, it is becoming increasingly possible to predict the outcomes of enhancements and evaluate the likely utility of such approaches *vis-à-vis* alternative fisheries management measures (Lorenzen, 2005, 2006; Michael *et al.*, 2009). This means that enhancements can be realistically appraised prior to major investments being undertaken. Experimental studies will typically be required to develop enhancements that appear promising in the prognostic evaluation and optimize operational enhancements, and such studies can greatly benefit from modern telemetry and tagging technologies (MacGregor *et al.*, 2002; Leber & Blankenship, 2011). Experimental releases provide powerful means of identifying optimal release strategies (Leber *et al.*, 1996) or assessing effect of enhancements on wild conspecifics and fish communities (Brennan *et al.*, 2008; Arthur, R. I. *et al.*, 2010).

Unfortunately, this body of knowledge has not been widely applied and it is pertinent to ask why. Failure to mainstream enhancement knowledge within the fisheries and aquaculture professions is likely to be a major factor. Sandström (2010, 2011) and Sevä's (2013) found access to adequate implementation resources (individuals and organizations that help managers learn about policies and best practice) to be a key factor explaining variation in the consistency and quality of decision making in implementation of fish stocking policies in Scandinavia.

VIII. ENHANCEMENT RESEARCH ADVANCES, INTEGRATES AND UNIFIES THE FISHERIES SCIENCES

Enhancements inspire and require various types of research. On one hand, there is disciplinary research dealing with problems such as behavioural conditioning of fish for release into the wild. On the other hand, there is integrative interdisciplinary research aimed at understanding interactions for example between demography and genetics, or between stock dynamics and fisher behaviour. Perhaps unsurprisingly, the greatest research activity and scientific progress to date has occurred in areas where enhancement issues intersect with disciplinary research questions, and where results can be obtained by analysing existing data or experimenting on a relatively small physical and temporal scale. The fruits of these endeavours have been described above (VIII).

Further progress in enhancement science is likely to rely increasingly on interdisciplinary studies that combine theory development with experimental tests of key assumptions and long-term manipulative experiments with whole enhancement systems. For example, the development of quantitative evolutionary-ecological theory of domestication and of hatchery-wild fish interactions will help to systematize and operationalize the body of empirical knowledge in this area. So far, there has been limited integration and theory development beyond population models that are primarily either ecological or genetic in focus and have not been confronted with data (Ford, 2002; Goodman, 2005; Lorenzen, 2005; Baskett & Waples, 2013). Further analysis of the role of enhancements in the dynamics of whole aquatic resource (social-ecological) systems will test the generality of the interactions between technical and governance control surmised here. This area is of critical importance for understanding and promoting social-ecological resiliency in aquatic resource systems that will increasingly combine fisheries, aquaculture and enhancements (Lorenzen, 2008*a*; van Poorten *et al.*, 2011; Camp *et al.*, 2013).

Research in these areas will not only advance the science bases of fisheries enhancements, but also harness the intellectual challenges and experimental opportunities of enhancement research to advance both fisheries ecology and aquaculture science. Eventually, this may lead to the re-emergence of a more unified fisheries science, one that is fit for addressing the challenges of aquatic resource management in a future where aquaculture and environmental changes are likely to be important drivers.

IX. ENHANCEMENTS PROVIDE UNIQUE OPPORTUNITIES FOR LEARNING ABOUT NATURAL FISH POPULATIONS AND FISHERIES

Engaging with enhancements forces scientists to ask new questions about fundamental aspects of fish biology. The question whether releases of hatchery-reared larvae could enhance *G. morhua* abundance in local fjords is believed to have motivated J. Hjort's ground-breaking research on fish migrations and the critical period concept of juvenile survival (Schwach, 1998; Secor, 2002). The question to what extent Pacific salmon *Oncorhynchus* spp. fry could be transferred between natal streams for enhancement and restoration purposes motivated and enabled experimental research on local adaptations (Reisenbichler, 1988). The quest to extend fisheries assessment models for the analysis of enhancements led to new generalizations about size and density-dependent processes in fish populations, some of which are now widely used in the assessment of wild stocks (Lorenzen, 2000, 2005, 2008*b*).

Enhancements also provide new opportunities to observe target organisms, often at a much greater level of detail than would be possible otherwise. A great deal of basic biological information on numerous fish species has been derived from observations in aquaculture facilities, in the course of learning how to culture the organisms. By enabling mass production and release of organisms at any life stage that have defined characteristics and can be marked visibly or identified genetically, enhancements also provide new opportunities for observing organisms in natural ecosystems (Leber & Blankenship, 2011). Possibilities range from, for example, measuring survival, growth and dispersal of fish released at a defined location and life stage to releasing fish of known disease or toxicological state to assess exposure to pathogens or toxicants.

Beyond mere observation, enhancements provide unique means for experimenting with natural populations and with capture fisheries (Miller & Walters, 2004; Hutchings, 2014). The ability to add fish of various life stages to natural populations, potentially in large numbers, can be used to push organisms and populations outside their natural limits in the quest to establish those limits and the mechanisms underlying their existence (Table II). Releases may also be used to decouple feedback mechanisms that would render certain processes difficult to observe in natural systems. For example, fishing effort responses to variation in fish abundance can be difficult to observe because a strong effort response also causes a quick reduction in abundance. Enhancements allow maintaining high fish abundance even when effort responses are strong, and it may not be coincidence that some of the best documented effort responses have indeed been measured in enhanced fisheries (Cox *et al.*, 2002). Enhancement through provision of artificial habitat also offers many opportunities for experimental studies on natural fish populations and fisheries (Lindberg *et al.*, 2006).

The greatest fundamental caveat to using hatchery fishes in experimental manipulations of natural populations is the fact that hatchery rearing tends to induce domestication effects that can modify morphological, physiological, behavioural, ecological and genetic traits of hatchery fish relative to those found in the wild population (Lorenzen *et al.*, 2012). Many domestication effects show a level of qualitative consistency across studies and species but are not as yet quantitatively predictable (Fleming & Petersson, 2001; Thorpe, 2004; Jonsson & Jonsson, 2006). The implications of domestication effects must be considered when designing experiments, and may well make certain experiments unfeasible.

TABLE II. Some suggested or implemented experiments enabled by enhancements that provide insights of relevance to fisheries science in general

Experiment	Principle	Implementation
Test for fitness consequences of adaptive genetic variation	Transfer of hatchery fish away from region of broodstock origin	Reisenbichler (1988); Mehner *et al.* (2009)
Marginal habitat value and the ideal free distribution (Miller & Walters, 2004)	Monitoring habitat selection of stocked fish in relation to habitat quality and fish abundance	Taylor *et al.* (2013)
Nature and strength of density-dependent processes (Miller & Walters, 2004)	Manipulating density at different life stages	Post *et al.* (1999) Nislow *et al.* (2004) Brennan *et al.* (2008)
Angler effort response to fish abundance and catch rates (Camp *et al.*, 2013)	Stocking to maintain contrast in abundance and catch rates (effort responses would naturally reduce contrast)	Loomis & Fix (1998); Cox *et al.* (2002) (observational studies, not actively experimental)

X. NEEDS, OPPORTUNITIES AND INCENTIVES FOR ENHANCEMENTS ARE BOUND TO INCREASE

Needs, opportunities and incentives for enhancements are likely to increase substantially over the next decades. Population growth and economic development will put great pressure on the habitats and ecosystems supporting inland and coastal fisheries(Wilson *et al.*, 2006; Vorosmarty *et al.*, 2010; Sale *et al.*, 2014) while at the same time increasing demand for aquatic food products and recreational fishing opportunities (Duarte *et al.*, 2009; Merino *et al.*, 2012). Traditional management and conservation measures will have an important role in helping to sustain fisheries, but will probably be insufficient (Hollowed *et al.*, 2013). Enhancements are likely to expand their role in sustaining food and recreational fisheries and in restoring biodiversity and ecosystem functioning in increasingly modified ecosystems (Brummett *et al.*, 2013; Lorenzen *et al.*, 2013). In the context of climate change adaptation, enhancement approaches have a useful role to play in assisted migration of freshwater species (Rahel *et al.*, 2008; Lawler & Olden, 2011). Early life stages of fish may also be more sensitive to temperature than later life stages (Rijnsdorp *et al.*, 2009) and enhancements could be used to maintain valuable fish populations where temperatures are suitable for later, but not early stages. New enhancement opportunities will emerge as more and more aquatic species are likely to be taken into culture (Duarte *et al.*, 2007), thereby enabling fishing stakeholders to obtain animals for stocking easily and relatively cheaply (Bell, 1999; Lorenzen, 2008*a*). The trend towards rights-based access to fisheries, mediated by individual quotas, licences, territorial use rights fisheries (TURF) is set to continue and will provide further incentives for stakeholders to pursue enhancements (Chu, 2009; Lorenzen *et al.*, 2010*b*). Effective science engagement will be more important than ever to ensure that enhancements are used effectively and responsibly in what is likely to be a perfect storm of needs, opportunities and incentives.

CONCLUDING THOUGHTS

There are compelling reasons, rooted in applied aquatic resource management and conservation needs as well as in fundamental scientific advancement, for fisheries scientists to care more about understanding and managing enhancements. In addition to outlining such reasons, the arguments presented above suggest several avenues towards increasing the engagement of the fisheries sciences with enhancements. Most fundamental, perhaps, is for fisheries scientists to recognize the unique nature of enhancements as fisheries systems that combine attributes of capture fisheries and aquaculture, and the fact that such systems are more common in management practice than may be apparent from a disciplinary vantage point. Fisheries scientists should familiarize themselves with the rapidly developing scientific foundations of fisheries enhancement and strive to apply this knowledge to the management, development or reform of enhancements within their sphere of responsibility. Substantial advances to fundamental understanding of fish ecology, evolution and fisheries dynamics may be realized from enhancement experiments, and it may be advantageous for fisheries research and management agencies to operate some enhancement programmes specifically for this purpose (Hutchings, 2014). Finally, fisheries scientists should realize the potential of enhancement initiatives for stakeholder engagement in fisheries management and research and the wider benefits that this may generate even in cases where the enhancement being pursued and evaluated is not ultimately technically successful.

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References

Amilhat, E., Lorenzen, K., Morales, E. J., Yakupitiyage, A. & Little, D. C. (2009a). Fisheries production in Southeast Asian farmer managed aquatic systems (FMAS) I. Characterization of systems. *Aquaculture* **296,** 219–226.

Amilhat, E., Lorenzen, K., Morales, E. J., Yakupitiyage, A. & Little, D. C. (2009b). Fisheries production in Southeast Asian farmer managed aquatic systems (FMAS) II. Diversity of aquatic resources and management impacts on catch rates. *Aquaculture* **298,** 57–63.

Anderson, J. L. (2002). Aquaculture and the future: why fisheries economists should care. *Marine Resource Economics* **17,** 133–151.

Anderson, J. H., Pess, G. R., Carmichael, R. W., Ford, M. J., Cooney, T. D., Baldwin, C. M. & McClure, M. M. (2014). Planning Pacific salmon and steelhead reintroductions aimed at long-term viability and recovery. *North American Journal of Fisheries Management* **34,** 72–93.

Arnason, R. (2001). The economics of ocean ranching: experiences, outlook and theory. *FAO Fisheries Technical Paper* **413**.

Araki, H. & Schmid, C. (2010). Is hatchery stocking a help or harm? Evidence, limitations and future directions in ecological and genetic surveys. *Aquaculture* **308,** S2–S11.

Araki, H., Cooper, B. & Blouin, M. S. (2007). Genetic effects of captive breeding cause a rapid, cumulative fitness decline in the wild. *Science* **318,** 100–103.

Araki, H., Berejikian, B. A., Ford, M. J. & Blouin, M. S. (2008). Fitness of hatchery-reared salmonids in the wild. *Evolutionary Applications* **1,** 342–355.

Arthur, R., Mees, C. & Halls, A. (2010). Assessing the impacts of fisheries management science: a review of the Department for International Development's fisheries management science programme. *Journal of Development Effectiveness* **2,** 158–172.

Arthur, R. I., Lorenzen, K., Homekingkeo, P., Sidavong, K., Sanvilaikham, B. & Garaway, C. J. (2010). Assessing impact of introduced aquaculture species on native fish communities: Nile tilapia and major carps in SE Asian freshwaters. *Aquaculture* **299,** 81–88.

Askey, P. J., Parkinson, E. A. & Post, J. R. (2013). Linking fish and angler dynamics to assess stocking strategies for hatchery-dependent, open-access recreational fisheries. *North American Journal of Fisheries Management* **33,** 557–568.

Baine, M. (2001). Artificial reefs: a review of their design, application, management and performance. *Ocean and Coastal Management* **44,** 241–259.

Bartley, D. M., Bondad-Reantaso, M. G. & Subasinghe, R. P. (2006). A risk analysis framework for aquatic animal health management in marine stock enhancement programmes. *Fisheries Research* **80,** 28–36.

Baskett, M. L. & Waples, R. S. (2013). Evaluating alternative strategies for minimizing unintended fitness consequences of cultured individuals on wild populations. *Conservation Biology* **27,** 83–94.

Bell, J. D. (1999). Restocking of giant clams: progress, problems and potential. In *Stock Enhancement and Sea Ranching* (Howell, B. R., Moksness, E. & Svåsand, T., eds), pp. 437–452. Oxford: Fishing News Books.

Bell, J. D., Leber, K. M., Blankenship, H. L., Loneragan, N. R. & Masuda, R. (2008). A new era for restocking, stock enhancement and sea ranching of coastal fisheries resources. *Reviews in Fisheries Science* **16,** 1–9.

Blankenship, H. L. & Daniels, E. (2004). A scientific and systematic redesign of Washington State salmon hatcheries. *American Fisheries Society Symposium* **44,** 561–572.

Blankenship, H. L. & Leber, K. M. (1995). A responsible approach to marine stock enhancement. *American Fisheries Society Symposium* **15,** 67–175.

Bohnsack, J. A. (1989). Are high densities of fishes at artificial reefs the result of habitat limitation or behavioral preference? *Bulletin of Marine Science* **44,** 631–645.

Bostock, J., McAndrew, B., Richards, R., Jauncey, K., Telfer, T., Lorenzen, K., Little, D., Ross, L., Handisyde, N. & Gatward, I. (2010). Aquaculture: global status and trends. *Philosophical Transactions of the Royal Society B* **365,** 2897–2912.

Brennan, N. P., Walters, C. J. & Leber, K. M. (2008). Manipulations of stocking magnitude: addressing density-dependence in a juvenile cohort of common snook (*Centropomus undecimalis*). *Reviews in Fisheries Science* **16,** 215–227.

Brown, C. & Dey, R. L. (2002). The future of enhancements: lessons for hatchery practice from conservation biology. *Fish and Fisheries* **3,** 79–94.

Brummett, R. E., Beveridge, M. C. M. & Cowx, I. G. (2013). Functional aquatic ecosystems, inland fisheries and the Millennium Development Goals. *Fish and Fisheries* **14,** 312–324.

Camp, E. V., Lorenzen, K., Ahrens, R. N. M., Barbieri, L. & Leber, K. M. (2013). Potentials and limitations of stock enhancement in marine recreational fisheries systems: an integrative review of Florida's red drum enhancement. *Reviews in Fisheries Science* **21,** 388–402.

Camp, E. V., Lorenzen, K., Ahrens, R. N. M. & Allen, M. S. (2014). Stock enhancement to address multiple recreational fisheries objectives: an integrated model applied to red drum *Sciaenops occelatus* in Florida. *Journal of Fish Biology* **85**, 1868–1889.

Cassani, J. R. (1995). Problems and prospects for grass carp as a management tool. *American Fisheries Society Symposium* **15,** 407–412.

Chu, C. (2009). Thirty years later: the global growth of ITQs and their influence on stock status in marine fisheries. *Fish and Fisheries* **10,** 217–230.

Cowx, I. G. (1994). Stocking strategies. *Fisheries Management and Ecology* **1,** 15–31.

Cowx, I. G. & Portocarrero Aya, M. (2011). Paradigm shifts in fish conservation: moving to the ecosystem services concept. *Journal of Fish Biology* **79,** 1663–1680.

Cox, S. P., Beard, T. D. & Walters, C. (2002). Harvest control in open-access sport fisheries: hot rod or asleep at the reel? *Bulletin of Marine Science* **70,** 749–761.

Drummond, K. (2004). The role of stock enhancement in the management framework for New Zealand's southern scallop fishery. In *Stock Enhancement and Sea Ranching: Developments, Pitfalls and Opportunities* (Leber, K. M., Kitada, S., Blankenship, H. L. & Svåsand, T., eds), pp. 397–411. Oxford: Blackwell Publishing.

Duarte, C. M., Marba, N. & Holmer, M. (2007). Rapid domestication of marine species. *Science* **316,** 382–383.

Duarte, C. M., Holmer, M., Olsen, Y., Soto, D., Marbà, N., Guiu, J., Black, K. & Karakassis, I. (2009). Will the oceans help feed humanity? *Bioscience* **59,** 967–976.

Eby, L. A., Roach, J. W., Crowder, L. A. & Stanford, J. A. (2006). Effects of stocking-up freshwater food webs. *Trends in Ecology and Evolution* **21,** 576–584.

Fleming, I. A. & Petersson, E. (2001). The ability of released, hatchery salmonids to breed and contribute to the natural productivity of wild populations. *Nordic Journal of Freshwater Research* **75,** 71–98.

Ford, M. J. (2002). Selection in captivity during supportive breeding may reduce fitness in the wild. *Conservation Biology* **16,** 815–825.

Fraser, D. J. (2008). How well can captive breeding programs conserve biodiversity? A review of salmonids. *Evolutionary Applications* **1,** 535–586.

Garaway, C. (2006). Enhancement and entitlement – the impact of stocking on rural households' command over living aquatic resources: a case study from the Lao PDR. *Human Ecology* **34,** 655–676.

Garaway, C. & Arthur, R. (2004a). *Adaptive Learning: Lessons from Southern Lao PDR*. London: MRAG Ltd. Available at http://www.worldlakes.org/uploads/Adaptive_Learning_Guidelines.PDF/

Garaway, C. & Arthur, R. (2004b). *Community Fisheries: Lessons from Southern Lao PDR*. London: MRAG Ltd. Available at http://www.fao.org/docs/eims/upload/agrotech/1918/R7335_App12.pdf/

Garaway, C. J., Arthur, R. I., Chamsingh, B., Homekingkeo, P., Lorenzen, K., Saengvilaikham, B. & Sidavong, K. (2006). A social science perspective on stock enhancement outcomes: lessons learned from Inland fisheries in southern Lao PDR. *Fisheries Research* **80,** 37–45.

Goodman, D. (2005). Selection equilibrium for hatchery and wild spawning fitness in integrated breeding programs. *Canadian Journal of Fisheries and Aquatic Sciences* **62,** 374–389.

Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T. & Ohlson, D. (2012). *Structured Decision Making: A Practical Guide to Environmental Management Choices*. Chichester: Wiley-Blackwell.

Halldórsson, J. E., Björnsson, B. Th. & Gunnlaugsson, S. B. (2012). Feasibility of ranching coastal cod (*Gadus morhua*) compared with on-growing, full-cycle farming and fishing. *Marine Policy* **36,** 11–17.

Halverson, M. A. (2008). Stocking trends: a quantitative review of governmental fish stocking in the United States, 1931 to 2004. *Fisheries* **33,** 69–75.

Halverson, A. (2010). *An Entirely Synthetic Fish: How Rainbow Trout Beguilded America and Overran the World*. New Haven, CT: Yale University Press.

Harig, A. L., Fausch, K. D. & Young, M. K. (2000). Factors influencing success of greenback cutthroat trout translocations. *North American Journal of Fisheries Management* **20,** 994–1004.

Hedrick, P. W., Hedgecock, D., Hamelberg, S. & Croci, S. J. (2000). The impact of supplementation in winter-run Chinook salmon on effective population size. *Journal of Heredity* **91,** 112–116.

Hilborn, R. (1998). The economic performance of marine stock enhancement programs. *Bulletin of Marine Science* **62,** 661–674.

Hilborn, R. & Eggers, D. (2000). A review of the hatchery programs for pink salmon in Prince William Sound and Kodiak Island, Alaska. *Transactions of the American Fisheries Society* **129,** 333–350.

Hildebrand, R. H. (2002). Simulating supplementation strategies for restoring and maintaining stream resident cutthroat trout populations. *North American Journal of Fisheries Management* **22,** 879–887.

Hollowed, A. B., Barange, M., Beamish, R. J., Brander, K., Cochrane, K., Drinkwater, K., Foreman, M. G. G., Hare, J. A., Holt, J., Ito, S.-i., Kim, S., King, J. R., Loeng, H., MacKenzie, B. R., Mueter, F. J., Okey, T. A., Peck, M. A., Radchenko, V. I., Rice, J. C., Schirripa, M. J., Yatsu, A. & Yamanaka, Y. (2013). Projected impacts of climate change on marine fish and fisheries. *ICES Journal of Marine Science* **70,** 1023–1037.

Holmlund, C. M. & Hammer, M. (2004). Effects of fish stocking on ecosystem services: an overview and case study using the Stockholm archipelago. *Environmental Management* **33,** 799–820.

Hunt, L. M., Sutton, S. G. & Arlinghaus, R. (2013). Illustrating the critical role of human dimensions research for understanding and managing recreational fisheries within a social-ecological system framework. *Fisheries Management and Ecology* **20,** 111–124.

Hutchings, J.A. (2014). Unintentional selection, unanticipated insights: introductions, stocking, and the evolutionary ecology of fishes. *Journal of Fish Biology* **85,** 1907–1926.

Hyatt, K. D. & Stockner, J. G. (1985). Responses of sockeye salmon (*Oncorhynchus nerka*) to fertilization of British Columbia coastal lakes. *Canadian Journal of Fisheries and Aquatic Sciences* **42,** 320–331.

Imamura, K. (1999). The organization and development of sea farming in Japan. In *Stock Enhancement and Sea Ranching* (Howell, B. R., Moksness, E. & Svåsand, T., eds), pp. 91–102. Oxford: Fishing News Books.

Johnson, B. M., Arlinghaus, R. & Martinez, P. J. (2009). Are we doing all we can to stem the tide of illegal fish stocking? *Fisheries* **34,** 389–394.

Jonsson, B. & Jonsson, N. (2006). Cultured Atlantic salmon in nature: a review of their ecology and interaction with wild fish. *ICES Journal of Marine Science* **63,** 1162–1181.

Jørgensen, C., Enberg, K., Dunlop, E. S., Arlinghaus, R., Boukal, D. S., Brander, K., Ernande, B., Gårdmark, A., Johnston, F., Matsumura, S., Pardoe, H., Raab, K., Silva, A., Vainikka, A., Dieckmann, U., Heino, M. & Rijnsdorp, A. D. (2007). Managing evolving fish stocks. *Science* **318,** 1247–1248.

Kaplan, S. & Kaplan, R. (2009). Creating a larger role for environmental psychology: the Reasonable Person Model as an integrative framework. *Journal of Environmental Psychology* **29,** 329–339.

Kitada, S. & Kishino, H. (2006). Lessons learned from Japanese marine finfish stock enhancement programmes. *Fisheries Research* **80,** 101–112.

Klinger, D. H., Turnipseed, M., Anderson, J. L., Asche, F., Crowder, L. B., Guttormsen, A. G., Halpern, B. S., O'Connor, M. I., Sagarin, R., Selkoe, K. A., Shester, G. G., Smith, M. D. & Tyedmers, P. (2012). Moving beyond the fished or farmed dichotomy. *Marine Policy* **38,** 369–374.

Knapp, G., Roheim, C. & Anderson, J. (2007). *The Great Salmon Run: Competition Between Wild and Farmed Salmon*. TRAFFIC North America. Washington D.C.: World Wildlife Fund.

Lawler, J. J. & Olden, J. D. (2011). Reframing the debate over assisted colonization. *Frontiers in Ecology and the Environment* **9,** 569–574.

Leber, K. M. (2013). Marine fisheries enhancement: coming of age in the new millennium. In *Sustainable Food Production* (Christou, P., Savin, R., Costa-Pierce, B. A., Misztal, I. & Whitelaw, C. B. A., eds), pp. 1139–1157. New York, NY: Springer Science.

Leber, K. M. & Blankenship, H. L. (2011). How advances in tagging technology improved progress in a new science: marine stock enhancement. *American Fisheries Society Symposium* **76,** 1–12.

Leber, K. M., Arce, S. M., Sterritt, D. A. & Brennan, N. P. (1996). Marine stock-enhancement potential in nursery habitats of striped mullet, *Mugil cephalus*, in Hawaii. *Fishery Bulletin* **94,** 452–471.

Levin, P. S. & Williams, J. G. (2002). Interspecific effects of artifically propagated fish: an additional conservation risk for salmon. *Conservation Biology* **16,** 1581–1587.

Li, J. (1999). An appraisal of factors constraining the success of fish stock enhancement programmes. *Fisheries Management and Ecology* **6,** 161–169.

Lindberg, W. J., Frazer, T. K., Portier, K. M., Vose, F., Loftin, J., Murie, D. J., Mason, D. M., Nagy, B. & Hart, M. K. (2006). Density-dependent habitat selection and performance by a large mobile reef fish. *Ecological Applications* **16,** 731–746.

von Lindern, E. (2010). Changing mental models to promote environmental ecosystem management: recreational fishermen and their fish stocking practices in Swiss running waters. PhD Thesis, University of Zurich, Switzerland.

Lintermans, M. (2013). A review of on-ground recovery actions for threatened freshwater fish in Australia. *Marine and Freshwater Research* **64,** 775–791.

Loomis, J. & Fix, P. (1998). Testing the importance of fish stocking as a determinant of the demand for fishing licenses and fishing effort in Colorado. *Human Dimensions of Wildlife* **3,** 46–61.

Lorenzen, K. (1995). Population dynamics and management of culture-based fisheries. *Fisheries Management and Ecology* **2,** 61–73.

Lorenzen, K. (2000). Allometry of natural mortality as a basis for assessing optimal release size in fish stocking programmes. *Canadian Journal of Fisheries and Aquatic Sciences* **57,** 2374–2381.

Lorenzen, K. (2005). Population dynamics and potential of fisheries stock enhancement: practical theory for assessment and policy analysis. *Philosophical Transactions of the Royal Society B* **360,** 171–189.

Lorenzen, K. (2006). Population management in fisheries enhancement: gaining key information from release experiments through use of a size-dependent mortality model. *Fisheries Research* **80,** 19–27.

Lorenzen, K. (2008a). Understanding and managing enhancement fisheries systems. *Reviews in Fisheries Science* **16,** 10–23.

Lorenzen, K. (2008b). Fish population regulation beyond "stock and recruitment": the role of density-dependent growth in the recruited stock. *Bulletin of Marine Science* **81,** 181–196.

Lorenzen, K., Garaway, C. J., Chamsingh, B. & Warren, T. J. (1998). Effects of access restrictions and stocking on small water body fisheries in Laos. *Journal of Fish Biology* **53**(Suppl. 1), 345–357.

Lorenzen, K., Amarasinghe, U.S., Bartley, D.M., Bell, J.D. Bilio, M., de Silva, S.S., Garaway, C.J., Hartmann, W.D., Kapetsky, J.M., Laleye, P., Moreau, J., Sugunan, V.V. & Swar, D.B. (2001). Strategic review of enhancements and culture-based fisheries. *Aquaculture in the Third Millennium* (Subasinghe, R.P., Bueno, P. Phillips, M.J. Hugh, C. & McGladdery, S.E.), 221–237, Rome: FAO..

Lorenzen, K., Steneck, R. S., Warner, R. R., Parma, A. M., Coleman, F. C. & Leber, K. M. (2010). The spatial dimensions of fisheries: putting it all in place. *Bulletin of Marine Science* **86,** 169–177.

Lorenzen, K., Leber, K. M. & Blankenship, H. L. (2010). Responsible approach to marine stock enhancement: an update. *Reviews in Fisheries Science* **18,** 189–210.

Lorenzen, K., Beveridge, M. C. M. & Mangel, M. (2012). Cultured fish: integrative biology and management of domestication and interactions with wild fish. *Biological Reviews* **87,** 639–660.

Lorenzen, K., Agnalt, A. L., Blankenship, H. L., Hines, A. H., Leber, L. M., Loneragan, N. R. & Taylor, M. D. (2013). Evolving context and maturing science: aquaculture-based enhancement and restoration enter the marine fisheries management toolbox. *Reviews in Fisheries Science* **21,** 213–221.

MacGregor, B. W., Peterman, R. M., Pyper, B. J. & Bradford, M. J. (2002). A decision analysis framework for comparing experimental designs of projects to enhance Pacific salmon. *North American Journal of Fisheries Management* **22,** 509–527.

McClure, M. M., Utter, F. M., Baldwin, C., Carmichael, R. W., Hassemer, P. F., Howell, P. J., Spruell, P., Cooney, T. D., Schaller, H. A. & Petrowski, C. E. (2008). Evolutionary effects of alternative artificial propagation programs: implications for viability of endangered anadromous salmonids. *Evolutionary Applications* **1,** 356–375.

Meffe, G. K. (1992). Technoarrogance and halfway technologies – salmon hatcheries on the Pacific coast of North America. *Conservation Biology* **6,** 350–354.

Mehner, T., Pohlmann, K., Elkin, C., Monaghan, M. T. & Freyhof, J. (2009). Genetic mixing from enhancement stocking in commercially exploited vendace populations. *Journal of Applied Ecology* **46,** 1340–1349.

Merino, G., Barange, M., Blanchard, J., Harle, L. J., Holmes, R., Allen, I., Allison, E. H., Badjeck, M. C., Dulvy, N. K., Holt, J., Jennings, S., Mullon, C. & Rodwell, L. D. (2012). Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate? *Global Environmental Change* **22,** 795–806.

Miao, W. M. (2009). Development of reservoir fisheries in China. In *Status of Reservoir Fisheries in Five Asian Countries* (De Silva, S. S. & Amarasinghe, U. S., eds), pp. 3–15. Bangkok: Network of Aquaculture Centres in Asia Pacific.

Michael, J. H., Appleby, A. & Barr, J. (2009). Use of the AHA model in Pacific salmon recovery, hatchery, and fishery planning. *American Fisheries Society Symposium* **71,** 455–464.

Miller, L. M. & Kapuscinski, A. R. (2003). Genetic guidelines for hatchery supplementation programs. In *Population Genetics: Principles and Applications for Fisheries Scientists* (Hallerman, E. M., ed), pp. 329–355. Bethesda, MD: American Fisheries Society.

Miller, J. M. & Walters, C. J. (2004). Experimental ecological tests with stocked marine fish. In *Stock Enhancement and Sea Ranching: Developments, Pitfalls and Opportunities* (Leber, K. M., Kitada, S., Blankenship, H. L. & Svåsand, T., eds), pp. 142–152. Oxford: Blackwell Publishing.

Miller, T. J., Blair, J. A., Ihde, T. F., Jones, R. M., Secor, D. H. & Wilberg, M. J. (2010). FishSmart: an innovative role for science in stakeholder-centered approaches to fisheries management. *Fisheries* **35,** 424–433.

Mobrand, L. E., Barr, J., Blankenship, L., Campton, D. E., Evelyn, T. T., Flagg, T. A., Mahnken, C. V. W., Seeb, L. W., Seidel, P. R. & Smoker, W. W. (2005). Hatchery reform in Washington State: principles and emerging issues. *Fisheries* **30,** 11–23.

Mobrand, Jones and Stokes Associates (2006). *The All-H Analyser (AHA) User Guide*. Vashon, WA: Mobrand Jones and Stokes Associates.

Naish, K. A., Taylor, J. E., Levin, P. S., Quinn, T. P., Winton, J. R., Huppert, D. & Hilborn, R. (2007). An evaluation of the effects of conservation and fishery enhancement hatcheries on wild populations of salmon. *Advances in Marine Biology* **53,** 61–194.

Nislow, K. H., Einum, S. & Folt, C. L. (2004). Testing predictions of the critical period for survival concept using experiments with stocked Atlantic salmon. *Journal of Fish Biology* **65**(Suppl. A), 188–200.

Oakerson, R. (1992). Analyzing the commons: a framework. In *Making the Commons Work Theory, Practice and Policy* (Bromley, D. W. & Feeny, R., eds), pp. 41–59. San Francisco, CA: Institute of Contemporary Stud..

Olla, B. L., Davis, M. W. & Ryer, C. H. (1998). Understanding how the hatchery environment represses or promotes the development of behavioral survival skills. *Bulletin of Marine Science* **62,** 531–550.

Olsson, P. & Folke, C. (2001). Local ecological knowledge and institutional dynamics for ecosystem management: a study of Lake Racken watershed, Sweden. *Ecosystems* **4,** 85–104.

Paquet, P. J., Flagg, T., Appleby, A., Barr, J., Blankenship, L., Campton, D., Delarm, M., Evelyn, T., Fast, D., Gislason, J., Kline, P., Maynard, D., Mobrand, L., Nandor, G., Seidel, P. & Smith, S. (2011). Hatcheries, conservation, and sustainable fisheries – achieving multiple goals: results of the Hatchery Scientific Review Group's Columbia River basin review. *Fisheries* **36,** 547–561.

Philippart, J. C. (1995). Is captive breeding an effective solution for the preservation of endemic species? *Biological Conservation* **72,** 281–295.

Pido, M. D., Pomeroy, R. S., Garces, L. R. & Carlos, M. B. (1996). *A Handbook for Rapid Appraisal of Fisheries Management Systems*. Manila: ICLARM.

Pikitch, E. K., Santora, C., Babcock, E. A., Bakun, A., Bonfil, R., Conover, D. O., Dayton, P., Doukakis, P., Fluharty, D., Heneman, B., Houde, E. D., Link, J., Livingston, P. A., Mangel, M., McAllister, M. K., Pope, J. & Sainsbury, K. J. (2004). Ecosystem-based fishery management. *Science* **305,** 346–347.

Pinkerton, E. (1994). Economic and management benefits from the coordination of capture and culture fisheries: the case of Prince William Sound pink salmon. *North American Journal of Fisheries Management* **14,** 262–277.

van Poorten, B. T., Arlinghaus, R., Daedlow, K. & Heartel-Borer, S. S. (2011). Social-ecological interactions, management panaceas, and the future of wild fish populations. *Proceedings of the National Academy of Sciences* **108**, 12554–12599.

Post, J. R., Parkinson, E. A. & Johnston, N. T. (1999). Density-dependent processes in structured fish populations: interaction strengths in whole-lake experiments. *Ecological Monographs* **69,** 155–175.

Rahel, F. J., Bierwagen, B. & Taniguchi, Y. (2008). Managing aquatic species of conservation concern in the face of climate change and invasive species. *Conservation Biology* **22,** 551–561.

Reisenbichler, R. R. (1988). Relationship between distance transferred from natal stream and recovery rate for hatchery coho salmon. *North American Journal of Fisheries Management* **8,** 172–174.

Reisenbichler, R. R., Utter, F. M. & Krueger, C. C. (2003). Genetic concepts and uncertainties in restoring fish populations and species. In *Strategies for Restoring River Ecosystems Sources of Variability and Uncertainty in Natural and Managed Systems* (Wissmar, R. C. & Bisson, P. A., eds), pp. 149–183. Bethesda, MD: American Fisheries Society.

Richards, R. A. & Rago, P. J. (1999). A case history of effective fisheries management: Chesapeake Bay striped bass. *North American Journal of Fisheries Management* **19,** 356–375.

Rijnsdorp, A. D., Peck, M. A., Engelhard, G. H., Möllmann, C. & Pinnegar, J. K. (2009). Resolving the effect of climate change on fish populations. *ICES Journal of Marine Science* **66,** 1570–1583.

Ross, M. R. & Loomis, D. K. (1999). State management of freshwater fisheries resources: its organizational structure, funding, and programmatic emphases. *Fisheries* **24,** 8–14.

Sale, P. F., Agardy, T., Ainsworth, C. H., Feist, B. E., Bell, J. D., Christie, P., Hoegh-Guldberg, O., Mumby, P. J., Feary, D. H., Saunders, M. I., Daw, T. M., Foale, S. J., Levin, P. S., Lindeman, K. C., Lorenzen, K., Pomeroy, R. S., Allison, E. H., Bradbury, R. H., Corrin, J., Edwards, A. J., Oburat, D. O., Sadovy de Mitcheson, Y., Samoilys, M. A. & Sheppard, C. R. C. (2014). Transforming management of tropical coastal seas to cope with challenges of the 21st century. *Marine Pollution Bulletin* **85,** 8–23.

Sandström, A. (2010). Institutional and substantial uncertainty – explaining the lack of adaptability in fish stocking policy. *Marine Policy* **34,** 1357–1365.

Sandström, A. (2011). Navigating a complex policy system – explaining local divergences in Swedish fish stocking policy. *Marine Policy* **35,** 419–425.

Sarewitz, D. (2004). How science makes environmental controversies worse. *Environmental Science and Policy* **7,** 385–403.

Sass, G. G. & Allen, M. S. (2014). *Foundations of Fisheries Science*. Bethesda, MD: American Fisheries Society.

Schwach, V. (1998). The impact of artificial hatching of cod on marine research. In *Historisch-Meereskundliches Jahrbuch*, Vol. 5 (Lenz, W. & Streicher, S., eds), pp. 27–47. Stralsund: Deutsches Meeresmuseum.

Secor, D. H. (2002). Historical roots of the migration triangle. *ICES Marine Science Symposia* **215,** 229–335.

Sevä, M. (2013). A comparative case study of fish stocking between Sweden and Finland: explaining differences in decision making at the street level. *Marine Policy* **38,** 287–292.

Svåsand, T., Kristiansen, T. S., Pedersen, T., Salvanes, A. G. V., Engelsen, R., Nævdal, G. & Nødtvedt, M. (2000). The enhancement of cod stocks. *Fish and Fisheries* **1,** 173–205.

Tammi, J., Appelberg, M., Beier, U., Hesthagen, T., Lappalainen, A. & Rask, M. (2003). Fish status survey of Nordic lakes: effects of acidification, eutrophication and stocking activity on present fish species. *Ambio* **32,** 98–105.

Taylor, J. E. (1999). *Making Salmon: An Environmental History of the Northwest Fisheries Crisis*. Seattle, WA: University of Washington Press.

Taylor, M. D., Fairfax, A. V. & Suthers, I. M. (2013). The race for space: using acoustic telemetry to understand emigration and ideal free distribution in a released predatory fish. *Reviews in Fisheries Science* **21,** 276–285.

Thorpe, J. E. (2004). Life history responses of fishes to culture. *Journal of Fish Biology* **65**(Suppl. 1), 263–285.

Tringali, M. D., Bert, T. M., Cross, F., Dodrill, J. W., Gregg, L. M., Halstead, W. G., Krause, R. A., Leber, K. M., Mesner, K., Porak, W., Roberts, D., Stout, R. & Yeager, D. (2007). *Genetic Policy for the Release of Finfishes in Florida*. Tallahassee, FL: Florida Fish and Wildlife Conservation Commission.

Tugend, K. I., Allen, M. S. & Webb, M. (2002). Use of artificial habitat structures in US lakes and reservoirs: a survey from the Southern Division AFS Reservoir Committee. *Fisheries* **27,** 22–27.

Utter, F. (2004). Population genetics, conservation and evolution in salmonids and other widely cultured fishes: some perspectives over six decades. *Reviews in Fish Biology and Fisheries* **14,** 125–144.

Utter, F. & Epifanio, J. (2002). Marine aquaculture: genetic potentials and pitfalls. *Reviews in Fish Biology and Fisheries* **12,** 59–77.

Vorosmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. & Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature* **476,** 555–561.

Walters, C. J. & Martell, S. J. D. (2004). *Fisheries Ecology and Management*. Princeton, NJ: Princeton University Press.

Welcomme, R. L. (2002). An evaluation of tropical brush and vegetation park fisheries. *Fisheries Management and Ecology* **9,** 175–188.

Wilson, S. K., Graham, N. A. J., Pratchett, M. S., Jones, G. P. & Polunin, N. V. C. (2006). Multiple disturbances and the global degradation of coral reefs: are reef fishes at risk or resilient? *Global Change Biology* **12,** 2220–2234.

Zimmerman, M. P. & Ward, D. L. (1999). Index of predation on juvenile salmonids by northern pikeminnow in the lower Columbia River basin, 1994–1996. *Transactions of the American Fisheries Society* **128,** 995–1007.

Zhou, S., Smith, A. D. M., Punt, A. E., Richardson, A. J., Gibbs, M., Fulton, E. A., Pascoe, S., Bulman, C., Bayliss, P. & Sainsbury, K. (2010). Ecosystem-based fisheries management requires a change to the selective fishing philosophy. *Proceedings of the National Academy of Sciences of the United States of America* **107,** 9485–9489.

Electronic References

Cowx I. G., Nunn A. D., Harvey J. P. & Noble R. A. A. (2012). Guidelines for stocking of fish within designated natural heritage sites. *Scottish Natural Heritage Commissioned Report* **513.** Available at http://www.snh.org.uk/pdfs/publications/commissioned_reports/513.pdf

FAO (1999). Global characterisation of inland fisheries enhancements and associated environmental impacts. *FAO Fisheries Circular* **945.** Available at ftp://ftp.fao.org/docrep/fao/005/x4186e/X4186E00.pdf

Welcomme, R. L. (1985). River Fisheries. *FAO Fisheries Technical Paper* **262**. Available at http://www.fao.org/docrep/003/T0537E/T0537E00.htm