CHAPTER 6.3

Management of freshwater fisheries: addressing habitat, people and fishes

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Abstract: This chapter describes approaches to the management of habitat, people and fish stocks that make up freshwater fisheries. Habitat management is advisable whenever habitat bottlenecks limit the productivity of a fishery. Harvest regulations are a useful conservation strategy when fishing mortality is high or specific sizes of fish are to be protected. Finally, stocking may be useful in situations where natural recruitment is lacking or extirpated species are to be restored. Planning of interventions necessitates a rigorous approach based on principles of adaptive management and structured decision-making. Given the many stakeholders affected by fisheries management measures in fresh water, an integrative, stakeholder-inclusive approach is recommended.

Keywords: angler, habitat management, harvest regulation, inland fisheries, stocking, minimum-size limit

Introduction

Similar to commercial marine fisheries, exploitation of freshwater fish stocks can lead to population declines and alter structural and functional properties and the ecosystem services generated by fishes (Holmlund & Hammer, 1999; Allan *et al.*, 2005; Lewin *et al.*, 2006). Freshwater ecosystems have also been strongly affected by anthropogenic change stemming from damming, habitat simplification for navigation, agriculture, hydropower, water extraction, acidification, eutrophication, pollution and release of non-native organisms (Richter *et al.*, 1997*a*; Dudgeon *et al.*, 2006). As a result, freshwater fishes are among the most threatened vertebrates worldwide (Freyhof & Brooks, 2011), which justifies dedicated management interventions and restoration activities to halt the alarming decline. The literature on mitigation, rehabilitation and restoration of inland waterbodies is rich and diverse (Cowx & Welcomme, 1998; Welcomme, 2001; Cooke *et al.*, 2005). Although most actions of aquatic ecosystem management will also affect fish populations, they are usually motivated by a broader environmental framework, also in legal terms (*e.g.* European Water Framework Directive). Reviewing this massive literature is beyond the scope of this chapter. Instead, we focus on the core inland fisheries management tools and approaches that are chosen to manage, directly or indirectly, inland fish stocks for fisheries purposes. We do so by acknowledging that in many situations, the main impacts on freshwater fish stocks lie outside the control of the fishery manager (Arlinghaus *et al.*, 2002) and may demand entirely different and more encompassing actions than those reported here.

Identifying a general fisheries management strategy

Fisheries management is the process by which reliable information is used to achieve management goals and operational objectives defined for fisheries resources. Overarching management goals for inland fisheries include (1) biologically sustainable use of freshwater fish stocks, (2) conservation of aquatic biodiversity and (3) equitable sharing of benefits among stakeholders (Welcomme, 2001). Within these well-accepted

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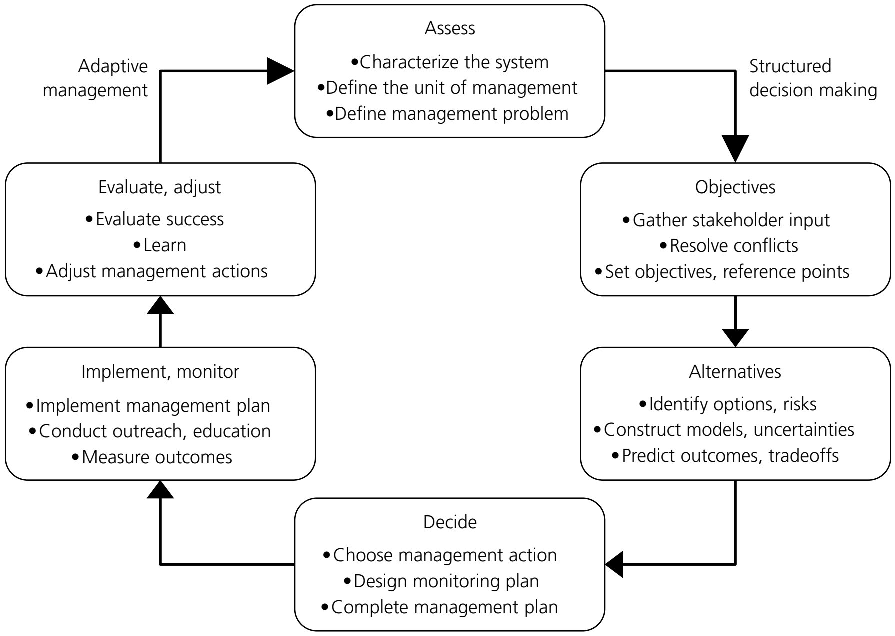

Figure 6.3.1 The inland fisheries management process formulated for structured decision-making and adaptive management. Note that the appropriate mix of management actions is decided in the 'decision box', which are then implemented and monitored for outcomes (Source: FAO (2012). Reproduced with permission of FAO).

goals, a considerable challenge revolves around the need to trade off diverse stakeholder values and to translate these into operational management objectives (Fenichel *et al*., 2013). Unfortunately, many usually smaller inland fisheries are not economically important enough to justify costly monitoring and management systems (Post *et al*., 2002). Hence, even if operational objectives are found, many inland fisheries require data-poor or even data-less management systems (Arlinghaus & Krause, 2013).

Notwithstanding availability of timely and accurate data, the process of inland fisheries management should employ a transparent and inclusive approach to achieving management goals and objectives. Because of the complexity of most inland fisheries and the uncertainty as to how particular policies function, it is advisable to follow an adaptive management approach that is designed to learn from past experiences (Fig. 6.3.1). This requires a cyclic process to help sort among competing management actions and find those that best suit the particular objectives and social–ecological conditions of the fishery. An adaptive management approach can either be passive or deliberately active (Walters, 1986) but has to involve stakeholders proactively and follow a structured decision-making process (Irwin *et al*., 2011). This chapter will focus on the various management tools that may be chosen as experimental interventions to explore within an adaptive management process.

Inland fishers commonly desire improvements in the catch rate, size of catch or opportunity for harvest. The manager must then confirm or diagnose causes behind reported inadequacies in the fishery and choose an appropriate course of action to achieve objectives. A simple decision tree to identify which general management strategy may prove useful given the biological properties of the target fish population (FAO, 2012) is given in Fig. 6.3.2. These strategies are directed at three key dimensions of inland fisheries: (1) the habitat, which usually transcends the aquatic–terrestrial interface; (2) the biota, including but not limited to the target fish population; (3) the humans involved in the fishery (Welcomme, 2001). Deciding on an appropriate strategy depends on objectives, the conditions of the ecosystem, non-fishing impacts and the current fishing mortality, natural mortality, growth and recruitment rate of the exploited fish population (Fig. 6.3.2). For example, when the objective is to increase catch rates from an overfished situation, harvest regulations may be advisable (Fig. 6.3.2). By contrast, low recruitment of a target species at low fishing mortality may call upon habitat enhancement or stocking as appropriate tools to contemplate (Fig. 6.3.2).

Managing habitat

Purpose of habitat management

Alteration and loss of habitat as a result of non-fishing-related anthropogenic activities are major threats to freshwater fisheries (Richter *et al*., 1997*a*) and on global scale have had greater impact on fish communities than inland fishing (Arlinghaus *et al*., 2002). It is thus not surprising that habitat management is the focus of many management initiatives ranging from policies that protect habitat to various enhancement and restoration techniques. Fisheries managers turn to habitat management where there is a bottleneck that limits a critical life stage and the productivity of

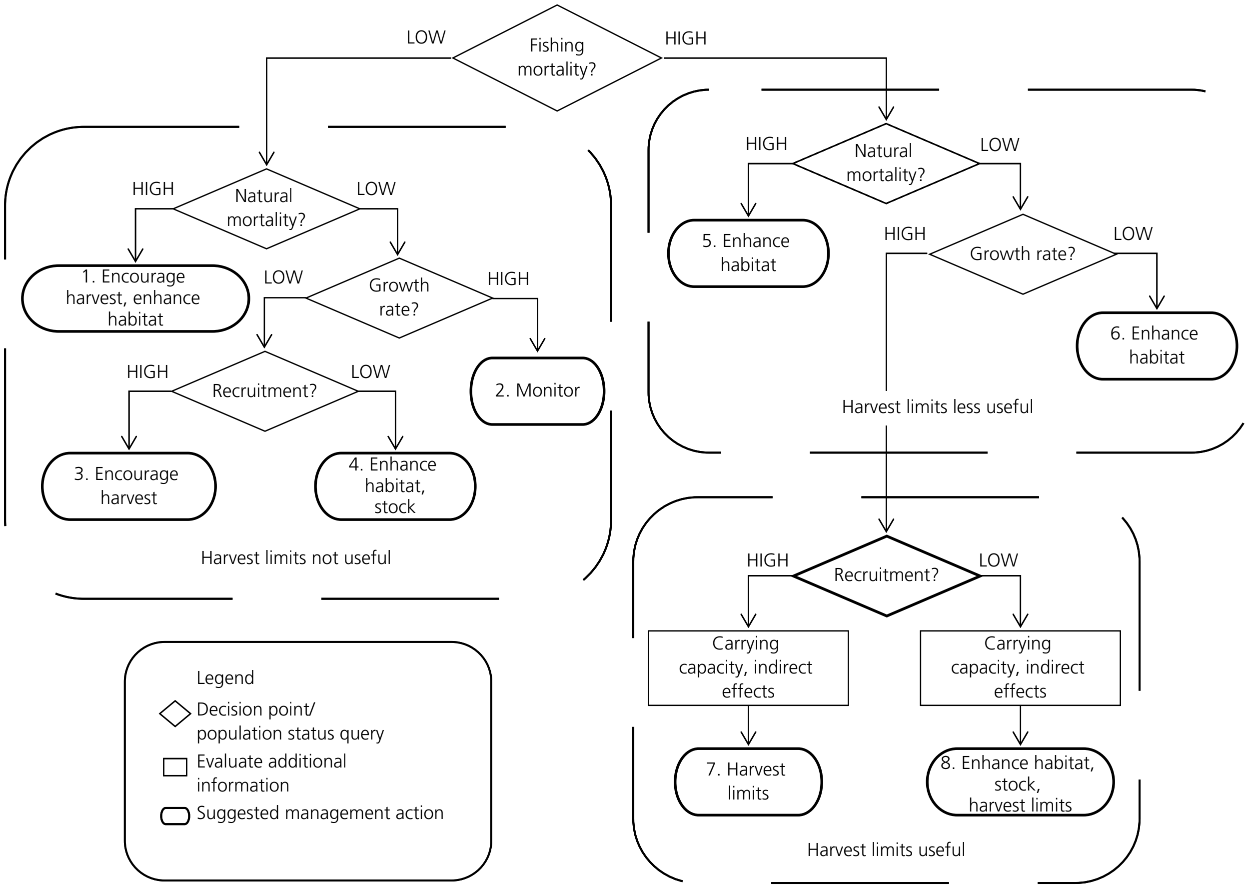

Figure 6.3.2 Generalized decision tree for inland fisheries management. An implicit assumption is that the management objective is to increase size and abundance of the target species within ecological limits of the system. A key decision node among general management strategies is the knowledge of the current levels of fishing mortality and whether fishing is considered excessive. When fishing mortality is low (1–4), harvest regulations would not be useful; rather, it may be advantageous to encourage harvest to alleviate potential issues with density-dependent growth or natural mortality (1 and 3). If fishing mortality is low but availability of fishes not considered high enough for the potential of the waterbody, habitat enhancement might prove very useful (4). This strategy might be complemented by conservation-oriented stocking to boost recruitment (4). When fishing mortality is high but natural mortality is also high (5) or growth of fishes is low (6), habitat improvements rather than harvest restrictions would similarly be indicated. The manager stands to make the greatest improvements to the fishery with harvest regulations when fishing mortality is high, natural mortality is low, and growth is high (7 and 8). It is only then that harvest limits can increase biomass and size structure of the target population. When natural recruitment is low, harvest regulations might be supplemented by habitat enhancement and stocking (4, 8) (Source: Adapted from FAO (2012). Reproduced with permission of FAO.

target species (Fig. 6.3.3) (Cowx & Welcomme, 1998; Bain & Stevenson, 1999). The bottleneck can arise from many sources, from insufficient spawning habitat through disruption to lateral and longitudinal connectivity to bottlenecks in the juvenile rearing stage and loss of habitat diversity (Fig. 6.3.3). Conceptually, the structure and function of habitat provide an upper bound on the stock–recruitment curve and also affect the slope of this curve (Hayes *et al*., 1996). By modifying habitat, fisheries managers can attempt to increase the slope and hence the productivity of exploited stocks (Walters & Martell, 2004). Also, managers may attempt to alter the asymptote (*i.e.* the carrying capacity) of a stock–recruitment curve. Habitat management may also be used to conserve threatened species.

Given the fundamental role of habitat in supporting freshwater fish populations and fisheries, protection of habitat from ongoing anthropogenic change is of primary concern. Obviously, not all freshwater habitats can be protected from alteration in light of societal trade-offs and priorities (*e.g.* for flood control or hydropower), so alternative approaches are often explored. Most contemporary efforts of habitat management focus less on restoration (*i.e.* attempting to reach a historical state) per se in favour of rehabilitation (*i.e.* attempting to achieve some elements of a past state) or enhancement (*i.e.* improvements over existing conditions). Mitigation is focused on refining development plans for fresh waters such that their impact on fish habitat is minimized (Cowx & Welcomme, 1998). An example includes installation of fish passage devices at newly constructed barriers in river ecosystems. Compensation is different in that it recognizes that habitat alterations are inevitable and requires that the user of ecosystems compensates for the loss in habitat. Examples include installation of artificial reefs, constructed wetlands or other fish habitat structures (Rubec & Hanson, 2009) or the

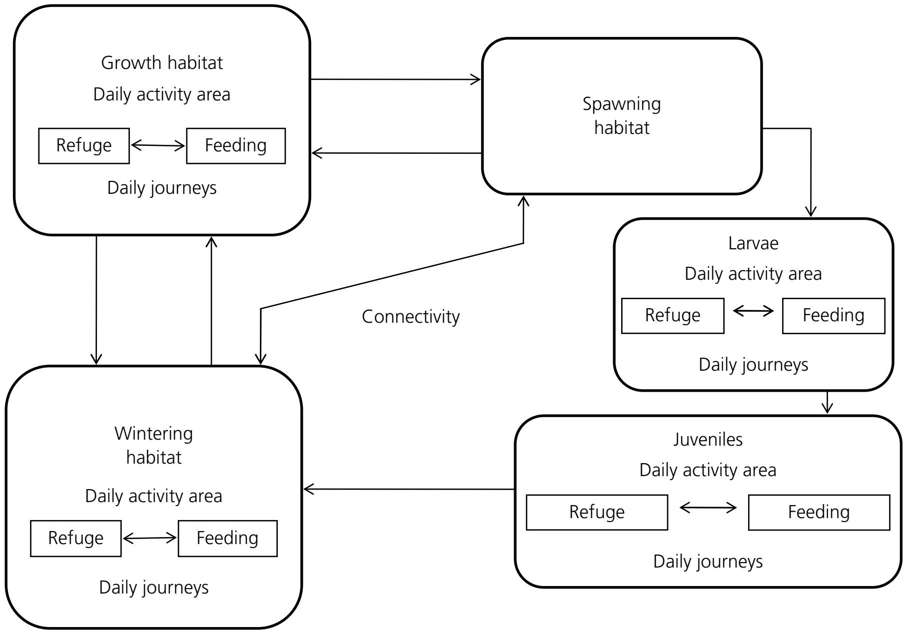

Figure 6.3.3 Functional habitat units for fishes (Source: Adapted from Cowx & Welcomme, 1998).

building of hatcheries for stocking. Having strong habitat protection policy is obviously a prerequisite for applying the concepts of mitigation and compensation in a regulatory framework. Even when such regulations exist, there is evidence that mitigation and compensation activities are not always effective. An audit of fish habitat compensation projects in Canadian freshwater systems, for example, revealed that although there were reasonable attempts to replicate structural elements of fish habitat, function (as measured by a reduction in productive capacity of fish habitat) was reduced in 63% of the compensated sites relative to the altered habitat prior to its alteration (Quigley & Harper, 2006). Also, there is ample evidence that stocking can rarely compensate for severe habitat loss (Walters & Martell, 2004) and hence must always be seen as a measure of last resort. Such examples emphasize that habitat protection for productive fisheries is more desirable than mitigation or compensation whenever socio-economically feasible.

For habitat management to be effective, one must consider both structure and function (Hobbs & Harris, 2001). Habitat management, however, often fails to address the functional outcomes and instead focuses on enhancing structure (Quigley & Harper, 2006). Managing for structure is certainly easier, and metrics of success are often straightforward (*e.g.* area of habitat restored, number of rocks added to river and number of trees planted in riparian zones). By contrast, the function of habitat (*e.g.* nutrient cycling and recruitment) is more difficult to monitor but is the critical factor for ensuring success of habitat management actions.

Habitat management is often popular among fishers because it is an obvious way of improving a fishery (Arlinghaus & Mehner, 2003; Hickley *et al.*, 2004), but due to non-linear and cross-scale effects, managing habitat is often as much art as science (Van Diggelen *et al.*, 2001). Every year, millions are spent on habitat restoration activities that fail to address the underlying problem that is limiting productivity (Miller & Hobbs, 2007). In some cases, habitat management may not be the best tool for the job (Fig. 6.3.2). Often, there are also severe budgetary and institutional constraints that prohibit engaging in large-scale habitat restoration activities (Cowx & Welcomme, 1998). The Society for Ecological Restoration developed a series of guidelines intended to assist practitioners in establishing the processes needed to engage in effective habitat management, which serves as a suitable starting point for anyone considering a habitat management project (Clewell *et al.*, 2000). Further planning guidelines, particularly for river restoration and rehabilitation, can be found in Cowx and Welcomme (1998), Welcomme (2001) and Roni *et al.* (2002).

Common habitat management techniques

There is a wide range of habitat management approaches available for lotic and lentic fresh waters. Some focus more on addressing fisheries-related issues, while others are focused more on biodiversity, ecosystem health and environmental quality. We primarily describe habitat management techniques that have the potential to address a limitation or constraint on fisheries productivity (Table 6.3.1). We direct readers to a rich literature on habitat management and ecological restoration in general (Hobbs & Norton, 1996; Falk *et al.*, 2006) and more specifically for wetlands (Zedler, 2000), lakes and reservoirs (Olem & Flock, 1990; Cooke *et al.*, 2005), large rivers (Cowx & Welcomme, 1998), small streams (Hunter, 1991; Roni & Beechie, 2012) and catchments (Frissell & Ralph, 1998; Roni & Beechie, 2012).

Table 6.3.1 Examples of management actions targeting habitat that may benefit fish populations and their ecosystems

Strategy/goal	Explanation and examples
Restore connectivity	Install fish passage structures or remove dams to alleviate barriers to fish movement and restore metapopulation dynamics
Nutrient abatement	Contain point and non-point sources of excess nutrients in the watershed (often phosphorus and nitrogen)
Nutrient supplementation	Phosphorus and nitrogen additions to enhance fish production or to compensate for cultural oligotrophication; in some regions, carcasses (*e.g.* Pacific salmon *Oncorhynchus* spp.) are added to streams
Reduce contaminants	Contain point and non-point sources of contaminants in the watershed (*e.g.* nitrates, metals and pesticides)
Liming	Addition of calcium carbonate (limestone or calcite) to neutralize acidified waters
Aeration	Increase dissolved oxygen concentration through physical means to prevent die-offs and undesirable chemical dynamics in hypoxic waters (*e.g.* dissolution of phosphorus and manganese and mercury methylation)
Manage turbidity	Soil run-off from the catchment, mixing by boats and bioturbation by fishes can all increase turbidity, limiting photosynthesis and increasing surface temperature; silt control devices or use of buffer zones can reduce turbidity
Manipulate flow and water level	Mimic natural water level and flow fluctuations in regulated waters; reservoir drawdowns can reduce reproduction of undesirable species; seasonal pulses can be used to stimulate upstream migration of fishes
Restore wetlands and estuaries	Wetlands provide many ecosystem services including water purification and fish production; constructed wetlands provide opportunities for habitat creation and compensation
Erosion control	Use of various erosion control structures (*e.g.* riprap and deflectors) in lentic and lotic systems to stabilize banks and reduce turbidity
Restore shoreline and riparian zones	Fishes benefit from large woody debris in littoral zones of lentic and lotic systems; excluding livestock protects riparian areas and reduces bank erosion of lotic systems; planting of vegetation
Improve spawning habitat	Addition of spawning substratum, construction of spawning channels
Supplement structure	Addition of structural elements that tend to congregate fishes but may not improve ecosystem productivity (*e.g.* fish aggregating devices and artificial reefs)

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Managing habitat in rivers

Rivers are subjected to many pressures, which are driven by societal requirements for land development, flood protection, water supply, hydropower generation, waste disposal, recreational amenities and navigation. These pressures alter transport of water and sediment, morphology and physical characteristics of the river, and trophic subsidies and interfere with migratory pathways (Poff *et al*., 1997), all of which can disrupt ecosystem function and affect fisheries yield (Postel *et al*., 1997). The expanding field of ecological river rehabilitation endeavours to rehabilitate rivers that have suffered anthropogenic disturbances by reintroducing habitat diversity while considering the broader landscape, riparian zones, upstream areas and fluvial geomorphology (Hobbs *et al*., 2011).

Management of physical habitat modifications in lotic systems

The scale of physical habitat management needed to achieve positive outcomes depends on the size of the system and the factors limiting productivity or otherwise contributing to degraded conditions. In large rivers, creating physical structure is a technological challenge. Channel structure can be modified to improve meander patterns through extensive placement of boulders and channel profiling (Nagayama *et al*., 2008). Materials such as large woody debris can also be added to increase complexity and provide cover for fishes (Fig. 6.3.4). Some researchers have questioned whether river restoration can succeed given the scale at which systems need to be modified (*e.g.* meanders and connecting backwater areas; Gore & Shields, 1995). Monitoring of such activities has been infrequent, precluding an assessment of success probabilities in large rivers (Roni, 2005). There are, however, some examples of where physical structure placement or other large-scale habitat modifications in large rivers have resulted in improvements in fish productivity (Cowx & Welcomme, 1998; see Fig. 6.3.4 for popular actions). As large rivers are always downstream of many smaller rivers and they have large catchment areas, a watershed approach to restoration of large lotic systems is usually preferred (Cowx & Welcomme, 1998; Roni & Beechie, 2012).

Given the smaller scale of streams and their catchments, physical habitat management activities often result in more immediate results than in larger rivers (Roni *et al*., 2002). Restoration of streams must include riparian habitats given the importance of shade, woody debris and plants to most stream ecosystems (Naiman *et al*., 2005). Maintenance of buffer strips (Osborne & Kovacic, 1993) and fencing of livestock to exclude them from streams (Platts & Wagstaff, 1984) represent important riparian-focused management activities. Placement of instream structure is common in small streams and is often done by volunteers or angling clubs (Middleton, 2001). Some structures are intended to deflect water to reduce erosion and create riffle–run–pool sequences, while others provide overhead cover or spawning habitat (Welcomme, 2001). Although stream restoration occurs on a diversity of systems, certainly the most effort has been directed towards salmonids (Hunter, 1991). Instream habitat enhancement appears most effective when employed after restoring natural processes (*e.g.* provision of connectivity and functional riparian system; Roni *et al*., 2002).

Figure 6.3.4 Various restoration strategies including (a) before and (b) after debris removal and structure placement in a stream, (c) before and (d) after dam removal on a stream and (e) construction of habitat structures in a dewatered embayment of a lake and (f) the subsequent planting of endemic vegetation in littoral habitats of a newly created embayment.

Despite the valiant effort of volunteers and practitioners and millions of pounds of investment on an annual basis, a systematic review on the effectiveness of instream structures as a management tool to increase salmonid abundance suggested that they provide no consistent benefit (Stewart *et al*., 2009). One of the reasons underlying the apparent failure of structure placement in increasing salmonid abundance may reflect the lack of broader programmes addressing the full suite of factors that constrain productivity (Roni *et al*., 2002).

Restoring connectivity in lotic systems

Habitat connectivity in lotic systems is critical for enabling fishes to move among habitats needed by various life stages. Associated with human activities including irrigation, hydropower and recreation, water control structures such as dams and weirs have been installed around the globe. For context, current estimates suggest that there are in excess of 45×10^3 large dams (primarily for hydropower and flood control) and 800×10^3 small dams (Dynesius & Nilsson, 1994; Rosenberg *et al*., 2000; Nilsson *et al*., 2005). Existing barriers that provide little societal benefit can be removed, but doing so can result in a variety of short-term negative consequences including silt mobilization (Bednarek, 2001). Dam removal is often contentious (Lejon *et al*., 2009), but there are an increasing number of success stories from small streams to large rivers. For example, Burroughs *et al*. (2010) reported that the removal of the Stronach Dam on the Pine River in Michigan resulted in an upstream range expansion for eight species formerly found only below the dam. In addition, most fish species studied showed an increase in abundance following dam removal.

Although dam removal or simply not constructing new dams may be of great benefit to riverine ecosystems, the reality is that barriers are important components of modern society. As such, provision of fish passage devices to enable fishes to move upstream and downstream of barriers is a very common mitigation measure and should be a regulatory requirement for new dams and for relicensing of existing ones. There are many types of fish passage devices to facilitate upstream passage. For example, locks and elevators can be used to lift fish over an obstruction. Fishways are designed to dissipate the energy in the water to enable fishes to ascend without undue stress (Clay, 1995). The common types of fishways include Denil, vertical slot, pool and weir and nature-like designs (Fig. 6.3.5). Successful implementation of fishways requires a thorough knowledge of the life history, behaviour and swimming ability of a species (Cooke & Hinch, 2013). Successful fish passage also requires that fishes both locate the entrance to a fishway and then are able to successfully ascend the device (Bunt *et al*., 2012). In a recent meta-analysis, Bunt *et al*. (2012) revealed that nature-like fishways (*e.g.* bypass channels with natural sediments; Fig. 6.3.5) had the highest levels of passage success but generally had poor attraction efficiency. Conversely, conventional constructed fishways (*e.g.* Denil, vertical slot, pool and weir) had comparatively low passage efficiency but high attraction efficiency. The development of general rules for fish passage is challenging, and there are many examples of failed fishway projects. Like other habitat management activities, however, proper monitoring and assessment is rarely conducted, making generalizations difficult (Roscoe & Hinch, 2010).

(a) (b)

Figure 6.3.5 (a) Small nature-like fishway to facilitate passage at a low-head dam and (b) a constructed vertical slot fishway at a barrier on a large river.

The science of fishways is continually improving, and what was once a science based on salmonids now has rich examples from many species and regions (Pavlov, 1989). There is also a movement to question the need for passage as barriers serve as means of restricting invasive species and passage of fishes from riverine environments into an upstream lentic reservoir may cause an ecological trap (McLaughlin *et al*., 2013). Downstream passage requires that fishes are provided a safe path avoiding turbines or other physical damages. As such, various guidance strategies including lights, bubble curtains and louvres are used to direct fish towards bypass channels or other fish collection devices (Coutant & Whitney, 2000). Diadromous species including the juvenile life stage of Pacific salmonids *Oncorhynchus* spp. and the adult phase of European eel *Anguilla anguilla* represent examples for which there is much desire to develop effective downstream passage.

Flow management in rivers

Virtually all lentic ecosystems are controlled by the hydrological regime (Junk *et al*., 1989). The changing quantity of water flowing in a river provides habitat and influences water quality, temperature, nutrient cycling, oxygen availability and the geomorphic processes that shape river channels and floodplains (Poff *et al*., 1997; Richter *et al*., 1997*b*). Natural riverine landscapes (riverscapes) are characterized by floodplain, natural flow regime, high hydraulic connectivity, a successional landscape mosaic with high habitat heterogeneity and complex land–water coupling and exchange (Fausch *et al*., 2002). The shape and size of river channels, the distribution of pool–riffle habitats and the stability of the substratum are all largely determined by the interaction between the flow regime and local geology and landform (Bunn & Arthington, 2002). Flow regime is thus a critical factor in determining both physical habitat structure and diversity in rivers and needs to be properly managed.

Existing methods for the estimation of environmental flows differ in input information requirements, types of ecosystems they are designed for, time which is needed for their application and the level of confidence in the final estimates (Hucksdorf *et al*., 2008). The methods range from purely hydrological methods, which derive environmentally acceptable flows from flow data and use limited ecological information or eco-hydrological hypotheses, to multidisciplinary, comprehensive methods, which involve expert panel discussions and collection of significant amounts of geomorphological and ecological data (Hucksdorf *et al*., 2008). Dammed rivers often have highly regulated flow regimes, and rehabilitation requires changes to dam operations to provide more natural environmental flows (Welcomme, 2001). In peaking systems with flows that vary on a diel basis relative to hydropower demand, regulators often prescribe the range of acceptable flows as well as the rate at which flows can be changed (*i.e.* ramping rates; Smokorowski *et al*., 2011) in an attempt to minimize stranding (Nagrodski *et al*., 2012). In some instances where flows have been modified to yield low and stable flows, the use of strategically timed pulse flows can be used to stimulate upstream movement of migratory fishes (Hasler *et al*., 2012) or to motivate spawning (Welcomme, 2001). In situations where flow rate is too fast (usually due to channelization) and young fishes are drifted away, decreased releases of flow from upstream control structures may be advisable (Welcomme, 2001).

Managing habitat in lakes and reservoirs

Possibly, the most important pressures acting of lake and reservoir fisheries are linked to water quality and water level perturbations (Moss, 2009) and less to physical habitat modification as in rivers. The quality of water is influenced by pollutants including organic wastes, nutrients, metals, poisons, suspended solids and cooling water from urban, industrial and agricultural sources. These drivers can act directly on the fishes, for example, toxicity of chemicals, or indirectly by changing environmental conditions and consequently the suitability of the habitat for fishes, mainly through eutrophication. Slight eutrophication arising from organic effluent discharges and run-off of nutrients can benefit fisheries through increased production (Hanson & Leggett, 1982; Stockner *et al*., 2000). When the nutrient load is too high and a hypertrophic ecosystem state is reached, however, excessive algal and plant growth may lead to reduced fish production and loss of fish diversity throughout periods of lethally low dissolved oxygen concentrations, especially in the hypolimnion (Schindler, 2006). Acidification of lakes due to acid discharge has the opposite effect because its final stage is an almost dead lake with no decomposition taking place. This type of pollution is most notable in North Europe and Canada where large numbers of lakes have been affected (Stoddard *et al*., 1999). Finally, natural fluctuations in water level are a common feature of most lakes and reservoirs as a result of seasonal and climatic variation in rainfall (Ploskey, 1986). The problem is, however, exacerbated in lakes and reservoirs used for water supply and hydroelectric power generation, which control the water level in response to supply demand and power generation requirements. This drawdown, and the way in which it is achieved, may be disadvantageous to the development of fisheries in reservoirs (Beam, 1983; Ploskey, 1986). The littoral zone can become barren, with exposed rock, gravels and sands, reducing the potential spawning and nursery areas for many fish species. In particular, the rapid drawdown associated with hydropower generation has an adverse effect on fishes that spawn in the littoral zone, killing eggs and larvae and thus reducing future recruitment to the fishable stocks of these species (Nagrodski *et al*., 2012). If this is the case, dedicated management interventions to combat pollution and flow are needed. These actions may be complemented with management of structure and refuges in the productive littoral zones of lakes (Winfield, 2004).

Managing physical habitat in lentic systems

Physical habitat modification in lentic systems is not nearly as well developed as a science as for lotic systems. Possible techniques include water level management; shoreline development, for example, reinstatement of riparian vegetation and ecotones; and creation of artificial or quasi-natural spawning grounds. Water level management essentially controls rapid (diel) water level fluctuations to protect breeding habitat for littoral spawning species. Artificial reefs made up of, for example, old tyres or woody debris, and replanting of submerged and emergent vegetation may be appropriate under certain conditions, such as in small stillwater fisheries (Hickley *et al.*, 2004). Research in Wisconsin (United States) has revealed that littoral structural complexity, especially in the form of woody debris, is important for fish communities in lakes and, when removed, it can have significant detriment to fish populations (Sass *et al.*, 2006). In reservoirs that are often void of littoral habitat, placement of old evergreen fir trees or other woody debris (including placement of half-log structures) can similarly provide shelter to early life stages of fishes and also improve reproductive success (Hunt & Annett, 2002; Wills *et al.*, 2004). Unfortunately, in many smaller systems, woody debris is removed by anglers in an effort to 'clean' shorelines or built angling sites, which may be counterproductive and should be avoided. Placement of offshore structures such as artificial reefs also occurs in fresh water (Bolding *et al.*, 2004), but not nearly as commonly as in marine systems. In general, use of natural materials (rocks and wood) in freshwater systems is preferable to boats, tyres or other materials that are often used in marine systems (Seaman & Sprague, 1991). Sometimes, structures are placed in systems to aggregate fishes rather than to address a bottleneck, which serves little to increase productivity but may still be a relevant management technique if it enables better access to fishes. Smokorowski and Pratt (2007) conducted a meta-analysis and emphasized that habitat enhancement activities in lakes have inconsistent outcomes. In general, the scope for physical modification is limited in lakes and reservoirs because nutrient level, temperature and general basis morphology seem to structure lentic fish stocks to a greater extent than the physical structure of the littoral (Mehner *et al.*, 2005; Brucet *et al.*, 2013). Hence, adding nutrients to smaller waterbodies is a viable enhancement technique in some regions of the world (Welcomme, 2001).

Managing pollution control, treatment and prevention in lakes and reservoirs

There are many and varied pollution control and prevention methods to reduce the impact and discharge of potentially polluting effluents to improve water quality and fisheries in lakes and reservoirs including removal of phosphate from detergents, which is increasingly being adopted in Europe and America to reduce eutrophication (Hammond, 1971); phasing out the use of persistent pesticides (Sun *et al.*, 2006); control of acidic emissions (Schindler, 1988); and diversion of effluents (Beklioglu *et al.*, 1999). Diversion of effluents may be desirable to allow one waterbody to be sacrificed for the sake of another; diversion may not merely transfer the problem elsewhere if the recipient system affords greater dilution or is more resilient in other ways. This technique, however, needs careful prior assessment to avoid unseen pitfalls. The persistence of pollutants and their transport and cycling mechanisms in the environment are major factors affecting the probable success of such measures once pollution has occurred (Connell, 1988).

Even though pollution may not be removed, its adverse effects on organisms may be ameliorated by adjusting water quality. Direct intervention can result in dramatic improvements, such as the aeration and destratification (Ashley, 1985) and liming (Clair & Hindar, 2005). These must, however, be considered short-term measures while more permanent pollution control measures are implemented. Natural purification processes can often provide longer-term solutions that form part of the pollution control strategy, such as the provision of riparian buffer zones (Osborne & Kovacic, 1993), which help to filter the effects of pollutants entering lakes, especially as a result of land use practices. Some pollutants can be removed by harvesting plants and animals, which have absorbed or incorporated them into their tissues (Susarla *et al.*, 2002). This offers the possibility of using organisms to bioconcentrate pollutants to clean up environments through selective harvesting.

Flow management and silt deposition in reservoirs

In particular, reservoirs suffer from flow-related habitat disturbances and sediment erosion, transfer and deposition resulting from inflow and pulsed flow. Too rapid withdrawal of water can cause stranding of fishes and loss of breeding sites and eggs attached to marginal bottom substrata, reducing survival and reproduction (Welcomme, 2001). Accelerated flooding will also destroy rooted vegetation and release sediments. Increased rate of silt deposition in reservoirs can only be managed through changing land use and control of upstream operations to avoid downstream release of sediments. Drawdown or overly rapid filling in reservoirs necessitates the active management of discharge patterns during reservoir operations. In some cases, drawdown can even have positive effect on some trophic layers by exposing prey fishes to predators as the refuges in the littoral zone are lost. Dewatering during spawning time might also be strategically used to control unwanted species that spawn in littoral zones.

Biomanipulation in lentic systems

In some circumstances, reducing nutrient input into the aquatic environment has little effect on water quality. Phosphorus and nitrogen locked in the sediments continue to be released over many years, despite reduced external loading. An alternative approach, which has received much attention in the 1980s through to the 1990s, is that of biomanipulation (Shapiro *et al.*, 1975). This approach, instead of concentrating solely on the nutrient source, targets the ecological trophic dynamics as influenced by fishes (Mehner *et al.*, 2004). Several studies have shown that removal of planktivorous fishes can lead to clear water, as a result of reduction on predation pressure on the large-bodied zooplankton that graze on the phytoplankton (Kitchell, 1992; Søndergaard *et al.*, 2008). The long-term success of biomanipulation depends on the external nutrient levels and on continued intervention into a usually resilient system (Mehner *et al*., 2004).

Managing people with regulations

Purpose of regulations

Regulations are the most ancient inland fisheries management measures (Hoffmann, 1996). Most inland fisheries regulations are promulgated in laws, bye-laws and official regulations in public fishing rights systems and are sometimes further extended by the holder of the fishing rights under private fishing rights systems such as those in Central Europe or by informal institutions on a voluntary basis (Cooke *et al*., 2013). The purposes of most fisheries regulations include managing social issues (*e.g.* attempt to distribute harvest more equitably), preventing overfishing, maintaining a suitable stock structure, maintaining fish welfare (for instance by demanding a rapid killing process; FAO, 2012) and manipulating an aquatic community (for example predator–prey interactions) (Arlinghaus *et al*., 2002). Many regulations such as quotas or length-based harvest limits are predominately directed towards selected commercially valuable or highly appreciated species of the fish community. Many regulations, however, are not backed up by controlled, replicated scientific studies but rather set arbitrarily and reflect practical experience (Johnson & Martinez, 1995; Wilde, 1997; Radomski *et al*., 2001). Because pressure on habitat and fish stocks will continue to intensify, the role of regulations in inland fisheries management will probably increase in the future (Noble & Jones, 1999).

Types of regulations

Regulations of harvest and landings are present in almost all inland fisheries and are particularly advisable when fishing mortality is high on otherwise self-reproducing stocks (Fig. 6.3.2). Regulations can either be input controls (regulating the amount and manner of fishing or inputs) or output controls (regulating the fate of the catch and the amount of harvest, the output; Morison, 2004), and they can either be formal or informal based on social norms and mutually agreed-upon rules of behaviour (Cooke *et al*., 2013). Popular input controls include closed areas, closed seasons, gear restrictions and other forms of access and effort controls, such as licensing. Common output controls include quotas, daily or weekly bag limits, length-based harvest limits and harvest tags, or specifically in recreational fisheries harvest bans via total catch-and-release policies (Table 6.3.2). While effort restrictions (*e.g.* limited entry) are relatively rare in inland fisheries as compared to marine commercial fisheries (Cox & Walters, 2002), managers can use a variety of indirect methods of manipulating the intensity of fishing. For example, requiring licences and fees or avoiding the development of access roads and boat ramps may prevent some from participating, and gear restrictions such as fly fishing-only sections or barbless hooks are frequently used to reduce the appeal and efficiency of recreational fisheries without directly controlling the amount of fishing effort.

Length-based harvest limits (Table 6.3.3), daily bag limits and annual quotas as output control measures have several purposes but are generally used to limit fishing mortality. Daily bag limits are probably the most common output control measure in recreational fisheries (Isermann & Paukert, 2010). These rules affect the per capita harvest rate and harvest expectations of

Table 6.3.2 Management actions and regulations targeting inland fishers and fish–fisher interactions

Control type	Explanation
Input controls	
Licensing and fees	Fees based on duration of licence, species, residency, status (*e.g.* youth, aged, military, student, native and tourist)
Gear restrictions	Hook and line, hook type, artificial *versus* bait, mesh sizes, length of gillnets and type of traps
Method restrictions	Motor trolling; attractants such as ground baiting, artificial light and scents
Closed times, seasons	Spawning period, aggregations and stressful environmental conditions
Closed areas	Spawning areas, aggregations, refuges and protected areas
User conveniences	Provision of boat landings, fishing piers and fish cleaning stations may attract recreational fishers
Effort restrictions	Limited entry and number of rods, lures and lines
Output controls	
Length-based harvest limits	Limit size of fishes retained (minimum, maximum, open or closed slot limits and 'one fish over a given size' limits)
Bag limits or quotas (daily, weekly and annual)	Limit number of fishes retained, daily or annually, and in possession with tags and stamps as variants for particular sizes
Sale of fishes	Prohibit commercialization or trade
Harvest restrictions	Restrict based on wild *versus* hatchery or conservation status, sometimes harvest of non-native fishes is liberalized to conserve native fishes
Harvest mandates, bounties	Encourage harvest of overabundant or undesirable species
Way of killing	In some countries, there is a mandate for rapid kill in recreational fisheries for fish welfare reasons

Source: FAO (2012). Reproduced with permission of FAO.
In general, input controls regulate the amount and manner of fishing, and output controls regulate the fate of the catch.

Table 6.3.3 Five commonly applied length-based harvest regulations used to manage inland fisheries and the associated vulnerability to harvest, management objectives and demographic conditions necessary for the tool to be effective

Size limit type	Fishes that must be released	Management objectives	Demographic conditions
Minimum	Fishes smaller than the size limit	Conserve recruits; produce larger fishes for reproduction and harvest	Low recruitment, rapid growth, low M; stocked populations
Maximum	Fishes larger than the size limit	Reduce abundance and competition among small fishes; maintain trophies and fecund large spawners	High recruitment, slow growth, moderate M
Open slot (harvest slot)	Fish above and below an intermediate size class (combination of minimum and maximum-size limits)	Protect young recruits and spawners; maintain yield and CPUE; protect large, fecund spawners, maintain trophies	Low recruitment, rapid growth, low M; particularly useful when size-dependent maternal influences affect recruitment and when fishing could deplete the spawning stock
Closed slot (protected slot)	Fishes within an intermediate size class	Reduce abundance and competition; allow harvest of large fishes	High recruitment, slow growth, high M
Total catch and release	All fishes	Improve CPUE and size, maintain stock in 'natural' condition, consumption prohibitions	Little interest in harvest by fishers, high F; sensitive stock; high contamination

Source: FAO (2012). Reproduced with permission of FAO.
CPUE, catch per unit of effort; F, fishing mortality; M, natural mortality.

people and thus their behaviour (Beard *et al.*, 2003). In many cases, however, unless bag limits are very restrictive potentially displacing effort or severely limiting the take, they will not reduce harvest mortality sustainably because few recreational fishers actually catch the daily limit. In these situations, effort controls and length-based limits on harvesting (Table 6.3.3) may be more effective for reducing fishing mortality. Effort can be controlled by limiting licence sales, and harvest quotas can be implemented with season-long bag limits (*e.g.* punched cards or harvest tags).

In contrast to marine fisheries, annual quotas are relatively rare in inland fisheries, which instead focus on a portfolio of alternative measures such as protected seasons, minimum mesh sizes and length-based harvest limits, sometimes completed with partial protected areas where fishing is prohibited. Because many inland fisheries are managed based on a set of regulations, it is very difficult to tease apart the relative effect of any given regulation type using observational data. Catch and release will be associated with almost all harvest restrictions. In extreme cases, total catch-and-release rules can increase use intensity of a fishery without depleting the fish population, unless hooking mortality exceeds *c*. 30% (Coggins *et al.*, 2007). The knowledge of hooking mortality is hence critical for many fishery managers (Arlinghaus *et al.*, 2007), and in case of undesirable levels, the manager may need to restrict tackle or fishing methods to maximize survival of released fishes.

Although in many cases regulations are aimed at limiting fishing mortality, in some cases, they may be used to maximize the take of undesirable fish species. Worldwide large-bodied non-native predators are thriving in many waterbodies, many of which were deliberately introduced by anglers (Johnson *et al.*, 2009). Predation by non-native fishes can reach very high levels and threatens many native fish populations (Eby *et al.*, 2006). One means of reducing the abundance of the non-native is to liberalize harvest so as to increase fishing mortality and produce 'intentional overfishing' for conservation reasons. Such measures may be complemented with gillnetting and trawling, installation of non-passable barriers and in extreme cases uses of chemicals to kill off entire waterbodies. Because some fisheries are today based on non-natives, such draconian measures are prone to much stakeholder conflict and demand an inclusive management process to reach consensus.

Length-based (alternatively termed size-based) harvest regulations and limits are another common form of output control, which prescribes the lengths of fishes that may be harvested and those that must be released (Table 6.3.3). By carefully tailoring length restrictions to match fish population characteristics and level of fishing effort in light of objectives, the manager can also use fishing as a means to manipulate fish population structure towards desired states. For example, individual growth in body mass can increase, and productivity can be enhanced by targeting fishing mortality on overabundant size and age classes, and recruitment can be improved by protecting age and size classes carrying the most fecundity and the most successful progeny (Arlinghaus *et al.*, 2010; Gwinn *et al.*, in press). Minimum-size limits may be used to prevent growth overfishing and conserve young fishes when they are relatively rare due to low recruitment (or in stocked populations). In order for a minimum-size limit to be effective, it is necessary that protected fishes have rapid growth and low natural mortality to allow them to recruit to the vulnerable population (Fig. 6.3.6). The manager may also wish to set the minimum-size limit above the size at maturation to allow fishes to spawn prior to being vulnerable to harvest. Note that although many fisheries are routinely managed based on minimum-size limits, there are a range of other tools (*e.g.* harvest slot length limits or protected slot length limits) that may offer better results under particular conditions (Fig. 6.3.6). Particularly when trophy fishes are to be maintained and numerical harvest to be maximized, minimum-size limits will not perform well at high

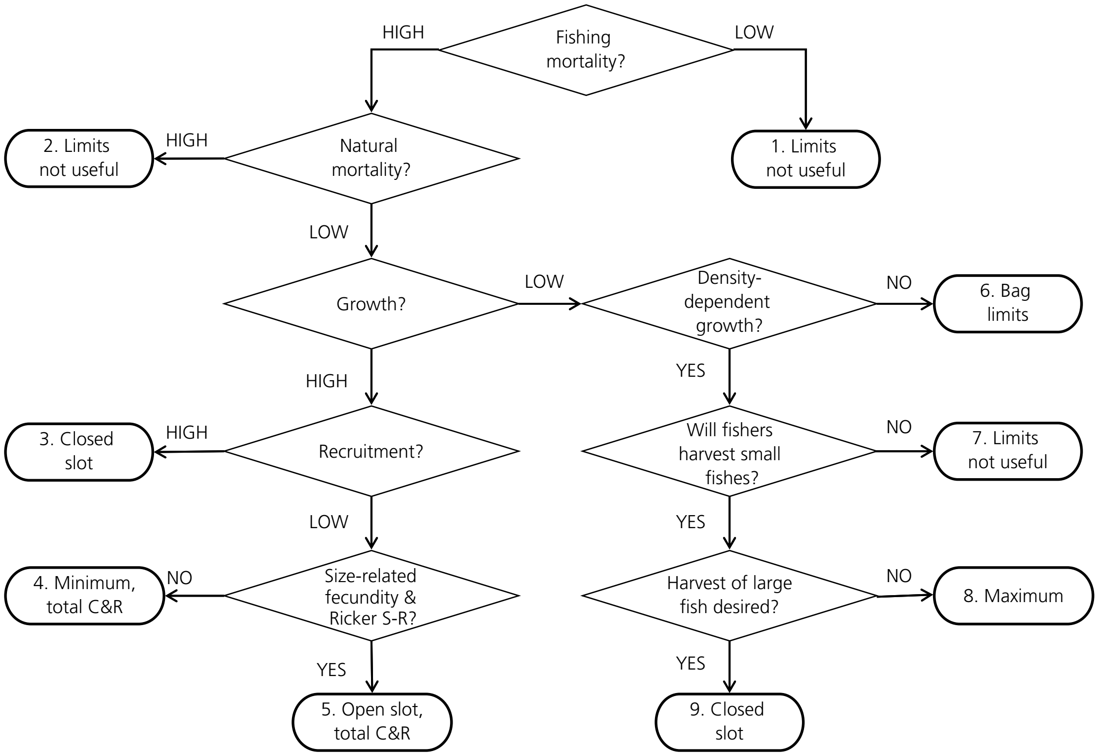

Figure 6.3.6 Decision tree for selecting appropriate size and bag limits based on the intensity of fishing, target fish population's demographic characteristics and fisher desires. When fishing mortality is low (1), harvest restrictions would not provide any benefit. If natural mortality is high (2), then deferring harvest will not result in more large fishes. The manager can expect size and bag limits to have the greatest impact on the number of large fishes when fishing pressure is high and fishes grow quickly and experience low natural mortality (3, 4 and 5). When growth is slow, size limits may be useful for reducing density-dependent growth depression by channelling harvest onto overabundant size classes (8 and 9). In cases where demographics of the stock are completely unknown, bag limits (6) should be established as a precaution against overharvest. Size-dependent fecundity means size-dependent influences of females on recruitment stemming from fecundity or egg quality influences. C&R, total mandatory catch and release; S–R, stock–recruitment relationship, with the Ricker curve (Ricker, 1954) being a specific one with overcompensation [Source: FAO (2012). Reproduced with permission of FAO].

fishing effort intensities, in which case harvest slots are the superior regulation (Fig. 6.3.6; Arlinghaus *et al.*, 2010; Pierce, 2010; Gwinn *et al.*, in press). When fish populations follow a Ricker stock–recruitment function with overcompensation, harvest slot will not only maximize numerical yield as shown by Gwinn *et al.* (in press), but they will produce maximized biomass yield, something that has traditionally been assumed to be achieved by minimum length limit regulations (R. Arlinghaus, R. N. M. Ahrends, M. S. Allen, D. C. Gwinn and C. J. Walters, Unpublished data).

Despite the frequent use of length-based harvest limits in nearly all inland waterbodies (Radomski *et al.*, 2001), most empirical studies evaluating the effectiveness of such regulations are single-system case studies that lack controls and long time series, and hence have low power to detect regulation effects (Allen & Pine, 2000). Using meta-analysis techniques, Wilde (1997) studied minimum length limits and protected slot length limits in largemouth bass *Micropterus salmoides* fisheries in the United States. He found protected slots to be effective in increasing the proportion of large fish in the stock, but they failed to increase angler catch rates, which may indicate that they did not elevate stock abundance. By contrast, minimum length limits elevated catch rates and population sizes (Wilde, 1997). Based on such results, some have questioned the general usefulness of minimum-size limits for ecological and evolutionary reasons (Conover & Munch, 2002; Law, 2007), and increasingly, alternative regulations are sought, in particular when maintaining large fish in the stock is considered important (Gwinn *et al.*, in press). In this context, the use of harvest slots has increasingly been proposed as alternative to protect large and old as well as immature fish for reaping ecological (Berkeley *et al.*, 2004; Venturelli *et al.*, 2009; Arlinghaus *et al.*, 2010), evolutionary (Conover & Munch, 2002; Law, 2007; Matsumura *et al.*, 2011) and fisheries benefits (Jensen, 1981; Arlinghaus *et al.*, 2010; Gwinn *et al.*, in press).

Informal institutions, enforcement and the human dimension

Any non-compliance of fishers and anglers with regulations and the resulting illegal harvest will reduce the efficiency of even the best planned fishery regulation (Gigliotti & Taylor, 1990; Sullivan, 2002). Non-compliance needs to be addressed by appropriate enforcement (Walker *et al.*, 2007) or by development of appropriate social norms. Although regulations are often formal, there are many opportunities for inland fishers to voluntarily adopt conservation-minded measures (either as individuals or more collectively as part of a fishing club or regional organization) to help support regulations (*e.g.* by reducing hooking mortality through appropriate gear choice). Informal institutions (rule in use) may make formal regulations superfluous (Cooke *et al.*, 2013). For example, in some fisheries, people voluntarily release all the fishes captured (Arlinghaus *et al.*, 2007), obviating the need for a restrictive harvest policy to reduce fishing mortality. Alternatively, people's 'unexpected' behaviour may render some official regulations ineffective when, for example, people refrain from harvesting small fishes under a protected slot regulation aimed at reducing density-dependent competition (Pierce & Tomcko, 1998).

Regulations should not be too complex or too system specific to reduce the information burden and increase the ease of communication and acceptability by fishers. Usually, more novel regulations are initially resisted, unless the benefits become obvious. Regulatory planning must involve a thorough understanding of the fishery's human dimensions and be complemented by professional outreach and communication that is tailored to the stakeholders. Managers should be aware of the emergence of voluntary behaviour that arises from education, outreach and the spread of new social norms, which can assist in sustaining fisheries using a 'softer approach' to resource stewardship. Such an approach is particularly effective in developing countries where formal management capacity and enforcement are often lacking and fisher communities are often closed and hence personal contact intimate. In these situations, rule breakers risk reputation loss, which promotes rule compliance. Where voluntary behaviour is not enough, Walker *et al.* (2007) provide examples of (surprisingly moderate) enforcement needs to ensure rule compliance in inland fisheries.

Enhancing or restoring fisheries using stocking

Together with measures to reduce unwanted species, stocking and introduction are fisheries management measures that directly target fish stocks (Arlinghaus *et al.*, 2002). Fisheries enhancement or restoration through stocking is mostly based on fishes produced in aquaculture but may also happen *via* the legal or illegal translocation of wild fishes.

Purpose of stock enhancement using stocking

Stocking can generate multiple benefits including increasing stock abundance and fishery yield or opportunity to catch, as well as aiding the conservation and restoration of depleted, threatened and endangered populations (Lorenzen *et al.*, 2012). While stocking can be used effectively in certain situations, many enhancements have failed to deliver significant increases in yield or other social or economic benefits or have had deleterious effects on the naturally recruited components of the target stocks (Hilborn, 1998; Walters & Martell, 2004). Depending on fishery status, fishing mortality and habitat conditions, different forms of stocking are warranted (Figs 6.3.2 and 6.3.7). In fisheries that are close to the natural carrying capacity and productive potential for the adult stock, stocking is unlikely to provide benefits and alternative strategies or 'do nothing' should be considered. Stocking for fishery enhancement may be considered when the adult stock is deemed to be below its carrying capacity due to recruitment limitation, a situation not uncommon in fish stocks even under natural conditions and often brought about by anthropogenic modification of critical juvenile habitat. Supplementation may be indicated where populations are very low in absolute numbers over extended periods to reduce extinction risk and loss of genetic diversity. Where limiting effects of habitat or overharvest on population abundance and productivity can be ameliorated, stocking may be used to speed up rebuilding or to reintroduce locally extirpated species. Finally, where anthropogenic habitat change effects are pervasive and cannot be controlled, the development of culture-based fisheries where fishable stocks are supported wholly by stocking is indicated. Sometimes, this includes the release of non-native organisms (*e.g.* rainbow trout *Oncorhynchus mykiss* in standing waterbodies in Central Europe). This practice is known as introduction or transfer of new species or genotypes, which is today seen very critical in western countries due to potentially pervasive impacts on native biodiversity, which can motivate costly 'clean-up' restoration activities (Johnson *et al.*, 2009). Due to space limitations, introductions shall not be discussed further in this chapter, and the reader is referred to the wider literature on this topic (Welcomme, 1988, 2001). All introductions have to follow rigorous ecological risk assessments due to potentially irreversible and long-lasting effects in the recipient ecosystems (EIFAC, 1988).

Types of stock enhancement systems

Different management applications call for different enhancement system designs. Lorenzen *et al.* (2012) identified five major stock enhancement types ranging from primarily production-oriented systems where the aim is to maximize production or availability of fishes while minimizing detrimental impacts on wild populations to conservation-oriented systems where the aim is to conserve or restore wild populations (Table 6.3.4). (1) Culture-based fisheries are fisheries that are largely or entirely dependent on releases of cultured fishes (Welcomme & Bartley, 1998). Most involve species that do not reproduce naturally in the system, which Cowx (1994) described as maintenance stocking. Some culture-based fisheries are stocked to support harvests far in excess of those that could be sustained through natural recruitment and can involve sterile hybrids or fishes that have been intentionally sterilized (*e.g.* triploid grass carp *Ctenopharyngodon idella* for vegetation control; Cassani, 1995). Other culture-based fisheries and ranching systems use species that are non-native to the region, which may be problematic for ecological and social reasons

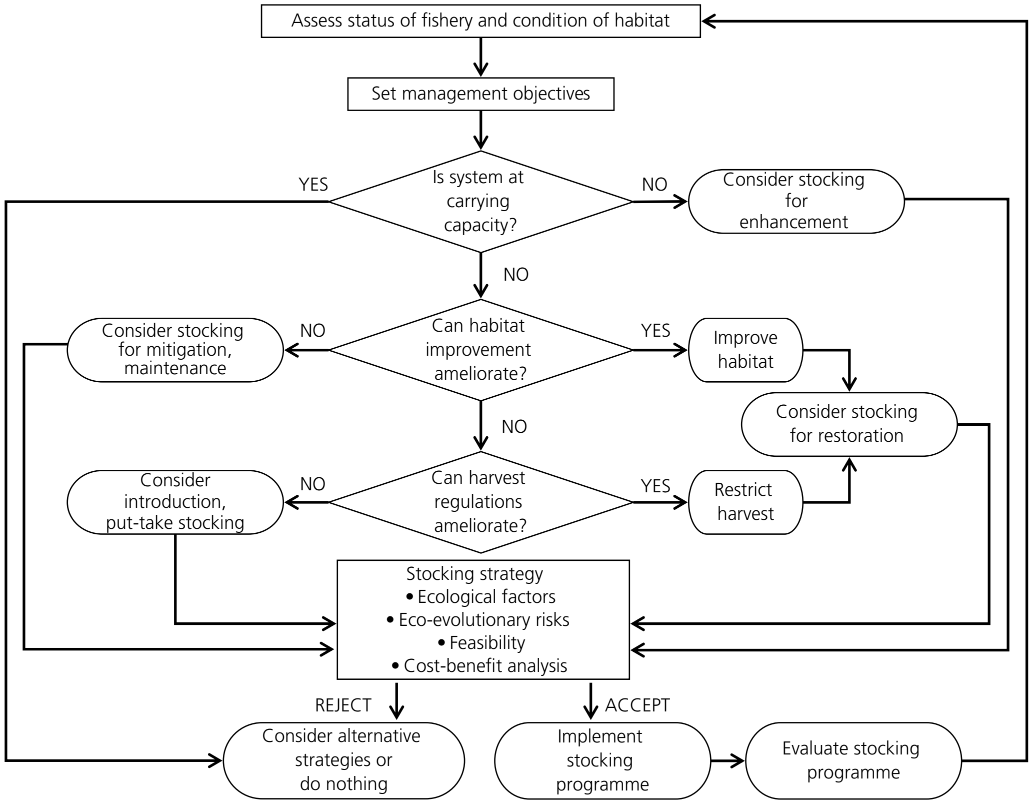

Figure 6.3.7 Outline of a decision tree for planning a stocking programme appropriate to fisheries status and habitat condition (Source: Modified from Cowx, 1994 and FAO, 2012).

when released in open waterbodies. Under certain situations, for example, put-and-take *O. mykiss* fisheries in small stillwaters in Central Europe, the ecological impacts of culture-based fisheries with non-natives may be small. In general, well-planned stocking and harvesting regimes in culture-based fisheries can be tailored to meet production objectives with few impacts on the wild stock components, often resulting in a population structure that maximizes somatic production and the abundance of catchable-sized fishes but is incompatible with sustaining natural recruitment of the target species (Lorenzen, 1995, 2005; also called put-grow-and-take fisheries if juvenile fishes are released or put-and-take when adults are released). Managing impacts on non-target species and the wider ecosystem can be a major consideration, due to the building up of populations that are not naturally present in the system and promotion of intensive harvesting that may also affect non-target species. (2) Stock enhancement involves the continued release of hatchery fishes into a wild population, with the aim of sustaining and improving fisheries in the face of intensive exploitation or habitat alteration. Stock enhancement is distinguished from culture-based fisheries and ranching by the presence of a naturally recruiting wild population and from the more conservation-oriented approaches of supplementation and restocking by its primary focus on fisheries production (Table 6.3.4). Examples of stock enhancements include Alaska salmon *Oncorhynchus* spp. enhancements and many smaller initiatives, mostly for recreational fisheries (Welcomme & Bartley, 1998; Hilborn & Eggers, 2000). Under certain conditions, stock enhancements can substantially increase overall abundance of catchable fishes and fisheries yield, but this will almost always involve some level of negative impact on the wild population component (Lorenzen, 2005). The challenge for population management in enhancements therefore is to achieve combined stock production or abundance targets while keeping impacts on the wild stock component within acceptable limits. Aquaculture production and genetic management of stock enhancements normally place great emphasis on producing seed fishes of wild-like phenotype and genotype, except in some cases where the stocked population components are intentionally separated from co-occurring wild components. Because stock enhancements aim to increase the abundance of existing stocks, normally to a level that will remain below the unexploited abundance of wild stock due to ongoing fishing exploitation, impact on non-target species and the wider ecosystem tend to be of lesser concern than in culture-based fisheries. (3) Restocking or stock rebuilding involves temporary releases of hatchery or wild fishes aimed at rebuilding depleted populations more quickly than would be achieved by natural recovery. Restocking from nearby waters is used widely to restore freshwater fisheries after pollution events or in conjunction with

Table 6.3.4 Typology of enhancement fisheries systems

	Culture-based fisheries biomanipulation	Fisheries stock enhancement (integrated or separated programmes)	Restocking or stock rebuilding	Supplementation and captive breeding	Reintroduction 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
Culture system					
Domestication type	Domesticated, mixed	Mixed, wild-like	Wild-like	Wild-like	Wild-like
Developmental manipulations	Sterility, conditioning for natural environment and return or recapture	Conditioning for natural environment, in separated programmes also for return or recapture, possibly sterility	Conditioning for natural environment	Conditioning for natural environment	Conditioning for natural environment
Genetic management	Selection for high return to fishing gear	Integrated programmes: as for restocking Separated programmes: selection for high return and separation of wild and stocked fishes	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
Natural system					
Release	Early stages and juveniles or large 'catchable' fishes, high density	Large juveniles, moderate–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
Biological characteristics					
Cultured species	Native or non-native	Native	Native	Native	Native
Wild population	Usually absent	Present (large, but possibly depleted)	Present (depleted)	Present (small, declining)	Absent (locally extinct)
Biological interactions	Interspecific ecological	Intraspecific ecological, genetic	Intraspecific ecological, genetic	Intraspecific ecological and genetic	Interspecific ecological

Source: Adapted from Lorenzen *et al*. (2012).

habitat restoration (Philippart, 1995). Theoretical analyses and empirical evidence show that where populations have been depleted by overfishing, a substantial reduction in fishing intensity is always required to achieve stock rebuilding (Fig. 6.3.2), and restocking is likely to be effective as an additional measure only in very depleted populations (Lorenzen, 2005). In restocking, release numbers must be substantial relative to the abundance of the remaining wild stock if rebuilding is to be significantly accelerated. Aquaculture and genetic management are clearly focused on maintaining the characteristics of the wild population. (4) Supplementation is defined here as the continued release of cultured fishes into very small and declining populations. Supplementation primarily serves conservation aims and specifically addresses threat processes in small and declining populations: demographic stochasticity, loss of genetic diversity and Allee effects (Caughley, 1994). Supplementation has been used most widely in salmonids (Hedrick *et al*., 2000; Hilderbrand, 2002). Captive breeding is often part of supplementation efforts. Population management in supplementation typically involves only moderate releases to not depress the wild population component further, stringent restrictions on harvesting and auxiliary measures such as habitat restoration and control of non-native species. Genetic management is focused on maintaining the structure and adaptations of the wild stock and often involves breeding plans designed to increase the genetically effective population size compared to that of the same population under random mating (Hedrick *et al*., 2000). Supplementation can mitigate against extinction from demographic stochasticity and maintain or expand genetically effective population size but may carry short- and medium-term fitness costs (Fraser, 2008; McClure *et al*., 2008). (5) Reintroduction and translocation involve temporary releases of cultured or captured wild fishes with the aim of re-establishing a locally extinct population

(Philippart, 1995). The fishes to be released may have been cultured, possibly for multiple generations, or may be brought into captivity only briefly as part of a translocation of wild stock. Reintroduction aims at establishing a healthy population that is genetically adapted to the local environment, self-sustaining, genetically compatible with neighbouring populations so that substantial outbreeding depression does not result from straying and interbreeding between populations and sufficiently diverse genetically to accommodate environmental variability over many decades (Reisenbichler *et al.*, 2003). Genetic management of such programmes is particularly challenging because unless a representative and sufficiently large sample of the original population has been brought into captivity prior to its extinction in the wild, the reintroduced population must be assembled from populations other than that originally present. Reisenbichler *et al.* (2003) point out that while it is generally best to adhere to the ancestral lineages for the species to be restored, establishment success is likely to be greatest for fishes from populations adapted to similar environmental conditions, which may not always be those now extant from the lineage that was originally present in the release habitat.

Considerations for successful use of stocking in fisheries enhancement and restoration

Key considerations for the use of stocking are outlined in the responsible approach to fisheries enhancement (Lorenzen *et al.*, 2010). The recent version of the responsible approach divides the considerations into three stages, starting from an initial appraisal of the potential for enhancement to contribute to fisheries management goals (stage 1) *via* technology development and pilot studies (stage 2) to operational implementation (stage 3) (Table 6.3.5). Here, we summarize key aspects that have to be considered when the approach is implemented into the practice of stocking.

Population dynamics in various stocking systems

The population dynamics of stocked fisheries are influenced by size and density-dependent processes. Natural mortality rates within fish populations are strongly size and age dependent, typically being orders of magnitude higher in early life stages than in adults and declining throughout the juvenile stages according to a fairly consistent allometric scaling (Lorenzen, 2000). Compensatory density dependence is manifested mostly in mortality in juveniles and in growth and reproductive variables in older fishes (Rose *et al.*, 2001; Lorenzen, 2008*a*). While density-dependent mortality in juveniles exerts the strongest compensatory response in many fish populations, density-dependent growth in older (recruited) fishes can also exert a strong effect and sets the ultimate limits to carrying capacity (Lorenzen, 2008*a*).

The dynamics of culture-based fisheries are driven entirely by stocking, harvesting and the mortality and growth processes that apply to the life stages represented in the stocked population.

Table 6.3.5 Elements of the updated responsible approach to fisheries enhancement

Stage I: Initial appraisal and goal setting
Understand the role of enhancement within the fishery system
Engage stakeholders and develop a rigorous decision-making process
Quantitatively assess contributions to fisheries management goals
Prioritize and select target species and stocks for enhancement
Assess economic and social benefits and costs of enhancement
Stage II: Research and technology development including pilot studies
Define enhancement system designs
Develop appropriate aquaculture systems
Use genetic resource management
Use disease and health management
Ensure that released hatchery fishes can be identified
Use an empirical process for defining optimal release strategies
Stage III: Operational implementation and adaptive management
Devise effective governance arrangements
Define a management plan with clear goals and decision rules
Assess and manage ecological impacts
Use adaptive management

Adapted from Lorenzen *et al*. (2010).

Perhaps the majority of culture-based fisheries rely on stocking of large juveniles or even catchable-sized fishes, and the key biological processes driving their dynamics are then size dependence in mortality and density dependence in growth of released fishes. Lorenzen (1995) and Lorenzen *et al.* (1997) explored the dynamics of such fisheries theoretically and in a case study. Key insights were that the overall yield is determined by the combination of stocking density, size at stocking and fishing pressure. The highest yields are achieved when culture-based fisheries are stocked and harvested intensively. New biomass production is maximized when fishes are harvested as late juveniles, soon after the somatic growth is highest, while conversely, if large fishes are to be produced, it limits the overall biomass production that can be achieved. In put-and-take recreational fisheries, fishes can be stocked at any size desired by anglers and recaptured within days or weeks at the most. Such fisheries can sustain very high catches without any biological production.

In stock enhancement, fishes are released into existing wild populations. Stocking of early life stages or small juveniles prior to the juvenile stages in which density dependence in survival is strongest will elicit a strong compensatory response, often to the extent that stocking has no net effect on the abundance of larger fishes but results in displacement of wild by hatchery fishes in proportion to their relative densities at the stage of stocking (Lorenzen, 2005). Releases of large juveniles after the life stages where density dependence in survival is strongest can raise abundance and biomass of large fishes beyond the level supported by natural recruitment, but the extent of this will be ultimately limited by compensatory growth responses (Lorenzen, 2005, 2008*a*). Where the wild stock is fished within sustainable limits, recruitment compensation implies that natural reproduction of released hatchery fishes will make at best a small net contribution to natural recruitment while posing potentially substantial ecological and genetic risks to wild stocks through replacement effects (Lorenzen, 2005). High and continuous releases may over time lead to complete replacement of the wild by cultured or feral populations (Ford, 2002; Lorenzen, 2005). The empirical evidence for replacement of wild by released cultured fishes is variable and may reflect the interplay of variable fitness of stocked fishes, duration of stocking, the habitat conditions of the recipient ecosystem and resilience of the native stock to compensate for competition with stocked fishes (van Poorten *et al.*, 2011). Because stock enhancements can depress wild population abundance and also have deleterious genetic impacts, it may be advantageous to separate cultured and wild population components as far as technically possible. Releasing hatchery fishes as advanced juveniles (thus reducing interactions with wild juveniles at the stage when compensatory density dependence is particularly strong) and selective harvesting of hatchery fishes, possibly combined with manipulations to induce sterility, can greatly reduce ecological and genetic interactions with wild fishes (Utter, 2004; Lorenzen, 2005).

Restocking is normally considered only for populations that have been depleted to a low fraction of their carrying capacity. In this case, compensatory density-dependent responses are expected to be weak until the population rebuilds substantially, and even the stocking of early life stages may contribute to a net population increase. Populations that are at a low fraction of carrying capacity (<*c*. 15%) may show depensatory density dependence (Allee effects), either 'trapping' the population at low abundance or leading to continued decline (Liermann & Hilborn, 2001). In such populations, release of fishes could increase abundance to levels where depensation does not occur and thus kick-start population recovery.

In supplementation programmes for populations that are very small in absolute terms, dynamics are similar to those described for stock enhancement, but release of additional fishes may be beneficial by reducing the threat of extinction due to demographic stochasticity despite eliciting a partial compensatory response (Hilderbrand, 2002).

Aquaculture production of seed and domestication effects

Rearing of fishes in hatcheries and other culture facilities subjects the organisms to an inadvertent or intentional process of domestication. Domestication processes occur inadvertently when fishes are brought into captivity but may be enhanced through measures such as selective breeding (leading to fully domesticated fishes) or reduced by measures such as habitat enrichment or life skills training aimed at producing more wild-like fishes (Lorenzen *et al.*, 2012). As a result, cultured fishes released into the wild tend to differ from their wild conspecifics in a wide range of morphological, behavioural, physiological and ecological attributes, which can lead to poor fitness (Sosiak *et al.*, 1979; Ersbak & Haase, 1983; Olla *et al.*, 1998). Indeed, natural mortality rates of released cultured fishes are highly variable but substantially higher on average than those of wild conspecifics of similar size (Lorenzen, 2000; Fleming & Petersson, 2001). Likewise, cultured fishes show lower reproductive success than wild fishes (Fleming & Petersson, 2001; McGinnity *et al.*, 2003). Cultured fishes may also be more susceptible to capture by fishing gear than their wild conspecifics (Mezzera & Largiadèr, 2001). Similarly, wild fishes not adapted to a recipient ecosystem will often show low survival in the wild.

Genetic management

Three main sets of issues are associated with the genetic management of hatchery programmes: (1) potential disruption of neutral and adaptive spatial population structure due to translocation, (2) impacts of hatchery spawning and rearing on genetic diversity of stocked fishes and consequently after release on the enhanced, mixed stock and (3) impacts of hatchery rearing on the fitness of released fishes and their naturally recruited offspring. Wild fish populations show spatial structure in selectively neutral markers where isolation has been sufficiently strong and long term (Utter, 2004). Hatchery practices should reflect and maintain this structure by using brood stock of local origin where possible and through appropriate brood stock management (Verspoor, 1997). Not doing so has been shown to carry substantial penalties in terms of post-release fitness, with implications for both enhancement effectiveness and risks to the wild population (Araki *et al.*, 2008; Fraser, 2008). The main risks to genetic diversity arise when wild populations of small effective population size are 'swamped' by hatchery fishes derived from comparatively small numbers of breeders (Ryman & Laikre, 1991). Loss of fitness is more difficult to avert than loss of diversity. Measures aimed at minimizing fitness loss include rearing in near-natural environments, minimizing time in captivity, partially replenishing brood stock with wild fishes in regular intervals, equalizing family size or fragmentation of brood stock to reduce potential for adaptation (Araki *et al.*, 2008; Frankham, 2008; Lorenzen *et al.*, 2012). Reduced fitness of cultured fishes reduces the effectiveness of enhancements but still poses risks to the wild population component, which are greatest when fitness is only moderately compromised (Lorenzen, 2005). Several excellent guidelines and policies have been developed for genetic management of enhancements, including Miller and Kapuscinski (2003) and Tringali *et al.* (2007).

Interspecific interactions and ecosystem effects

Interspecific interactions and ecosystem effects of stocking-based fisheries enhancement and restoration can arise through various biological or technical means. Intensive interspecific biological interactions can arise where released fishes increase the abundance of existing wild populations or establish new populations where the species was previously absent. In either case, the strongest impacts on other fish species are likely to arise due to predation from stocked piscivores or due to biogenic habitat modification by stocked species that may, for example, reduce macrophyte abundance or increase turbidity (FAO, 1999; Eby *et al*., 2006). Interspecific competitive interactions for food tend to be weaker but may also be significant (Levin & Williams, 2002). Impacts of stocked non-native species are widely perceived as a more serious threat to native biota than the release of native species. While non-native fishes undoubtedly have contributed to threats and extinctions of native fishes, the majority of non-native fishes have integrated into existing communities without causing extinctions or even drastic changes in the abundance of native species (Moyle & Light, 1996; Williamson, 1996; Gozlan, 2008). Hybridization between closely related cultured and wild species has been shown to occur and can contribute to loss of genetic integrity and fitness of the wild population (Hitt *et al*., 2003). Both competitive interactions and hybridization may be particularly prevalent where the stocked and wild species are closely related. When considering species for stocking, it is therefore important to weigh the relative risks of intraspecific interactions of stocking native species *versus* those of interspecific interactions associated with stocking and introduction of non-native species.

Diseases

Impacts on wild stocks from diseases introduced by or with the stocking material may occur *via* three mechanisms: (1) introductions of alien pathogens, (2) transfer of pathogens that have evolved increased virulence in culture and (3) changes in host population density, age and size structure or immune status that affect the dynamics of established pathogens. Introductions of alien pathogens are associated with the most dramatic disease impacts of stocked on wild fishes so far documented (Johansen *et al*., 2011). Controlling parasites in cultured fishes is crucial to minimizing disease interactions with wild fishes, but is not always effective and may not be sufficient, particularly where parasite transmission from wild to cultured fishes is difficult to avoid. It is therefore important to implement an epidemiological, risk-based approach to managing stocking-induced disease transmission that accounts for ecological and evolutionary dynamics of transmission and host population impacts (Bartley *et al*., 2006).

Human dimensions

Human dimensions, the motivations, attitudes and behaviours of fishing stakeholders and the governance arrangements in place to regulate the enhanced fisheries can have major implications for management outcomes (Lorenzen, 2008*b*). Three issues shall be mentioned here. Firstly, it is usually stakeholder needs that demand and justify stocking programmes (van Poorten *et al*., 2011). Moreover, many stocking programmes are user financed through licence fees, for example, in angling clubs. Stakeholder desires may also result in illegal translocation of fishes, which contributes to spread of non-native fishes (Johnson *et al*., 2009). Secondly, individual and collective responses of fishers to an enhancement programme may have unintended consequences such as an increase in fishing pressure on wild stock components (Hilborn & Eggers, 2000). Such responses may be used purposefully in recreational fisheries where increasing fishing effort and related economic benefits may be a key management objective (Loomis & Fix, 1998). Lastly, initiation and successful maintenance of enhancements depend on governance systems that allow for regulation of resource use and ensure that benefits of enhancements accrue to those bearing the costs (Lorenzen, 2008*b*).

Keys to securing additive effects of stocking

Based on the background information examined, five key considerations are finally outlined that may be considered to increase the chances of generating additive effects of stocking. Firstly, stocking is most likely to generate positive fisheries outcomes whenever competition with wild recruits is low or even absent due to reproduction failures. Otherwise, stocked fishes will compete with wild fishes and may partially replace wild fishes unless the latter are competitively superior, which is often the case. Secondly, stocked fishes have to be properly adapted to cope with environmental challenges and natural selection pressures, which involve ecological and genetic adaptation to conditions in the wild. Thirdly, additive effects are more likely when predation burden is low and stocked fishes survive at high rates. Elevated survival can be achieved by stocking large-bodied individuals that face lower predation losses. And finally, even the best adapted and prepared fish has to be released into the wild while minimizing transport and release-related stress risks. Otherwise, immediate losses to predators in the wild are very high. Because of the complexity of considerations, the reality of many stocking programmes is that they have to be ideally conducted as experimental releases using an adaptive management framework to learn the system-specific responses. Such approach is highly advisable before large investments into hatcheries or similar infrastructure happen that are difficult or impossible to reverse. We argue strongly against using stocking as a fix to environmental change or as a habitual practice because of the economic and ecological risks that such programmes carry.

Concluding remarks

The old adage that fisheries management is as much people as fish stock management is particularly true in the many small-scale freshwater fisheries. This is because of the multi-use patterns characteristic for most freshwater ecosystems where local inland fisheries are social–ecological systems nested within other regional social–ecological systems and sectors such as agriculture. Because of resulting tight cross-scale interactions among systems, sustainable inland fisheries are heavily dependent on decisions made elsewhere with respect to water management, flood control, hydropower and navigation. Therefore, within the details of planning and implementing particular fisheries management interventions such as harvest regulations or the type and amount of stocking, the fishery manager must ensure to be well represented in all external decisions that spill over to the quality of the fishery. Unfortunately, with few exceptions (*e.g.* North American Great Lakes), inland fisheries are often marginalized in the wider freshwater ecosystem management and suffer from low sociopolitical priority that reduces political and administrative support (Arlinghaus *et al*., 2002). Therefore, an inclusive planning and management approach that integrates fisheries within the broader scope of aquatic ecosystem management is often needed for sustainable inland fisheries. The reader is directed to relevant sources that outline elements of an integrative approach to inland fisheries planning and management (Cowx, 1998; Lorenzen, 2008*b*). A range of more specific studies may also provide concrete guidance for deciding about the concrete fisheries management actions that have been outlined in this chapter (*e.g.* introduction of fishes: EIFAC, 1988; Welcomme, 1988; fish stocking: Cowx, 1994; Welcomme, 2001; Arlinghaus *et al*., 2002; harvest regulations: Johnson & Martinez, 1995; FAO, 2012).

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