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REVIEW

The social, economic, and environmental importance of inland fish and fisheries

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Abstract: Though reported capture fisheries are dominated by marine production, inland fish and fisheries make substantial contributions to meeting the challenges faced by individuals, society, and the environment in a changing global landscape. Inland capture fisheries and aquaculture contribute over 40% to the world's reported finfish production from less than 0.01% of the total volume of water on earth. These fisheries provide food for billions and livelihoods for millions of people worldwide. Herein, using supporting evidence from the literature, we review 10 reasons why inland fish and fisheries are important to the individual (food security, economic security, empowerment), to society (cultural services, recreational services, human health and well-being, knowledge transfer and capacity building), and to the environment (ecosystem function and biodiversity, as aquatic "canaries", the "green food" movement). However, the current limitations to valuing the services provided by inland fish and fisheries make comparison with other water resource users extremely difficult. This list can serve to demonstrate the importance of inland fish and fisheries, a necessary first step to better incorporating them into agriculture, land-use, and water resource planning, where they are currently often underappreciated or ignored.

Key words: food security, freshwater ecosystems, importance of fish, inland fisheries.

Résumé : Bien que la capture de poissons rapportée par les pêcheries soit dominée par la production marine, les poissons et les pêcheries de l'intérieur des terres apportent des contributions substantielles pour rencontrer les défis rencontrés par les individus, les sociétés et l'environnement dans un paysage en changement global. Les captures des pêcheries de l'intérieur et l'aquaculture contribuent à la hauteur de 40 % à la production mondiale rapportée pour les poissons à nageoires, à partir de moins de 0,01 % du volume total de l'eau sur terre. Ces pêcheries fournissent de la nourriture pour des milliards et un moyen de subsistance pour des millions de gens, partout au monde. Dans cette revue, en utilisant des preuves venant de la littérature, les auteurs examinent 10 raisons pour lesquelles, les pêcheries et les poissons de l'intérieur sont importants pour les individus (sécurité alimentaire, sécurité économique, l'autonomisation), pour la société (services culturels, services récréatifs, santé humaine et bien-être, transfert de connaissances et capacité à construire) et pour l'environnement (fonction écosystémique et biodiversité, comme « canaris » aquatiques, pour le mouvement « aliments verts »). Cependant, les limitations actuelles pour évaluer les services fournis par les poissons et les pêcheries intérieures rendent les comparaisons avec les autres utilisateurs de la ressource en eau extrêmement difficile. Cette liste peut servir à démontrer l'importance des poissons et des pêcheries de l'intérieur, une première étape essentielle pour mieux les incorporer avec l'agriculture, l'utilisation du territoire et la planification des ressources en eau, où elles sont actuellement sous-estimées, voire totalement ignorées. [Traduit par la Rédaction]

Mots-clés : sécurité alimentaire, écosystèmes d'eau douce, importance des poissons, pêcheries de l'intérieur.

Introduction

Inland waters are defined by the Food and Agriculture Organization of the United Nations (FAO) as lakes, rivers, streams, canals, reservoirs, and other land-locked waters (FAO 2014*a*). While inland is generally synonymous with freshwater, inland waters do include land-locked saline water bodies such as the Caspian Sea (FAO 2014*a*). Inland waters comprise approximately 0.01% of the total volume of water on earth (Stiassny 1996).

Inland fishes reside in these waters. They comprise approximately 40% of all fish species and 20% of all vertebrate species (Helfman et al. 2009). However, the difficulty in assessing aquatic biodiversity, particularly in developing countries and remote areas, suggests that inland fishes are more diverse than the reported estimates (Cooke et al. 2012). Additionally, 65% of inland habitat is classified as moderately or highly threatened by anthropogenic stressors (Vörösmarty et al. 2010), so populations may be extirpated even before they are documented.

Inland fisheries are both capture fisheries and aquaculture of inland fish species for food, income, or recreation. In discussions of global capture fisheries, inland fisheries are often overwhelmed

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by marine fisheries because of the sheer magnitude of reported marine catches (marine catches are approximately seven times higher than inland catches; FAO 2014*b*). However, several lines of evidence (e.g., consumption studies) suggest that inland fisheries harvest is often unrecorded or drastically underreported, particularly with reference to the prevalence of small-scale or artisanal fishing (i.e., subsistence and local trade) in inland waters (Hortle 2007; FAO 2010*a*, 2012; Welcomme et al. 2010; Bartley et al. 2015). In addition to harvest, inland aquaculture has experienced considerable growth over the past decade. Considering both aquaculture and capture fisheries, inland fisheries contribute over 40% of the world's capture finfish fisheries and aquaculture production (excluding plants, mammals, crustaceans, echinoderms, and mollusks; Fig. 1; FAO-FIGIS 2014).

Despite their demonstrably large contribution, public support and political will are often difficult to obtain for inland fishes, and consequently, they generally receive little consideration in water resource allocation decisions (Cooke et al. 2013). Generally, issues that may adversely affect inland fish, such as climate change or invasive species, do not rank highly among issues of public concern (Novacek 2008), and the time horizon of inland fisheries issues is often beyond the traditional scale of political action (Kates et al. 2001). While strong laws do protect fish and fisheries in some cases (e.g., U.S. Endangered Species Act), they are not the norm globally. Only one-third of countries with inland fisheries even submit catch statistics to FAO (FAO 2010*a*). We (the authors) agree with FAO (2010*a*) that the lack of awareness is because information about inland fishes and fisheries is inherently difficult to acquire because inland fishes are diverse and the fisheries they support are often small-scale and highly dispersed.

We reviewed the relevant literature and engaged in a series of structured discussions (i.e., list generating exercises that were consolidated in group discussions) to compile a consensus list of 10 reasons why inland fish and fisheries are important to the individual, society, and the environment (Table 1; Fig. 2). While we acknowledge that marine fish and fisheries provide many of the same services, we specifically focus our review on inland systems because, to our knowledge, no global review on the value of inland fish and fisheries currently exists.

The individual

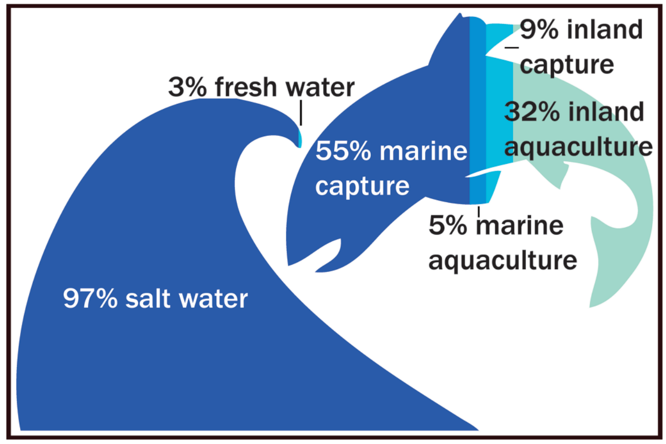
Inland fisheries provide food for billions and livelihood for millions of people worldwide (FAO 2014*b*). The relative contribution of inland fisheries to a country's food and economic security is dependent on its level of economic development and social context and, often, this is higher in the developing world and emerging economies. Inland fisheries contribute significantly to food security and economic security by providing primary sources of animal protein, essential nutrients, and income (Welcomme et al. 2010). The food and income benefits provided by inland capture fisheries and aquaculture can afford opportunities for empowering individuals where opportunities in other sectors are limited.

Food security

Inland fishes are important food and nutritional resources, especially rural economies in developing countries (Welcomme et al. 2010). Low-income food-deficit countries account for 80% of the total reported harvest from inland capture fisheries (Kapetsky 2003). Over 90% of global inland capture fisheries production is used for human consumption, the majority of which is in the developing world (Welcomme et al. 2010). For example, fish account for 50% of all animal protein consumed in Bangladesh (Thilsted et al. 1997).

Critically, the contribution of inland fisheries to meeting food security is considered grossly underestimated (Welcomme et al. 2010). In the Lower Mekong Delta, there is a 221% discrepancy between the official yield figures of 1.2 million tonnes and estimated consumption of 2.6 million tonnes (Hortle 2007). While

Fig. 1. Proportional contribution of global finfish production from marine capture fisheries, marine aquaculture, inland capture fisheries, and inland aquaculture in 2012 (excluding plants, mammals, crustaceans, and mollusks; FAO-FIGIS 2014) with the global proportion of salt and fresh water (note only 0.01% of water is habitable for inland fish; Stiassny 1996).



yields from small-scale artisanal fishing (e.g., subsistence, local trade) do not often enter a market economy and consequently are not often recorded (Bartley et al. 2015), they represent the primary animal protein source for many of the rural poor and are crucial to global food security.

Inland fish are particularly important in addressing "hidden hunger" (micronutrient deficiencies and their related health issues; e.g., Kennedy et al. 2003). Inland fishes provide protein, omega-3 fatty acids, vitamin D, calcium, B vitamins, vitamin A, iron, zinc, and lysine to those where other nutritional sources are not available or are cost-prohibitive (Thilsted et al. 1997; Roos et al. 2007; Youn et al. 2014). Particularly in the developing world, small fish eaten whole provide an important source of nutrients (e.g., calcium and vitamin A) that are difficult to obtain through other dietary sources (Roos et al. 2007). Consumption of inland fish has been shown to mitigate the effects of some micronutrient deficiency-related illnesses, such as rickets in Bangladeshi children (Craviari et al. 2008). Moreover, because these often small inland fishes can be readily dried or preserved, they also provide year-long nutrient sources, such as dried kapenta (*Limnothrissa miodon*; *Stolothrissa tanganicae*) in Zambia (Musumali et al. 2009). Secondarily to direct human consumption, inland fish can also be used in feed for livestock and aquaculture operations. For example, sun-dried dagaa (*Rastrineobola argentea*) is used as chicken feed around Lake Victoria when not suitable for human consumption.

Economic security

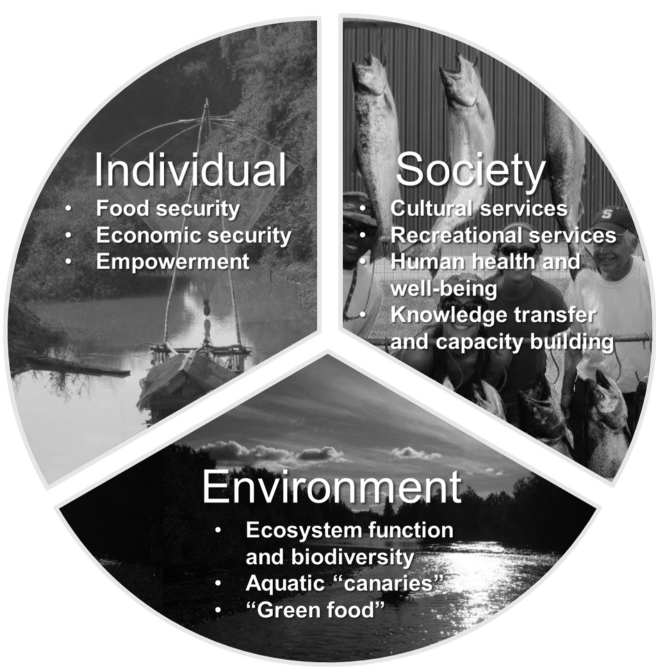
Eighty percent of inland capture fisheries are reported to be operating in the developing world (Kapetsky 2003). Many of these fisheries are conducted by the rural poor, often for subsistence and small-scale economic security. While inland capture fisheries account for less than 14% of the global harvest total (Fig. 1), these fisheries support at least 21 million fishers (36% of all capture fishers worldwide) and over 36 million more are employed in post-harvest activities, indicating that inland fisheries have a proportionally higher influence on livelihoods than marine fisheries, particularly in Asia and Africa (FAO and WorldFish Center 2008; FAO 2014*b*).

Inland capture fisheries and aquaculture are fundamental to food sovereignty globally. In many areas of the world, inland capture fisheries are a last resort when primary income sources fail due to, for instance, economic shifts, war, natural disasters, and water development projects. They serve as social safety-nets, providing alternative or supplemental sources of income, employment,

Table 1. The importance of inland fishes and fisheries to the individual, society, and the environment by the numbers.

Importance of inland fish and fisheries to	Supporting statistics
The individual	
Food security	Over 90% of global inland capture fisheries production is used for human consumption, mostly in the developing world (Welcomme et al. 2010).
Economic security	Inland capture fisheries support at least 21 million fishers (36% of all capture fishers worldwide) and over 36 million more are employed by post-harvest activities (FAO and WorldFish Center 2008, FAO 2014*b*).
Empowerment	More than 60 million people in low income countries rely upon inland fisheries as a source of livelihood and women represent over half the individuals in inland fisheries supply chains (FAO 2014*b*).
Society	
Cultural services	The heritage, spiritual, and aesthetic value of inland fishes can be considered "priceless" (Harris et al. 1989).
Recreational services	The annual net value of recreational fishing in the Laurentian Great Lakes is estimated as high as US$1.47 billion (Poe et al. 2013).
Human health and well-being	Zebrafish are arguably the second most-used medical and pharmaceutical model behind mice (Lieschke and Currie 2007).
Knowledge transfer and capacity building	Inland fisheries take place in many of the 5 000 000 km^2 of inland lakes and impoundments and 662 000 km^2 of rivers across the globe (Verpoorter et al. 2014), often transecting political boundaries.
The environment	
Ecosystem function and biodiversity	Inland fishes occupy all major inland aquatic habitats and comprise approximately 40% of all fish species and 20% of all vertebrate species (Helfman et al. 2009).
Aquatic "canaries"	Inland fish serve as warnings for current and impending impacts on humans from environmental change and 65% of their habitats are at risk from anthropogenic stressors (Vörösmarty et al. 2010).
"Green food"	Sustainable aquaculture has a more efficient food conversion ratio (<2 kg of dry feed per 1 kg of gain) than poultry (2-to-1), pigs (4-to-1), and cows (7-to-1; Brown 2002).

Fig. 2. Conceptual diagram of the importance of inland fishes and fisheries to the individual, society, and the environment.



and food (Welcomme et al. 2010). Besides income and livelihoods through direct fishing activities, inland fisheries generate substantial income and job opportunities through secondary service activities, such as gear provision and maintenance, processing, and distribution (Welcomme et al. 2010). Secondary activities increase the market value of the fish products, increasing the economic value of inland fisheries overall. Recreational fishing and tourist activities, in particular, have strong economic multiplying effects for the experiential activities in addition to the market value of the fish (Southwick Associates 2013).

Statistics on the economic contribution of inland capture fisheries are limited because the outputs are often very local in scope, with fish traded locally or consumed directly by the fishing families (FAO and WorldFish Center 2008). However, the value of particular inland fisheries can provide some indication of economic importance more generally. A study of six river basins in West and Central Africa, for example, found that local capture fisheries supported 227 000 full-time fishers and had a first-sale value of US$295 million (Neiland and Bene 2006). In the Lower Mekong Basin, total fish production is about 3.9 million tonnes, with a first sale value of US$7 billion (MRC 2010). Perhaps more importantly, the value of inland fisheries transcends economic statistics because these fisheries also serve a critical non-monetary role in the case of subsistence where no financial transactions occur.

Empowerment

Inland fisheries provide opportunities to empower individuals to meet their own physical and psychological needs and provide for their dependents. This role is particularly important in poverty prevention for marginalized populations including ethnic minorities, the rural poor, and women (Weeratunge et al. 2014). For ethnic minorities in the Mekong Basin, lack of land ownership prohibits involvement in agricultural activities (MRC 2010). Inland fisheries empower them with a low investment opportunity for subsistence and livelihood. Women, as another example, typically have low empowerment in developing countries. But, they comprise 20% of the world's inland fishers and complete around 90% of post-harvest processing (FAO 2014*b*). For comparison, women comprise 43% of the agricultural labor force in developing countries (FAO 2010*b*).

Inland capture fisheries, and the individuals they empower, are threatened by new and intensive ways of using and manipulating global freshwater resources, including hydropower, flood mitigation, recreation, and agriculture and aquaculture ventures (e.g., Orr et al. 2012). To address these concerns, cooperative management has had some success in creating more sustainable fisheries governance institutions (Jentoft 2005). These systems develop by government institutions working with stakeholders to create systems of mutual benefit, make joint management decisions, and empower groups to produce more effective solutions than either party could have done on its own. Successful co-management attempts, those that empower the participants, can be seen in the developing world, such as the 2011 regulatory overhaul of the Zambian side of Lake Kariba (Madzudzo et al. 2014). But, cooperation attempts can be unsuccessful if power structures are too unevenly distributed. For example, hydropower proposals on the mainstem of the Mekong River have largely neglected implications for fisheries (Orr et al. 2012). Successful co-management operations must create environments in which individuals are empowered by their communities to engage government officials and participate in the decision-making process that influences their own well-being (Jentoft 2005).

Society

Inland fish and fisheries play an important role in communities around the globe. In many cultures, inland fish are sacred and contribute to community identities (Weeratunge et al. 2014). They also support valued recreational activities worldwide (Cooke and Cowx 2004). Inland fish species also contribute to advancements in disease control and medical research benefiting human health and well-being (e.g., larvivorous fish and medical research model organisms). Additionally, management of inland fisheries provides opportunities for knowledge transfer and capacity building across political jurisdictions (UNU-INWEH 2011).

Cultural services

Cultural services provided by inland fish include spiritual services (e.g., sacred, religious), inspirational (e.g., art, folklore), and aesthetic (i.e., Tengberg et al. 2012). To many, these services are considered priceless and cannot be valued in market terms (Harris et al. 1989). In developed and developing countries, inland fisheries provide a sense of community identification and occupational attachment (Weeratunge et al. 2014). In particular, traditional ecological knowledge (TEK) — knowledge formed from the experiences and observations acquired over time from direct human contact with a specific environment — has facilitated the harvest of inland fish for subsistence and has helped maintain traditions, values, and cultures (Berkes 2012).

The strong linkage between inland fish and human culture can result in a fish becoming a cultural icon with community importance that extends beyond food value: for example, koi (*Cyprinus carpio*) in eastern Asian culture, lake sturgeon (*Acipenser fulvescens*) in the Laurentian Great Lakes, and Murray Cod (*Maccullochella peelii peelii*) in southeastern Australia serve as unifying symbols of regional identity. The sense of identification for fishing communities has been described as having fishing "in the blood" (Smith et al. 2003), which can foster environmental stewardship. The role of fish as cultural icons has also been proposed as a means to promote conservation as flagship or umbrella species where conservation efforts for iconic fish (e.g., Mekong giant catfish (*Pangasianodon gigas*)) could result in broader ecosystem-level improvements (see Simberloff 1998).

Recreational services

Recreational fisheries are a large sector of inland fish services; however, inland fish also support non-fishing sectors including diving, snorkeling, boating, and the public and private aquarium trade. In industrialized countries, the economic value of recreational fisheries exceeds subsistence and commercial fisheries in inland waters (FAO 2010*a*). These expenditures are not limited solely to those enterprises directly linked to fishing activities; they generate jobs in other sectors including the tourism industry, restaurants, and hotels. For example, the annual net value of recreational fishing and its associated activities in the Laurentian Great Lakes is estimated as high as US$1.47 billion (Poe et al. 2013).

Recreational services directly link inland fish to much more than just recreational fisheries. In the Pantanal region of South America, snorkeling in clear, tropical, freshwater drives the tourism for the region (Cooke et al. 2013). The ornamental fish industry is also largely driven by inland fish species. Over 90% of home aquarium fish trade is represented by freshwater species (www.iucnffsg.org).

Beyond economic value, the fish seen on the angler's line, through a snorkeler's mask, or inside an aquarium's glass provides an opportunity for people to engage with the natural world. For example, aquarium visits have been shown to have a lasting impact on conservation knowledge and interest of visitors (Adelman et al. 2000). Similarly, recreational users of inland systems often volunteer to participate in a wide variety of "citizen science" and conservation ventures, ranging from organized activities, such as shoreline clean-ups, to citizen enforcement, including voluntary enforcement of conservation practices in the Mongolian taimen (*Hucho taimen*) recreational fishery (Jensen et al. 2009).

Human health and well-being

Inland fish provide a number of important benefits to human health and well-being including pest control, biomedical research, and a connection with the outdoors. Larvivorous fish, such as western mosquitofish (*Gambusia affinis*) and Arabian killifish (*Aphanius dispar*), are frequently used for the control of disease-carrying (e.g., malaria, Dengue fever, yellow fever) mosquitoes. Larvivorous fish can be used in areas, such as rice fields, where use of chemical insecticides is unsafe or ineffective or where mosquitos are pesticide resistant (Lacey and Lacey 1990; Hemingway and Ranson 2000), but there can be unwanted consequences of their use (e.g., declines of other aquatic invertebrates, amphibians, and other fish species; Pyke 2008).

Inland fish species are used extensively as biomedical research models, in particular Medaka (*Oryzias latipes*) and zebrafish (*Danio rerio*). Zebrafish are arguably the second most-used medical and pharmaceutical model behind mice (Lieschke and Currie 2007). They are particularly useful for human disease research because they obviate some ethical and practical issues associated with using higher vertebrates (Lieschke and Currie 2007). Zebrafish have served as a model for ecotoxicology (e.g., Fraysse et al. 2006), cancer genetics, drug discovery, regenerative medicine, and tissue repair, where they have potential to address some aspects of organ dysfunction, injury, and trauma (e.g., Goessling and North 2014).

Inland fish also contribute to human well-being through the connection that they forge between humans and nature. For example, recreational angling has a variety of psycho-social benefits including relaxation, stress relief, and reduction in negative emotions (Floyd et al. 2006). Fishing, especially in urban areas, also can contribute to reductions in substance abuse among youth (i.e., "hooked on fishing, not on drugs" programs that introduce youth to fishing as an alternative to destructive activities) and help to address the concept of nature deficit disorder (Louv 2008) where adults and children have become disconnected with the natural world. Although these benefits are difficult to quantify, they contribute to the health and well-being in urban areas.

Knowledge transfer and capacity building

Inland fisheries take place in many of the 5 000 000 km^2 of inland lakes and impoundments and 662 000 km^2 of rivers across the globe (Verpoorter et al. 2014), often transecting political boundaries. While TEK relates to knowledge transfer within one culture, knowledge transfer and capacity building can also cross cultures and political jurisdictions. The value of inland fisheries has led to conflict between jurisdictions over access, control, and harvest in modern times (e.g., Salayo et al. 2006). But, as the world becomes increasingly connected, opportunities for jurisdictions to cooperate are expanding and inland fisheries provide a number of examples of how shared management and transfer of knowledge of scientific or management practices can lead to more sustainable practices.

Though not the norm (see FAO 2007), instances of cooperation and knowledge transfer between political jurisdictions can be found across the globe. The Great Lakes Fishery Commission (www.glfc.org), for example, was created in 1955 when Canada and the United States agreed to coordinate research that would "permit the maximum sustained productivity" of fish stocks and implement a program to control invasive sea lamprey (*Petromyzon marinus*). In Africa, the Lake Victoria Fisheries Organization (www.lvfo.org) was created in 1994 to facilitate sustainable harvests for the nations bordering Lake Victoria: Kenya, Tanzania, and Uganda. In Asia, Cambodia, Lao PDR, Thailand, and Vietnam became full signatories (China and Myanmar are "dialogue partners") to the Mekong River Commission (www.mrcmekong.org/) in 1995, pledging to focus on the sustainable development and management of natural resources, such as fisheries. In Europe, the International Commission for the Protection of the Danube River (www.icpdr.org/) was created in 1998, and 14 of the 19 countries within the basin are cooperating to ensure "the sustainable and equitable use of waters."

Knowledge transfer and cooperation can also occur between distant ecosystems experiencing common challenges (i.e., telecoupling; Liu et al. 2013). Scientists and managers from the African and Laurentian Great Lakes have been transferring knowledge and sharing management successes over the past several decades (e.g., UNU-INWEH 2011). Furthermore, organizations such as FAO and many international development agencies, seek to transfer knowledge of aquaculture "best practices" that can reduce the possible negative effects of aquaculture (e.g., contaminants in fish tissue, poor water quality, impacts on wild fish) to developing countries (Hasan and New 2013). Although the nature of inland fisheries provides the potential for conflict across jurisdictions, they have increasingly fostered cooperation and knowledge transfer as people recognize that long-term sustainability of inland fisheries can benefit all.

The environment

Inland fish species are present in almost every inland ecosystem on earth (Dudgeon et al. 2006). These inland fishes also serve as indicators of ecosystem function and ecosystem change (Allan 2004). Additionally, because of the low environmental impact of many inland capture fisheries and aquaculture operations, they can be recognized as relevant to the "green food" movement.

Ecosystem function and biodiversity

Fish occupy almost all major aquatic habitats (Helfman et al. 2009). Inland fish can play critical roles in the function of their ecosystems (Holmlund and Hammer 1999; Dudgeon et al. 2006). For example, predatory species, such as northern pike (*Esox lucius*) have significant impacts on fish community composition (He and Kitchell 1990). Other fish species have been shown to alter the habitats in which they live, from herbivorous grass carp (*Ctenopharyngodon idella*) modifying aquatic vegetation (Wittmann et al. 2014) to flannelmouth characin (*Prochilodus mariae*) influencing sedimentation rates in Andean streams (Flecker 1997).

Fish impacts on habitat are not limited to the local scale; migratory fishes such as Pacific salmon (*Oncorhynchus* spp.), alewife (*Alosa pseudoharengus*), and *Semaprochilodus* spp. transport energy and nutrients to support distant aquatic and terrestrial food webs (e.g., Wipfli and Baxter 2010). When functioning properly, inland ecosystems provide many valuable services to people (i.e., provisioning, regulating, supporting, and cultural services; e.g., detoxification of wastes, management of infectious diseases; Holmlund and Hammer 1999; Hassan et al. 2005).

Inland fishes account for approximately 40% of all fish species and 20% of all vertebrate species (Helfman et al. 2009). Biodiversity of inland fishes, at both species and population levels, also confers important benefits. When people rely upon functioning ecosystems for their basic needs, natural disasters and other disturbances to those ecosystems can be devastating. Natural ecosystems that recover quickly from such disturbances have resilience. Ecosystems with high species richness exhibit increased resilience (Downing and Leibold 2010), highlighting the importance of diverse inland fish communities.

However, species assemblages are not the only factor moderating the impacts of disturbance on fish populations. A diversity of biologically relevant characteristics among fish populations of the same species (e.g., alternate life histories) also has been shown to improve resilience to perturbations (Schindler et al. 2010). Kovach et al. (2015), for instance, found temporal patterns in migration timing for Pacific salmon species in southeast Alaska. These diverse, resilient inland ecosystems provide reliable sources of food when disasters occur and will become even more critical when amplified by climate change.

Biodiversity confers benefits to aquaculture as well. Genetic diversity within species provides the building blocks for selective breeding and stock improvement, and enables the creation of transgenic fishes, such as genetically modified Atlantic salmon (*Salmo salar*) that grow more quickly and require less food than non-modified fish (Gjedrem 2000). Technological advances, such as transgenic fishes, require a portfolio of genes that exist in the wild, placing value on biodiversity for the future of inland aquaculture. And, increasingly, technology can be used to safeguard biodiversity from escaped aquaculture fish (e.g., sterile triploids).

Aquatic "canaries"

The central role of inland fish in aquatic ecosystems makes them good indicators of ecosystem change. Like the proverbial "canary in the coal-mine," inland fish are used as warnings for current and impending impacts on human well-being from environmental change. Beyond overfishing, aquatic ecosystems are faced with both direct and indirect anthropogenic influences that may have undesirable consequences. Threats from eutrophication, flow modification, destruction or degradation of habitat, and invasion by exotic species place 65% of freshwater habitats at risk (Dudgeon et al. 2006; Vörösmarty et al. 2010). The large scope of these threats arises because inland aquatic habitats are in close proximity to a variety of anthropogenic activities (e.g., agriculture, deforestation, hydropower) and because aquatic habitats integrate environmental influences throughout a watershed (Allan 2004).

Fish respond directly to some environmental stressors such as toxic and thermal pollution, flow regime change, and climate change (Dudgeon et al. 2006). Fish also respond indirectly to stressors that impact their environment. For example, the massive die-offs of introduced alewives in Lake Michigan during the 1960s brought to public and political attention large ecological changes occurring in the Laurentian Great Lakes. Around the globe, inland fish populations and species assemblages often indicate changes in nutrient inputs to their watersheds (Ludsin et al. 2001).

Inland fishes respond to many aquatic and terrestrial environmental changes throughout their watersheds, making them valuable bioindicators of ecosystem health. The Index of Biotic Integrity (IBI) is a commonly used in-situ assessment tool for freshwaters based in part on the local fish assemblages, particularly the presence or absence of species intolerant to habitat perturbations (Karr 1981). Due to their representative susceptibility to many chemicals and key role in aquatic ecosystems, inland fish species are also commonly used as laboratory models to assess water quality and environmental toxicology in the chemical and pesticide approval processes (Barbour et al. 1999).

"Green food"

When sustainably harvested or farmed, inland fish can be considered part of the "green food" movement for more environmentally friendly sourcing of food. Sustainable harvest of wild inland fish can have relatively few environmental costs, especially when compared with replacement livestock products (Orr et al. 2012). The local nature of most of inland capture fisheries (both harvest and consumption) indicates low dependence on fossil fuels for gear manufacture, transportation to and from fishing sites, and preservation and post-harvest fish transportation (Welcomme et al. 2010) compared with many other sources of food.

Sustainable aquaculture, of both herbivorous and omnivorous species, also has a more efficient food conversion ratio (<2 kg of dry feed per 1 kg of gain) than poultry (2-to-1), pigs (4-to-1), and cows (7-to-1) (Brown 2002). It is also important to note that inland aquaculture species are predominately lower trophic level than marine aquaculture species, relying upon more sustainably sourced feed (e.g., algae, not wild caught fish). More broadly, sustainable inland aquaculture can be featured in integrated food systems such as rice field-fish culture which, in China alone, produces almost one million tonnes of fish and almost 10 million tonnes of rice with more environmentally friendly management practices (Weimin 2010).

However, not all inland capture fisheries and aquaculture operations have minimal environmental impacts or sustainable management. There are numerous examples of overfishing of inland fish populations (Allan et al. 2005) and instances of unwanted bycatch (e.g., MacMillan and Roth 2012; Stoot et al. 2013). Likewise, some negligent inland aquaculture practices can have significant impacts on the environment, such as nutrient loading, release of cultured species, and propagation of disease (Kapuscinski and Brister 2000). As the most cultivated species group, for example, carps have a long history of environmental impact: invasions and alteration of native aquatic communities that create challenges for fisheries managers across the globe (e.g., Rasmussen et al. 2011). Concerns notwithstanding, inland capture fisheries and inland aquaculture have low environmental costs compared with many alternative animal-derived food sources.

Summary and moving forward

Inland fish serve as a major source of protein, essential fats, and micronutrients for hundreds of millions of people, particularly in rural communities (Thilsted et al. 1997; Roos et al. 2007; Youn et al. 2014). More than 60 million people in low income countries rely upon inland fisheries as a source of livelihood and women represent over half the individuals in inland fisheries supply chains (FAO 2014*b*). While still a large number, this is widely accepted to be an underestimate given the difficulties with reporting in the sector (Bartley et al. 2015). Inland fish and fisheries provide cultural and recreational services and contributions to human health and well-being. They empower those involved in the sector, contribute to the "green food" movement, and provide a means for knowledge transfer and capacity building across political jurisdictions. As key components of most inland ecosystems on earth, inland fish are integral to ecosystem function and biodiversity. In this role, they also serve as environmental indicators for global change.

Inland fish and fisheries are, however, often impacted by and compete with other societal needs and uses of water resources, such as agriculture, human consumption, power generation, and effluent disposal. Inland fish biodiversity, which is important to ecosystem function and services, is threatened by these pressures and many more (e.g., habitat degradation, water pollution, species invasion, flow modification, and overexploitation), making inland fishes one of the most endangered groups of species in the world (Dudgeon et al. 2006). These threats to biodiversity also threaten the services that inland fishes and fisheries sustain.

Moving forward, acknowledging the complexities inherent in the relationship between inland fish, inland fisheries, and other water resource users will be crucial. The social, economic, and environmental risks to inland fish are often inextricably linked to benefits derived from other water uses. However, due to limitations in assessment, services provided by inland fish and fisheries are undervalued and, consequently, lose in comparisons with other water sectors. Appropriate valuations are needed for relevant comparisons. While this is beyond the scope of this review, ultimately, there is a need for valuation models to recognize the full breadth of services provided on a common platform. We suggest that acknowledging the value of inland fish and fisheries is the first step in effectively balancing the benefits of these services with supporting sustainable water use. We propose this list (Table 1; Fig. 2) as a starting point to raise the profile of inland fish and fisheries to better incorporate them in agricultural, land-use, and water resource planning.

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