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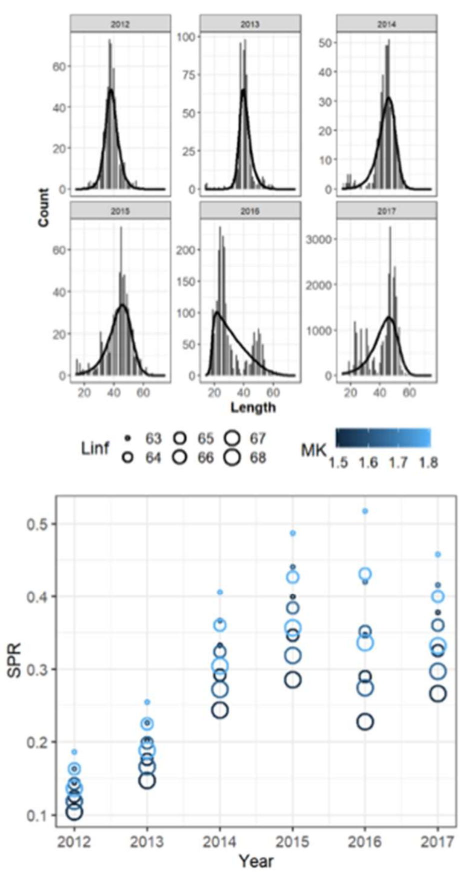

Cover image: Composite graphics from this issue, photograph showing sábalo fisheries in the Paraná River. © FAO/Claudio Baigún.

SIZE-BASED ASSESSMENT OF DATA-LIMITED INLAND FISH STOCKS – REVIEW AND APPLICATIONS

Samuel Shephard
Senior Research Officer
Inland Fisheries Ireland
Dublin, Ireland

John Valbo-Jorgensen
Fishery Resources Officer
FAO Fisheries Division, Rome, Italy

Jorge Abadía
Biologist
Dirección General de Investigación y Desarrollo
Autoridad de Recursos Acuáticos de Panamá, Panama City, Panama

Claudio Baigún
Principal Investigator
CONICET-Universidad Nacional de General San Martín, Buenos Aires, Argentina

Carolina R. C. Doria
Laboratory Coordinator
Universidade Federal de Rondônia, Porto Velho, Rondônia, Brazil

Nidia N. Fabré
Principal Investigator
Universidade Federal de Alagoas, Maceió, Alagoas, Brazil

Victoria J. Isaac
Full Professor
Universidade Federal do Pará, Belém, Pará, Brazil

Ngor Peng Bun
Fish Community Ecologist
Inland Fisheries Research and Development Institute
Fisheries Administration, Phnom Penh, Cambodia

Mauro L. Ruffino
Interim Coordinator
Permanent Secretariat, Amazon Cooperation Treaty Organization, Brasilia, Federal District, Brazil

Simon J. Funge-Smith
Senior Fishery Resources Officer
FAO Fisheries Divison, Rome, Italy

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PREPARATION OF THIS DOCUMENT

The preparation of this circular was funded by FAO's regular programme. In 2016, the Thirty-second Session of the Committee on Fisheries (COFI) *inter alia* recommended "the development of an effective methodology to monitor and assess the status of inland fisheries ... to support their management". COFI requested that FAO develop such an assessment methodology. This was echoed by the first Advisory Roundtable on the Assessment of Inland Fisheries, which FAO organized in 2018 in partnership with the United States Geological Service and Michigan State University to provide guidance on possible ways to proceed with the assessment of inland fisheries. The roundtable highlighted the need for tools to assess the status of inland fisheries that take into consideration the data-poor situation, and the constraints on human and financial resources that characterizes many of the countries most reliant on inland fisheries resources.

Following the advice of the roundtable, a study was initiated to review and test length-based assessment methods that are based on fish life-history parameters and require few types of data that can be obtained with low effort and cost, and that have already been successfully tested on tropical marine small-scale fisheries, but only to a limited extent in freshwater fisheries. This should be considered a first step towards developing indicators that are intuitive and easily understood by different stakeholders, and can inform the managers about the performance of the management plan developed under an ecosystem approach to fisheries management, which is the tool that FAO is promoting as the most appropriate for the management of inland fisheries,

The literature review and data analysis were performed by Samuel Shephard, Inland Fisheries Ireland Dublin, Ireland. The following researchers and their institutions provided data for analysis, participated in the interpretation of the results, and wrote an introduction for each case study:

- Nile tilapia, Lago Bayano, Panama: Jorge Abadía, Dirección General de Investigación y Desarrollo, Autoridad de Recursos Acuáticos de Panamá, Panama City, Panama.
- Sábalo, Paraná Basin, Argentina: Claudio Baigún, Instituto de Investigación e Ingeniería Ambiental, CONICET-Universidad Nacional de General San Martín, Buenos Aires, Argentina.
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- Dai fishery, Tonlé Sap River: Ngor Peng Bun, Inland Fisheries Research and Development Institute, Fisheries Administration, Phnom Penh, Cambodia.

The outcomes of the work were presented to a panel of international experts in 2019 at a second roundtable for constructive feedback and identification of the limitations.

John Valbo-Jorgensen, Simon Funge-Smith and Valérie Schneider, FAO, coordinated the work, and edited and formatted the document.

ABSTRACT

Assessment of data-limited fish stocks is a rapidly evolving topic in marine fisheries, and is supported by an increasing focus on the socio-economic and ecological importance of small-scale fisheries. The challenges in such systems can be compounded in inland fisheries, which are often complex, spatially dispersed and difficult to monitor. This publication reviews the application of empirical indicators and simple size-based models usually used in marine fisheries, but also applicable in inland systems. It presents case study applications for important fisheries in the Amazon River (Brazil), Tonlé Sap River (Cambodia), Paraná River (Argentina) and Lago Bayano (Panama). These studies consider issues including spatial separation of life-history stages, strong modality in population size structure, and fishing gear selectivity. Local scientific experts interpreted trends in stock state. Empirical indicators showed strong decline in size structure and relative abundance for one of the four assessed Tonlé Sap stocks. The length-based spawning potential ratio model suggested that two of the three assessed Amazon Goliath catfish stocks, and the sábalo stock in the Paraná River, were below sustainable spawning potential ratio reference points. The Lago Bayano tilapia stock appeared healthy. The review concludes that data-limited assessment methods developed for marine stocks may provide guidance for the sustainable management of important target species in inland fisheries. The methods tested are probably less applicable in non-selective fisheries where small species are preferred, or in river fisheries with extreme dependence on flood pulses. Important considerations are species life history and spatial distribution, environmental variability, and fishery sampling strategy.

CONTENTS

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Ian G. Cowx and Rachel Ainsworth, Hull International Fisheries Institute, School of Environmental Sciences, University of Hull, United Kingdom of Great Britain and Northern Ireland; William Taylor and Devin M. Bartley, Department of Fisheries and Wildlife, Michigan State University, United States of America; T. Douglas Beard, Jr, and Abigail Lynch, National Climate Change and Wildlife Science Center, United States Geological Survey, United States of America; Michael Cooperman, Omega Advisors, New York, United States of America; Jeppe Kolding, Department of Biological Sciences, University of Bergen, Norway; David Lymer, Sötvattenslaboratoriet, Sweden; Alexis Peña, Dirección General de Investigación y Desarrollo, Autoridad de Recursos Acuáticos de Panamá, Panama; Gretchen Stokes, National Science Foundation Graduate Research Fellow School of Natural Resources and Environment, University of Florida, United States of America; Paul van Zwieten, Aquaculture and Fisheries Group, Wageningen University, Netherlands; Derek Vollmer, Betty and Gordon Moore Center for Science, Conservation International, United States of America; Olaf Weyl, DST/NRF Research Chair in Inland Fisheries and Freshwater Ecology, South African Institute for Aquatic Biodiversity, South Africa; and the following FAO Fisheries and Aquaculture Department staff members: Felix Marttin, Cherif Touelib, Nicolas Gutierrez and Rishi Sharma.

ABBREVIATIONS AND ACRONYMS

BOFFFF	big old fat fecund female fish
CPUE	catch per unit of effort
EAFm	ecosystem approach to fisheries management.
F	fishing mortality
F/M	relative fishing mortality
GTG LB-SPR	length-structured version of the LB-SPR model that uses growth-type groups (GTG) to account for size-based selectivity
HCR	Harvest control rule.
K	growth coefficient (expresses the rate at which the asymptotic length [L_∞] is approached)
L_∞/L_{inf}	asymptotic body length (the length that the fish of a population would reach if they were to grow indefinitely)
L_c	length at first capture
$L_{F=M}$	length-based proxy for MSY where $L_{F=M} = 0.75L_c + 0.25\ L_\infty$
L_{mat}	length of a species at maturity in a population
$L_{mat50\%}$	size at which 50 percent of the population of a given species becomes sexually mature
$L_{mat95\%}$	size at which 95 percent of the population of a given species becomes sexually mature
L_{max}	maximum length of a given species in a population
$L_{max5\%}$	mean length of largest 5 percent of the individuals of a species in a population
L_{mean}	mean length of individuals larger than the length at first capture (L_c)
L_{opt}	length that maximizes fishery yield (= 2/3 L_∞)
LB-SPR	length-based spawning potential ratio (approach that compares the observed length composition of a fishery catch and the theoretical length distribution of the stock in an unfished state and calculates the spawning potential ratio)
LBI	length-based indicator
LEK	local ecological knowledge
LFI	large fish indicator
M	natural mortality (M = Z - F).
M/K	ratio of natural mortality to growth rate
MP	management procedure
MSE	management strategy evaluation
MSFD	European Union Marine Strategy Framework Directive.
MSY	maximum sustainable yield
P_{mat}	proportion of fish in the catch that are larger than L_{mat}
P_{mega}	proportion of fish larger than L_{opt} + 10 percent

P_{obj}	composite indicator of population size structure ($P_{obj} = P_{mat} + P_{opt} + P_{mega}$)
P_{opt}	proportion of fish larger than L_{opt}
RP	reference point
SL	standard length (i.e. length of the fish excluding the caudal fin)
SPR	spawning potential ratio (the proportion of unfished reproductive potential left at any given level of fishing pressure)
SSB	spawning stock biomass
TL	total length (i.e. length from the most anterior to the most posterior part of the fish)

1. INTRODUCTION

Constraints on fisheries survey infrastructure (Costello *et al.*, 2012) or time (Bentley, 2015) mean that many fish stocks remain “data-limited”. According to FAO, slightly more than 10 percent of the world’s commercially fished marine fish stocks are assessed (FAO, 2010), and unassessed stocks may be in a generally worse state (Costello *et al.*, 2012). Many stocks supporting small-scale and subsistence coastal or inland fisheries are unassessed. Inland fisheries are extremely important to numerous rural communities (Smith, Khoa and Lorenzen, 2005; Lynch *et al.*, 2016), and make a critical dietary contribution in low food-security regions (Kawarazuka and Béné, 2010; McIntyre, Liermann and Revenga, 2016). However, despite their socio-economic relevance, inland fisheries are often poorly monitored, resulting in unreliable catch estimates, which limit understanding of the status of fished stocks (Welcomme *et al.*, 2010; Beard *et al.*, 2011; Bartley *et al.*, 2015; Fluet-Chouinard, Funge-Smith and McIntyre, 2018). There is now an imperative to develop and apply appropriate methods for the assessment of data-limited inland fish stocks (Cooke *et al.*, 2016).

There is much to be gained by sharing ideas between marine and inland fisheries systems (Cooke *et al.*, 2014), and also between commercial and recreational fisheries (Cooke and Cowx, 2006). Data-limited stock assessment methods are well developed in the marine environment, but many inland fisheries scientists and managers are unaware of their availability and potential (Lorenzen *et al.*, 2016). Management using reference points is correspondingly much less prevalent in inland fisheries (Welcomme, 2001). The science of small-scale fisheries encompasses inland waters, but addressing the complex, persistent or reoccurring (Khan and Neis, 2010) problems of these highly complex social-ecological systems will require a broadening of perspectives that cuts across academic disciplines (Jentoft and Chuenpagdee, 2019).

The desirable outcome of biologically sustainable fisheries depends on maintaining spawning stock biomass (SSB) and preventing significant truncation of age structure (Hsieh *et al.*, 2006). Size-selective fishing pressure typically depletes a population and simultaneously curtails the upper end of the size distribution. In situations of limited data, empirical (“model-free”) indicators can capture trends in both components: abundance indices (e.g. catch per unit of effort [CPUE]), and demography (McDonald *et al.*, 2017). Such indicators are not typically data- or expertise-hungry (Geromont and Butterworth, 2015) and can be derived for important stocks in many data-poor fisheries (Chrysafi and Kuparinen, 2016). Depending on data availability, they can provide anything from a robust state assessment down to “a rough indication of the state of a fishery” (Lorenzen *et al.*, 2016). These characteristics suggest that simple empirical indicators offer a tractable starting point for assessment of important single stocks within assemblages supporting very data-poor inland fisheries.

Empirical indicators are frequently used for single species and stocks, but have also been incorporated into broader frameworks to support an ecosystem approach to fisheries management (EAFm). Indicators that are close to raw observational data and require limited permutations and few assumptions were selected as preferable for an EAFm on Lake Malawi (van Zwieten, Banda and Kolding, 2011). A well-developed marine example is the European Union’s Marine Strategy Framework Directive (MSFD), which has implemented a broad suite of ecological indicators to monitor the state of the marine environment across the whole of the Northeast Atlantic. The MSFD identifies “population age and size distributions” as indicators of the health of a stock (Probst, Kloppmann and Kraus, 2013), and applies the large fish indicator (LFI; Greenstreet *et al.*, 2010; Shephard, Reid and Greenstreet, 2011) as an indicator of community size distribution. The LFI captures the proportion of “large” fish in the assemblage, and thus reflects both size-selective fishing and recruitment of small fish/species. Community-level indicators are probably the only realistic option where many species are harvested together and their management cannot be separated, e.g. in inherently multispecies tropical fisheries (Kolding and van Zwieten, 2014; Lorenzen *et al.*, 2016).

Ecological indicators (e.g. of fish population or community state) can be used “operationally”, having well-understood pressure–state relationships and objective management reference points (RPs). Model-free management procedures (MPs) using empirical indicators have the potential to be effective as the basis for decision-making in data-limited fisheries (Dowling *et al.*, 2015; McDonald *et al.*, 2017) and may be a good starting point for single-species fisheries that may later move towards management using simple models (Babcock *et al.*, 2013; Bentley, 2015). Empirical MPs based on relative abundance or mean length have shown considerable promise by consistently satisfying conservation performance metrics (Geromont and Butterworth, 2015; Sagarese *et al.*, 2018). Alternatively, indicators may take a "surveillance" role in tracking ecological state, providing complementary information (including warning signals) that inform and support science, policy and management (Shephard *et al.*, 2015). Surveillance indicators may be an accessible tool for acquiring basic understanding of the state of currently unassessed fish stocks in diverse inland systems (Shephard *et al.*, 2019a). Users could be co-management groups that need only an approximate impression of state to inform technical measures or "nudges" in fishing behaviour (Mackay *et al.*, 2018), or "barefoot ecologists" (Prince, 2003) working at the local level in complex small-scale systems (Andrew *et al.*, 2007).

Empirical and reference direction approaches should not mask the fact that "there is no substitute for better data" (Dowling *et al.*, 2018). Where applicable, model-based methods can strongly reduce assessment uncertainty in data-limited situations, and potentially have the significant advantage of incorporating management RPs. A promising single-species assessment tool is the length-based spawning potential ratio (LB-SPR) model (Hordyk *et al.*, 2015a, 2015b, 2016). The spawning potential ratio (SPR) is defined as the proportion of unfished reproductive potential left at any given level of fishing pressure (Goodyear, 1993; Walters and Martell, 2004), and is commonly used to set target and limit RPs for fisheries. The unfished length distribution of a fish population can be predicted from the ratio of natural mortality to growth rate (M/K), when the von Bertalanffy asymptotic length (L_∞) is known. Inputs of length at maturity (L_{mat}) then allow unfished spawning potential to be estimated from expected numbers of fish at size (Hordyk *et al.*, 2015b). The LB-SPR approach uses maximum likelihood methods to find the values of relative fishing mortality (F/M) and selectivity-at-length that minimize the difference between the observed length composition of a fishery catch and the expected (predicted) length distribution, and calculates the resulting SPR. The estimated SPR can then serve as an indicator of the status of the stock for management of the fishery. The LB-SPR approach has been applied convincingly to assessment of tropical reef fisheries (Prince *et al*., 2015; Babcock, Tewfik and Burns-Perez, 2018), where fishers have participated in data collection, but has yet to be widely tested in freshwater environments.

There have been several authoritative reviews of data-limited fish stock assessment and management frameworks (e.g. Dowling *et al.*, 2015; Geromont and Butterworth, 2015), but these works typically focus on marine systems. The aim of this review is to provide a brief summary of available empirical indicator frameworks that can be applied at fish-stock and assemblage levels, with the objective of evaluating the potential for application in resource- and capacity-constrained inland fisheries. Size-based indicators are considered because these may be most accessible in tropical multispecies fisheries, where even basic life-history information may be lacking. A simple framework for visual presentation of size-based surveillance metrics is applied; this approach supports elicitation of expert knowledge of stock trends (Shephard *et al.*, 2019a). The LB-SPR approach is then implemented for stocks where input life-history parameters are available. Case study applications are provided for inland fish stocks in Southeast Asia, and Central and South America.

2. EMPIRICAL INDICATORS

Some data-limited fisheries are monitored using landings records and estimates of CPUE. Harvest control rules (HCRs) based on CPUE are used to manage at least 13 marine stocks in Australian scalefish and shark fisheries (Little *et al.*, 2011) as well as rock lobster fisheries (Punt *et al.*, 2012). However, a common problem with catch information is misreporting at various levels, from individual vessels up to national statistics. Bartley *et al.* (2015) discuss the range of issues that affect the reliability of inland fisheries data. In inland systems, CPUE-based assessments have so far been most successful in the recreational fisheries of developed countries, where there is adequate funding and infrastructure to support rigorous data collection and analysis. The context is completely different in developing countries with complex subsistence fisheries, where investment in monitoring is limited and there is little or no understanding of stock status (Bartley *et al.*, 2015). Capacity building in sample design and application is essential to avoid statistical errors (Cowx *et al.*, 2003; De Graaf *et al.*, 2015). In large rivers, for example, even if catch can be assessed at main landing ports, effort is difficult to estimate as fish are collected and landed by intermediaries, and effort data can therefore not be easily computed. In these systems, household surveys (Neiland *et al.*, 2000; Beard *et al.*, 2011; Fluet-Chouinard, Funge-Smith and McIntyre, 2018) have been used to indirectly estimate catch volumes, but are rarely able to give an idea of catch trends or stock status.

Size-based approaches may work better than CPUE in such systems. Fishing is typically size-selective, removing the largest individuals and species. This impact can change the size and trophic structure of individual populations and of the whole fish community, and has been widely observed, including in tropical river fisheries (Fabré *et al.,* 2017; Doria, Lima and Angelini, 2018; Van Damme *et al*., 2019). A large number of ecological indicators have been proposed for the evaluation of fishing-induced change in fish population and community size structure (Rochet and Trenkel, 2003; Shin *et al.*, 2005). These indicators can track fishing pressure even in changing environmental conditions, including climatic variation (Blanchard *et al.*, 2005; Shin *et al.*, 2018). An important advantage of length-based indicators (LBIs) is that they require only a representative length frequency for the sampled stock or assemblage. This information can be derived from fisheries-independent surveys or from catch. Local fishers have participated in some surveys, providing reliable and cheap length-frequency data for assessment (Ticheler, Kolding and Chanda, 1998; Prince *et al.*, 2015; Van Damme *et al*., 2019).

Often, LBIs are combined with information on life-history characteristics, such as L_{mat}, to compare empirical length-structure and size-based fishing rate with theoretical values that could represent RPs. Froese (2004) suggested a "simple" set of three LBIs: P_{mat} (the proportion of fish in the catch that are larger than L_{mat}); P_{opt} (the proportion of fish larger than optimal harvest length [the length that maximizes fishery yield, $L_{opt} = 2/3\ L_{\infty}$]); and P_{mega} (the proportion of fish larger than L_{opt} + 10 percent). However, a simulation study by Cope and Punt (2009) showed that the three Froese (2004) LBIs are not always sufficient to ensure protection from overfishing. They combined the LBIs to provide a new measure that they call P_{obj} ($P_{obj} = P_{mat} + P_{opt} + P_{mega}$) that can distinguish the fishery selection pattern and that informs a decision tree to determine whether SSB is above a target RP. The Froese (2004) indicators have subsequently been extended into a suite of LBIs (Table 1) that have associated RPs for assessment of stock status relative to proxies for maximum sustainable yield (MSY; ICES, 2015), and which support a traffic-light framework (Caddy *et al.*, 2005).

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Table 1

Length-based indicators and maximum sustainable yield proxy reference points suggested by WKLIFE V

Statistic	Calculation	Threshold	Indicator	Current reference point	Property
$L_{max5\%}$	Mean length of largest 5%	L_∞	$L_{max5\%} / L_\infty$	> 0.8	Conservation of large individuals
$L_{95\%}$	Ninety-fifth percentile of length	L_∞	$L_{95\%} / L_\infty$	> 0.8	
P_{mega}	Proportion of individuals above L_{opt} + 10%	0.3–0.4	P_{mega}	> 0.3	
$L_{25\%}$	Twenty-fifth percentile of length distribution	L_{mat}	$L_{25\%} / L_{mat}$	> 0.3	Conservation of immature individuals
L_{mean}	Mean length of individuals larger than L_c	L_{mat}	L_{mean}/L_{mat}	> 1	
L_c	Length at first catch (length at 50% of mode)	L_{mat}	L_c / L_{mat}	> 1	
L_{mean}	Mean length of individuals larger than L_c	$L_{opt} = 2/3L_\infty$	L_{mean} / L_{opt}	≈ 1	Optimal yield
L_{mean}	Mean length of individuals larger than L_c	$L_{F=M}$= ($0.75L_c + 0.25L_\infty$)	$L_{mean}/L_{F=M}$	≥ 1	Maximum sustainable yield

Source: Adapted from ICES, 2015.

The Froese (2004) indicators and Cope and Punt (2009) decision tree have been applied effectively to some important stocks in a number of small-scale reef fisheries in Belize (Babcock *et al.*, 2013; Babcock, Tewfik and Burns-Perez, 2018) and Haiti (Karnauskas *et al.*, 2011). These studies were able to produce informative estimates of fish-stock state, which concurred with estimates from simple model-based assessments (see below).

However, even using the Cope and Punt (2009) approach, it remains difficult to define robust stock-specific RPs. Empirical methods are good at providing insight into the direction of stock status, but cannot provide an objective indication of whether a stock is currently healthy or sustainably fished. The ability to use objective RPs is an advantage of model-based methods (see below).

In inland systems, the ICES (2015) LBIs and the Cope and Punt (2009) decision tree have been applied, as far as this review found, only to assessment of resident (Fitzgerald, Delanty and Shephard, 2018; and Table 2) and migratory (Shephard *et al.*, 2018; 2019a) trout (*Salmo trutta*) stocks.

Table 2

Annual assessments using length-based indicators calculated for an inland fish (*Salmo trutta*) stock

Length-based indicator	$L_{mean}/L_{F=M}$	L_c/L_{mat}	$L_{25\%}/L_{mat}$	L_{mean}/L_{mat}	L_{mean}/L_{opt}	$L_{95\%}/L_{\infty}$	$L_{max5\%}/L_{\infty}$	P_{mega}
Reference point	≥ 1.0	> 1.0	> 0.3	> 1.0	≈ 1.0	> 0.8	> 0.8	> 0.3
1978	1.01	0.70	0.87	1.04	0.78	0.68	0.72	0.02
1994	1.09	0.70	0.87	1.12	0.84	0.83	0.85	0.13
1998	1.15	0.63	0.73	1.12	0.84	0.90	0.96	0.25
2001	1.15	0.70	0.90	1.18	0.88	0.87	0.93	0.24
2005	1.11	0.77	0.93	1.20	0.90	0.85	0.89	0.18
2006	1.13	0.83	0.93	1.27	0.95	0.97	1.01	0.25
2013	1.12	0.70	0.93	1.15	0.86	0.82	1.00	0.16

Notes and sources: The reference points (RPs) for each indicator are from ICES (2015). Green indicates that the LBI value reaches or exceeds the RP in the assessment year (adapted from Fitzgerald, Delanty and Shephard, 2018).

In the latter case, it was found that the RPs proposed by ICES (2015) should be adjusted for sea trout and perhaps other diadromous fish in order to account for differences in life history, such as survival to old age, which shape resilience to fishing. This study did not consider how indicators might be combined, e.g. "one out, all out", to produce an overall evaluation of state, which complicates reaching decisions on the state of a stock.

Length-based indicators have also been applied to assessment of lamprey stocks sampled as juveniles (Shephard *et al.*, 2019b), and this concept may have some application in inland fisheries targeting juvenile potamodromous fishes. Size-based indicators have been combined with CPUE to support a model-free fisheries assessment framework (McDonald *et al.*, 2017). Harvest control rules based on RPs for mean length in the catch can achieve certain management objectives (Klaer, Wayte and Fay, 2012; Jardim, Azevedo and Brites, 2015), although accounting for uncertainty in length at age is important, and the HCRs may not be effective for stocks, or assemblages (see below), fished well before size at maturity.

At the community and ecosystem level, size-based metrics show relatively consistent responses to selective fisheries, and "unfished" indicator RPs may be predicted (Rochet and Trenkel, 2003; Jennings and Dulvy, 2005). Selection and application of size-based indicators (Rochet and Rice, 2005; Shin *et al.*, 2005) have been advanced by the ongoing IndiSeas Working Group (e.g. Shin *et al.*, 2010). Size-based indicators for ecological monitoring have been implemented at a large scale under the European Union's MSFD. The most developed example is the LFI, which is listed under MSFD Descriptor 4 Food Webs. The LFI describes the proportion of large fish in the community (Greenstreet *et al.*, 2010), mainly reflecting change in abundance of large species rather than large individuals within species (Shephard *et al.*, 2012). The LFI can be interpreted for different communities (Shephard, Reid and Greenstreet, 2011) and can robustly track fishing pressure in size-selective fisheries (Halouani *et al.*, 2019). Such an approach has been proposed to assess the health of inland fisheries based on the capture of large migratory species (Baigún, 2015).

A contrasting situation can be evident in multispecies fisheries using non-selective gear, e.g. in the African Great Lakes. In this case, there is no obvious curtailment of length structure, and the fishery approximates to balanced harvesting (Kolding and van Zwieten, 2014; Kolding *et al.*, 2016). In these systems, small fish can be preferred by consumers, and so fishery activity may occur rather evenly across the fish-community size spectrum. This pattern of fishing does not curtail the size distribution, but rather maintains the size-spectrum slope while diminishing overall biomass. Size-based indicators will not capture fishing impacts at the species or assemblage level in these situations. A similar case may be found in floodplain fisheries where the juveniles of annually recruiting species are caught by non-selective traps as the annual flood pulse contracts back into the main river channel.

In inland systems, Welcomme (1999) reviewed the use of assemblage-level LBIs for monitoring tropical floodplain river fish communities, where fisheries can still be size- and species-selective (Hallwass and Silvano, 2016; Doria, Lima, and Angelini*,* 2018). Length-based indicators were included in a diverse suite of indicators evaluated for an EAFm framework in Lakes Malawi and Malombe, where strong temporal shifts from larger to smaller species have been observed (van Zwieten, Banda and Kolding, 2011). Mean length of fish declined across species with successive de-watering events (deliberate draining of small ponds and swamps for irrigation and/or fish harvesting) in wetlands of the lower Mekong River (Martin *et al.*, 2011). A set of empirical indicators was shown to capture fishing-induced changes in the fish community of the Tonlé Sap (Ngor *et al.*, 2018). The Tonlé Sap study is of interest because it successfully demonstrates the use of indicators based on size and life history to describe temporal change in relative abundance of large and small fish species in a heavily fished multispecies inland fishery. Changes in mean length in the sábalo fishery were also demonstrated by Baigún, Minotti and Oldani (2013) in the Paraná River in response to increased fishing pressure resulting from a growth in export of fish products. The diminishing stocks of larger fish species (and compensation effects among smaller species) observed in this study are in common with observations from other large inland systems (Welcomme, 1999; García Vásquez *et al.*, 2009), although not in some African artisanal fisheries systems such as Lake Kariba (Kolding and van Zwieten, 2014; Kolding *et al.*, 2016).

3. INDICATORS FROM SIZE-BASED MODELS

A key limitation of size-based indicators is the difficulty involved with defining RPs that can be used to guide management actions. Modelling approaches can address this problem by specifying the population parameters associated with a healthy stock, and comparing observed parameters with this good-state expectation. The size-based LB-SPR model estimates the SPR for a stock (Hordyk *et al.,* 2015a, 2015b). The LB-SPR model has been applied convincingly to assessment of tropical reef fisheries (Prince *et al*., 2015; Babcock, Tewfik and Burns-Perez, 2018), where fishers have participated in data collection.

The case study of Babcock, Tewfik and Burns-Perez (2018) is of particular relevance as it applies a set of empirical indicators and the LB-SPR to a group of valuable species within a fish assemblage that supports small-scale spear and hook-and-line fisheries. Species sample size in Babcock, Tewfik and Burns-Perez (2018) was often small ($\geq$ 60) due to limited data, and the issue of gear selectivity pattern (see below) is discussed. Both empirical and LB-SPR assessments provided similar estimates of stock state that were consistent with expert expectation. This successful implementation for individual species that are commonly caught suggests potential for application in inland systems where length data are available for particularly important species.

The LB-SPR requires inputs of the M/K ratio (natural mortality M / von Bertalanffy growth coefficient K), mean asymptotic length L_∞, and descriptions of size at maturity specified as $L_{mat50\%}$ and $L_{mat95\%}$ (the sizes at which, respectively, 50 percent and 95 percent of the population mature). The model is sensitive to misspecification in these life-history parameters, which can be difficult to estimate for some stocks (Hordyk *et al.*, 2015a). Monte Carlo simulations with random draws of parameters over a range of likely values for each parameter have been suggested as a useful way to capture some of the uncertainty arising from poorly understood biology (Hordyk *et al.*, 2016).

This review did not encounter any applications of LB-SPR to inland fish stocks. This may be partly explained by the model assumption of asymptotic selection, which is characteristic of trawl fisheries. In contrast, most inland fisheries operate gillnet or hook-and-line gear, which typically show dome-shaped selection curves where the smallest and largest fish are not retained. It is expected that LB-SPR will overestimate F/M and underestimate the SPR when confronted with data from a fishery with dome-shaped selectivity, because the "missing" large fish will be assumed to have been caught. Simulation testing showed that the method did indeed underestimate the SPR in some test species (Hordyk *et al.*, 2015a), and this issue was discussed but remained unresolved in Babcock, Tewfik and Burns-Perez (2018). The extended growth-type group (GTG) LB-SPR approach (Hordyk *et al.*, 2016) can incorporate information on selectivity in cases where this has been estimated by gear trials. Recent work has extended the GTG LB-SPR model to include the option of dome-shaped selection (Hommik *et al.*, 2020), for case study assessments of brown trout (*Salmo trutta*) stocks in four Irish lakes. Bayesian Monte Carlo methods were used to include uncertainty around estimates of life-history parameters for each stock. This ongoing example shows that the LB-SPR can be applied to data-limited inland fish stocks sampled by standardized gillnet surveys. Estimates of the SPR (with RPs) could be combined with empirical indicators in visual plots to support expert evaluation of stock state (see above).

4. EXPERT KNOWLEDGE

Quantitative assessment of fish stocks typically includes subjective decisions that can be strongly informed by different forms of expert knowledge (Francis, 2011). The problems and priorities in small-scale fisheries require a broadening of perspectives that cuts across academic disciplines and bridges division between scientific and local knowledge (Jentoft and Chuenpagdee, 2019). Integrating scientific and other knowledge is challenging but productive for environmental management (Raymond *et al.*, 2010; Drescher *et al.*, 2013); it can provide information about model parameters (McDonald *et al.,* 2017) and become the basis for conservation decisions (Martin *et al.*, 2012). Stakeholders targeting a stock can acquire valuable knowledge of the commercial fishing and ecological history and status of the stock (Chrysafi, Cope and Kuparinen, 2017), and expert judgement of ecological state can result in similar classifications to quantitative metrics (Pasquaud *et al.*, 2012; Feio *et al.*, 2016).

Dichmont and Brown (2010) pooled knowledge of scientists, industry and managers in a cooperative environment to implement simple decision rules based on catch rates. McDonald *et al.* (2017) documented the process of implementing a fisheries management system with limited information, from design to application in public policy. They proposed an adaptive system of multiple indicators and RPs with a focus on fishers' participation. In inland fisheries, there are many examples of co-management (see review in Béné and Neiland, 2006). These initiatives imply scope to integrate expert knowledge as a "data-less" (Johannes, 1998) narrative with simple empirical indicators in interpretation of status. However, some co-managed systems would benefit from a systematic framework for using LBIs for decision-making and setting HCRs, especially where a stock is overfished, but not yet critically depleted. This highlights the need for some technical support from fisheries agencies to co-management groups.

It is unlikely that dedicated surveys and associated analytic assessments will become available for diverse data-limited stocks of inland fishes. This is simply because of the resources required. Relying on appropriate indicator trends may be the most efficient and transparent approach, although it must be acknowledged that this can be still demanding and potentially expensive (Dowling *et al.*, 2008).

Parallel use of biological (e.g. size-based) indicators alongside stock abundance (e.g. CPUE) assessments allows for a trajectory from single-species assessments towards a future indicator-based EAFm that can inform co-management processes (Cotter *et al.*, 2009). A comprehensive set of environmental, CPUE and size-based indicators were selected by van Zwieten, Banda and Kolding (2011) to assess the fisheries of Lake Malawi, where there is ongoing work to apply an ecosystem approach (Njaya, 2018). Using only length-based HCRs may not be sufficient to recover depleted stocks, but combining mean length with CPUE can succeed in recovering an overfished stock (Miethe and Dobby, 2018; ICES, 2018).

Accessible model-free assessment frameworks can combine size-based indicators with CPUE and local ecological knowledge (LEK) of trends over time to support appropriate HCRs (including spatial management) and achieve specified social, ecological and economic objectives (Dowling *et al.*, 2008; McDonald *et al.*, 2017; 2018; Shephard *et al.*, 2019a).

It is important that any data-limited method should not be applied as a low-risk or technically trivial exercise, and the process, uncertainties and outcomes must be critically confronted (Dowling *et al.*, 2018). This goal will be facilitated in developing inland fisheries if the selected indicators are intuitive and can be understood by different stakeholders, potentially including those responsible for data collection and local fishers who may have to implement, or comply with, associated simple HCRs. Simple and sensitive empirical indicators were preferred in the Malawi case study (van Zwieten, Banda and Kolding, 2011). Degnbol (2001) listed certain desirable properties for sustainability indicators, which are adapted and listed in Table 3.

Empirical indicators of CPUE and size structure can fulfil most of these requirements, as they are conceptually simple and are likely to reflect fisher's understanding that commercially fished stocks and assemblages will probably show reduced abundance and loss of larger individuals and species. It is important that indicators be presented in a way that is intuitive and visually appealing, and that clearly shows positive or negative changes in state.

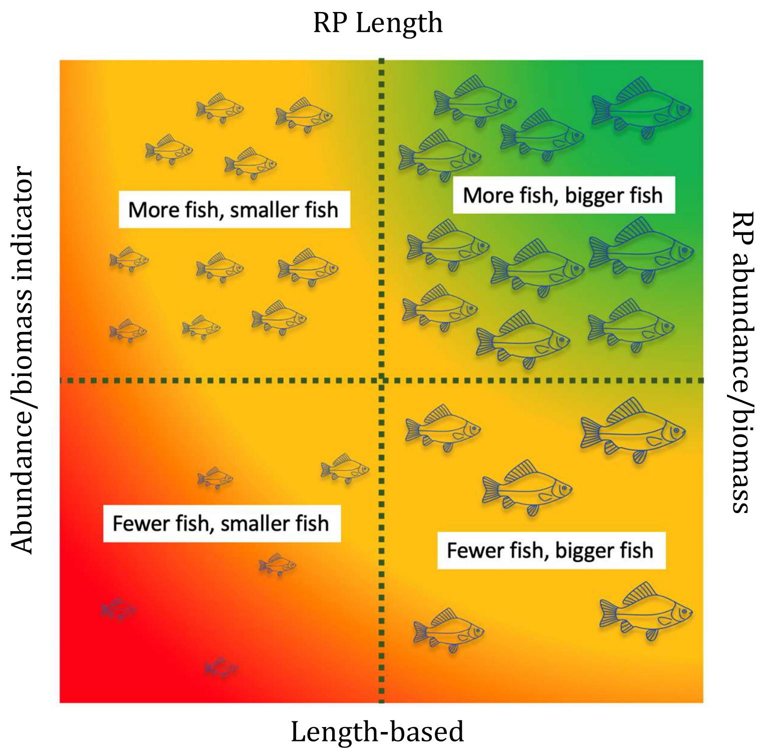
Table 3

Desirable properties for sustainability indicators (after Degnbol, 2001)

Property	**Description**
Observable	Within affordable/sustainable economic resources for research
Self-evident	To all stakeholders – either directly or by transparency in the observation process
Understandable	They should have a research-based substance, and reflect analytical soundness They should reflect features according to stakeholders' understanding of the resource system
Acceptable	By fishers By the public at large
Related to management	They should indicate a direction of action – qualitatively or through associated reference points (RPs) They should respond to management measures

This review implemented a recent format for plotting pairs of CPUE and size-based indicators to illustrate trends towards or away from expected better or poorer state (Figure 1a; Shephard *et al.*, 2019a).

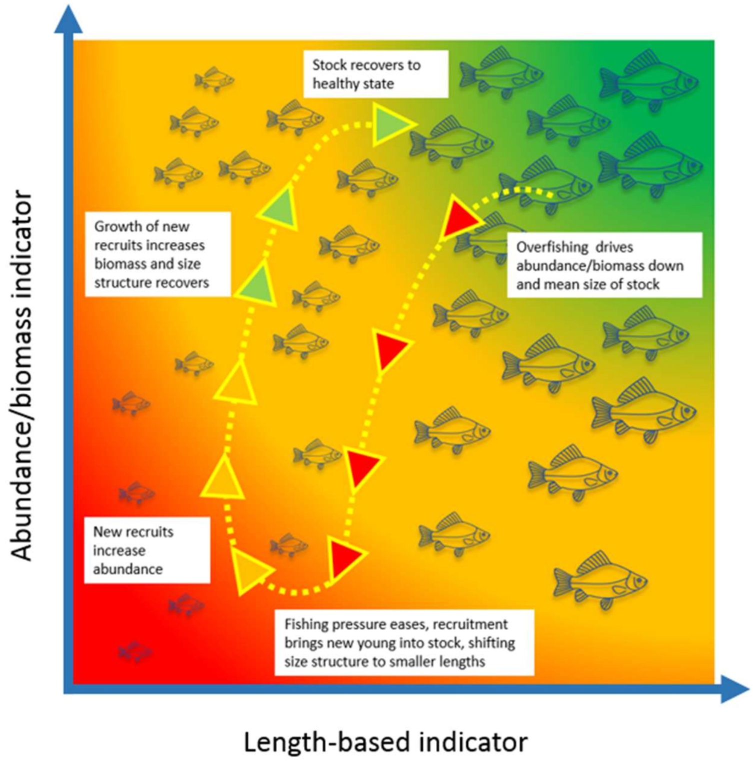
Figure 1a Presenting surveillance indicators for data-limited inland fish stocks



Notes: The x-axis is an appropriate length-based indicator, and the y-axis is an associated CPUE indicator. Coloured regions refer to poor (red), moderate (amber) and good (green) states. The dashed thresholds are potential management reference points (RPs) that may be defined by expert knowledge, although a reference direction approach is simpler.

Figure 1b

Conceptual trajectory for length and biomass/abundance indicators following overfishing and subsequent recovery



The plot in Figure 1a supports evaluation of well-understood reference directions (Rochet and Trenkel, 2003; Jennings and Dulvy, 2005), which may be sufficient for some individual target stocks and also for assemblages targeted by species- and/or size-selective fisheries. Indicator trends could be related to the starting condition and to the history of the stock, as understood from expert narrative (Canales, Hurtado and Techeira, 2018) and LEK. Stocks that were impacted before the available time series might be expected to show movement in a positive direction, while stocks that started in good state should not move in a negative direction (Rochet *et al.*, 2005). It is possible to anticipate likely trajectories as fishing mortality curtails abundance and size structure, followed by possible recovery following management (Figure 1b).

Relying on reference direction rather than RPs allows some constraints to be relaxed, although indicator direction and response time may be influenced by the life-history stage that is sampled for a given stock. This empirical and reference approach should not mask data limitations, or the reality that model-based methods can strongly reduce assessment uncertainty. However, the proposed plots are flexible because they present information simply, and this could extend to more robust model outputs such as size-based fishery indicators, e.g. the SPR from the LB-SPR (Hordyk *et al.*, 2015a). An appropriate combination of empirical and modelled indicators would be informative as additional data become available (Babcock, Tewfik and Burns-Perez, 2018).

New assessment approaches should be explicitly structured to accommodate and employ expert information (Kuhnert, Martin and Griffiths, 2010). The contribution of expert knowledge may be particularly important with a reference direction approach, both to understand the likely starting condition of a fishery and also to interpret apparent patterns in the quantitative stock history (Fazey *et al.*, 2006; Stratoudakis *et al.*, 2015). Experts can make reasonable prior predictions about fish stock status, although some bias should be anticipated (Chrysafi, Cope and Kuparinen, 2017). The value of fishers' knowledge is now well established, and has the capacity to reject or challenge implausible results of assessment models (Duplisea, 2018). Notably, there is high value in additional information regarding historical stock depletion or fishing effort (Carruthers *et al.*, 2014); where such information is available in an unprocessed state, it should also be leveraged.

5. HYDROECOLOGICAL PRESSURES

Considering stakeholder engagement in management objectives and broader sustainability goals, a final issue is that inland fisheries systems differ in a fundamental aspect to most marine small-scale fisheries. There are frequently higher-level issues, such as hydropower dam building, disconnection, flow alteration and pollution, that contribute to multiple interacting anthropogenic pressures (Beard *et al.*, 2011). Most of these issues are mediated through flow, which represents the main driver of biotic and abiotic conditions in large river systems (Naiman *et al.*, 2008). Fish abundance and assemblage structure change with the seasonal flood cycle (Winemiller and Jepsen, 1998; Arrington, Winemiller and Layman, 2005; Arrington and Winemiller, 2006). Hydrology and related variables associated with flood pulses thus strongly influence fisheries performance (Halls and Welcomme, 2004; Castello, Isaac and Thapa, 2015; Rabuffetti *et al.*, 2016). Welcomme (1985) and MRAG (1993) demonstrated strong global-scale relationships between flooded area and catch for large floodplain rivers. However, catch responses to flood pulses could be species-specific (Lima, Kaplan and Doria, 2017). Flood pulses may represent the main force governing fish recruitment and cohort strength in large floodplain rivers, particularly for periodic species (Winemiller and Rose, 1992). In the Paraná River, there is a strong relationship between high flood events and the recruitment of migratory species (Gomes and Agostinho, 1997; Bailly, Agostinho and Suzuki, 2008; Suzuki *et al.*, 2009; Oliveira *et al.*, 2015; Lozano *et al.*, 2019). Baran, Van Zalinge and Ngor (2001) demonstrated that fish production was closely related to the flood levels in the Mekong River Basin, and particularly in the Tonlé Sap system.

Hydroecological indices can be derived from river attributes such as flow. Baigún, Minotti and Oldani (2013) developed two habitat hydrological indices (the Channel Connectivity Index and the Floodplain Connectivity Index) as proxies of nursery habitat accessibility and permanence during the sábalo larval growth period. Such approaches take advantage of hydrological attributes (Welcomme, 1985; Neiff and Neiff, 2003), and can be used to predict performance in data-limited fisheries. From the perspective of size-based indicators, fish community modelling studies could help anticipate likely trajectories of population size structure under certain pressure scenarios, e.g. impaired recruitment due to loss of floodplain spawning habitat. Length-based indicators might then become useful in understanding the impact of fisheries versus other pressures.

At present, fishery effects on size structure have an extensive theoretical basis, but effects of hydrological pressures are much less understood. Even so, the importance of hydrological processes for large river fisheries production highlights the diverse potential pressures imposed on inland fisheries. The complex environment requires that inland systems be managed at a social-ecological watershed scale using ecosystem approaches to ensure long-term sustainable and resilient fisheries (Nguyen *et al.*, 2016). Addressing these issues will typically require a transdisciplinary approach (Bower *et al.*, 2019).

6. CASE STUDIES

Inland fisheries vary considerably between regions in terms of ecosystem type, fishing methods and target assemblage. The appropriate assessment approach and management framework will also differ, partly in response to the local social-economic situation. Characterizing key fishery types helps to clarify important management knowledge needs, and identify cases where size-based methods are most likely to succeed (Table 4).

Size-based stock assessments, based on empirical indicators or models such as the LB-SPR, are uncommon in inland systems. Fürst, Volk and Makeschin (2010) suggested that "Appropriate (ecosystem) management requires (i) harmonizing and integrating different data sets, (ii) selecting the right indicators, (iii) fitting the right models to the right scale, and (iv) integrating data, indicators and models into systems that allow both a high level of participation and flexibility in application to different questions." This framework was used to inform a set of assessment case studies, which are presented here to provide a template for other users. The intention is to provide a hierarchy of approaches, which can be applied depending on data availability, where the starting point is expert knowledge only, moving up to empirical indicators, and then to the LB-SPR where life-history parameter estimates are available.

The review above suggests that size-based assessment may be applicable to fisheries that target one or a few single stocks, but that these approaches are likely to be less valuable in non-selective multispecies fisheries. The case studies thus focus on ecologically important target species, or species that form the bulk of the catch in a fishery. Previous inland fishery applications of LBIs (Fitzgerald, Delanty and Shephard, 2018; Shephard *et al.*, 2018; 2019a) and the LB-SPR (Hommik *et al.*, 2020) have focused on temperate salmonids, but there is a pressing need to evaluate these techniques in data-limited tropical and temperate systems for non-salmonid species. Case studies were thus chosen for fish stocks in the Tonlé Sap (Mekong River Basin, Cambodia), the Amazon River Basin (Brazil), Paraná River (Argentina) and Lago Bayano reservoir (Panama). Each case was evaluated for data quality, and the availability of supporting life-history information. An empirical indicator approach or model (the LB-SPR) was then selected and applied. Challenges identified in each case were highlighted and discussed.

Table 4

Summary of key inland fishery types and associated knowledge needs for assessment

Fishery types	**Nature of the fishery**	**Management objectives**	**Management strategies/mitigation**	**Application of assessment: what needs to be known**	**Potential applications and limitations for length-based tools**
Floodplain/wetland fisheries Developing country (e.g. Bangladesh, Brazil, Cambodia, Colombia, Lao People's Democratic Republic, Thailand)	Mixed species Large and small floodplain Adapted to rapid growth in short growing season Disperse from refuges All fish utilized Gear: hooks, traps, trap ponds to large fixed fence traps, gillnets	Food fisheries Open-access, maximize food access	Connectivity between rivers, waterbodies and floodplains Protect critical habitats (e.g. dry season refuge, spawning and rearing/feeding habitats) Maintain flood-pulse seasonality and predictability Sufficient broodstock to recruit No effort limits Some restrictions on gear, areas (e.g. fish sanctuaries) and season Ensure that sufficient fish return to refuges in dry season or to complete life cycle Scarce management guidelines Fisheries management should be oriented to assure food security	Assumptions about target size of fish do not apply (take all) Is recruitment adequate to maintain production? Impacts of stocking/enhancement /habitat/refuge measures Overall state of the fishery	Strong annual recruitment pulses, targeted as juveniles or small species may require use of fish community-level length-based indicators (LBIs) Single-species LBIs and LB-SPR may work for a few key larger longer-lived species

Fishery types	**Nature of the fishery**	**Management objectives**	**Management strategies/mitigation**	**Application of assessment: what needs to be known**	**Potential applications and limitations for length-based tools**
Large river fishery Developing country (e.g. Amazon catfish, mainstream Mekong, Paraná)	Mixed species Migratory large species Smaller species more local Upstream migration, downstream larval drift Gears: cast-nets, gillnets, hooks, traps, trammel nets, seine nets, stationary trawl (dai), trawl	Maximize food fishery Different species may be specifically targeted by gear, season or location Protect large & iconic migratory species Manage commercial fishery	Ensure migration, e.g. impacted by dams/barriers Protect refuge areas, e.g. deep pools / floodplain residual ponds key bottlenecks and conservation areas Development of fishing agreements Restrictions on gear Some size restrictions and time closures Protect vulnerable iconic species Fisheries management should be oriented to assure food security and livelihoods	Need specific information on iconic large species Are migrations being impacted (upstream spawning movement / downstream recruitment)? Are some species more vulnerable than others? Impacts of barriers and mitigation measures (flows/releases) What is state of the fishery in general? Influence of fishing effort under different hydrological scenarios Impact of extraordinary floods on recruitment and cohort strength	Assemblage-level LBIs may be appropriate for multispecies non-selective fisheries LBIs and LB-SPR will function for important larger target species, e.g. catfishes or selected species within targeted assemblages
Large African rift lake Developing country (e.g. Lake Malawi, Lake Victoria)	Large economic species targeted by specific gear Small pelagic fisheries targeted by other gear Gear: gillnets, light attracting lift nets, trawls, hooks, seines	Maximize food fishery Different species may be specifically targeted in gear/location	No limits on effort for small pelagics, management controls targeted at higher-value species Some gear-specific restrictions Manage commercial fishery	Larger species fished within limits? Small pelagic fishery sustainable Are management measures unreasonably restricting the fishery from one or more species?	LBIs will not function for small pelagic fisheries or for fisheries, e.g. small-mesh gillnets that are not size- and species-selective and, hence, do not curtail the size distribution / size-spectrum slope

Fishery types	Nature of the fishery	Management objectives	Management strategies/mitigation	Application of assessment: what needs to be known	Potential applications and limitations for length-based tools
			Specific separate measures from small pelagic fishery	Is overall fishing effort excessive? Can the fishery be sustained? Is the object of food provision competing with economic viability?	LBIs and LB-SPR might be applicable to the single-species Nile perch fishery, where life-history parameters are known
Large reservoir fishery Developing country (e.g. Asian reservoirs, Lake Kainji, Lake Kariba)	Introduced species to establish fisheries, e.g. small pelagics, peacock bass or tilapia, rainbow trout A few economic species targeted by specific gear Small pelagic fisheries targeted by light attraction, lift nets, gillnets, hooks, traps	Maximize food fishery Different species may be specifically targeted in gear/location	Some management controls on access Some gear-specific restrictions Manage commercial fishery Specific separate measures from small pelagic fishery	Are larger species fished within limits? Is the small pelagic fishery sustainable? Are management measures unreasonably restricting the fishery from one or more species? Is overall fishing effort excessive? Impacts of stocking & enhancement measures Can the fishery be sustained? Is the object of food provision competing with economic viability? Should exotic species be maintained in sustainable levels?	

Fishery types	Nature of the fishery	Management objectives	Management strategies/mitigation	Application of assessment: what needs to be known	Potential applications and limitations for length-based tools
				Biodiversity conflicts	
Anadromous delta fishery Developing country (e.g. hilsa, Ayeyarwady)	Anadromous species are highly seasonal Some very valuable, others not Fixed gear, bagnets, gillnets, some hook-and-line, cast-nets	Maximize food fishery Different species may be selected by gear/season/location Manage commercial fishery	Ensure migration (impacted by dams/barriers) Restrictions on gear (e.g. bagnets at river mouths) Protection of vulnerable iconic species	Overall state of the fishery State of key migratory anadromous species Impact of barriers	
Commercial river fishery Developed country (e.g. eel and glass eel, salmon, shads and catfish fisheries)	Limited number of food species targeted Single gear types, eel nets/traps, longlines, bagnets, fyke nets	Economic and sustainable food fishery Manage commercial fishery Limit impacts on non-target species & ecosystem	Manage commercial fishery Ensure migration (impacted by dams/barriers) Effort restriction/licensing Restrictions on gears/seasons Protection of vulnerable iconic species Stocking & enhancement	Overall state of the fishery of target species Economic viability of commercial fishery State of key migratory anadromous species Impact of barriers Assess effectiveness of management measures Impact of stocking & enhancement measures	
Commercial lake fishery Developed country (e.g. whitefish)	Limited number of food species targeted Mainly gillnets, longlines	Economic and sustainable food fishery Manage commercial fishery	Manage commercial fishery Effort restrictions & licensing	Overall state of the fishery of target species Economic viability of commercial fishery	

Fishery types	**Nature of the fishery**	**Management objectives**	**Management strategies/mitigation**	**Application of assessment: what needs to be known**	**Potential applications and limitations for length-based tools**
		Limit impacts on non-target species & ecosystem	Restrictions on gear/seasons Stocking & enhancement Protection of vulnerable iconic species	State of key migratory anadromous species Impact of barriers Assess effectiveness of management measures Impact of stocking & enhancement measures	
Recreational river fishery Developed country (e.g. trout, sturgeon) Developing country (e.g. catfish, mahseer)	Limited number of sport species targeted Rod and line	Recreational catch Biodiversity	Sustain population Ensure migration (impacted by dams/barriers) Status of protected species	Overall state of fishery & target species State of key anadromous species Impact of barriers Effectiveness of management measures Impact of stocking & enhancement measures	
Recreational lake fishery Developed country (e.g. trout, bass)	Limited number of sport species targeted Rod and line, gillnets (Finland)	Recreational take Biodiversity	Sustain population Status of protected species	Overall state of fishery & target species Assess effectiveness of management measures Impact of stocking & enhancement	
Recreational reservoir fishery	Limited number of sport species targeted	Recreational take Biodiversity	Sustain population Status of protected species	Overall state of fishery & target species	

Fishery types	**Nature of the fishery**	**Management objectives**	**Management strategies/mitigation**	**Application of assessment: what needs to be known**	**Potential applications and limitations for length-based tools**
Developed country (e.g. trout, bass) Developing country (e.g. bass)	Rod and line, gillnets (Finland)		Manage recreational vs commercial fisheries	Assess effectiveness of management measures Impact of stocking & enhancement	
Commercial inland sea fishery (e.g. kilka)	Limited number of food species targeted Mainly gillnets, longlines and trawling	Economic and sustainable food fishery Manage commercial fishery Limit impacts on non-target species & ecosystem	Manage commercial fishery Effort restrictions & licensing Restrictions on gear/seasons Stocking & enhancement (e.g. sturgeon) Protection of vulnerable iconic species, e.g. sturgeon	Overall state of the fishery of target species Economic viability of commercial fishery State of key migratory anadromous species and vulnerable species Impact of barriers Assess effectiveness of management measures Impact of stocking & enhancement measures	

6.1 "DAI" (FIXED BAGNET) FISHERY, TONLÉ SAP, MEKONG RIVER (CAMBODIA)

6.1.1 INTRODUCTION TO THE TONLÉ SAP SYSTEM AND DAI FISHERY

Key facts	
Name of the waterbody/river:	Tonlé Sap River
Type of waterbody/river or tributary river:	Major tributary to the Mekong River connecting it to the Great Lake
Size of waterbody/size of river basin:	85 000 km^2
Gear:	Dai (bagnet)
Total number of species present:	141
Target species:	At least 86% are cyprinids; no other family contributes more than 4% (Halls *et al.*, 2013a)
Total annual catch:	Up to 35 000 tonnes/season
Number of fishers:	About 2 000 people work seasonally in the dai fishery
Management regulations:	Only allowed at specific sites Fishery is only open from October to March Minimum mesh size
Data availability:	2001–2004 and 2007–2015

The Tonlé Sap River is an important tributary to the Mekong River. It provides the connection between the Tonlé Sap Great Lake and the Mekong River, through which the lake alternately fills and empties. The lake area differs by up to 600 percent between seasons. Fish perform large-scale seasonal movements in and out of the lake and the surrounding floodplains, and important fisheries take advantage of this bounty. One of the key fisheries is the dai fishery, which takes place in the lower section of the Tonlé Sap River, stretching about 4–30 km north of Phnom Penh (Ngor *et al.*, 2018). The location has been unchanged for more than a century (Halls *et al.*, 2013b).

A dai is a stationary trawl or bagnet (Figure 2); it is commercial-scale, and the largest fishing gear in the Mekong Basin. The dai nets are anchored in 14 rows, with 1–7 dai units in each row. Each anchoring location is auctioned by the government to the highest bidder for exclusive exploitation over a two-year period. The rules regulating the fishery including the dai location, gear restriction, payment and harvest are described in the so-called "burden book", which is an annex to the law on fisheries in Cambodia (FiA, 2006).

A dai primarily consists of two bamboo rafts, a long bagnet and a boat or a floating house. The two bamboo rafts are located at the opening of the net to keep it open; they are linked together by bamboo poles and held in place by anchors in the river. A small boat or raft is placed between the two bamboo rafts to stabilize the entire dai structure. The dai mouth is about 25 m wide, and the height of its opening varies according to the water depth. The dai is about 100–120 m long, with mesh sizes tapering down from about 15 cm at the entrance to 1 cm at the codend. The floating house, to which the dai codend is attached, and on which the catches are emptied, is positioned at the end of the bagnet, downstream of the two bamboo rafts. Dai technical details and illustrations are given in Deap, Degen, and Van Zalinge (2003). On average, some 18–25 labourers may be needed to operate a dai depending on the intensity of the fish migration (Hap and Ngor, 2001).

The fishery takes place during the receding water levels from about October to March, although it may start later or end sooner depending on the flow. The dai fishery targets mainly migratory (riverine) fish species that utilize the Tonlé Sap floodplain in the wet season as their rearing/feeding habitat before returning to the Mekong River mainstream through the Tonlé Sap River during drawdown, seeking dry season refuge. Large and medium-sized fishes tend to migrate at the beginning of the season (October–November) (Ngor, 2000). Lunar phases have an important impact on the fisheries, as there is an increase in migration activity, and therefore a peak in the fishery is registered 7–14 days after the new moon when about 50–100 percent of the moon is visible (Halls *et al.*, 2013a).

Catches may be up to 80 tonnes per dai per day (Halls *et al.*, 2013a). Dais are relatively unselective fishing gear and catch up to 141 species, but the catches are dominated by small-bodied mud carps of the genus *Gymnostomus* often less than 25 cm long. They contribute significantly to food and nutrition security by supplying fresh fish and processed fish products, e.g. fish paste (prahoc), and fermented and smoked fish (Ngor and Hem, 2001; Halls *et al.*, 2013b; Ngor *et al.*, 2018).

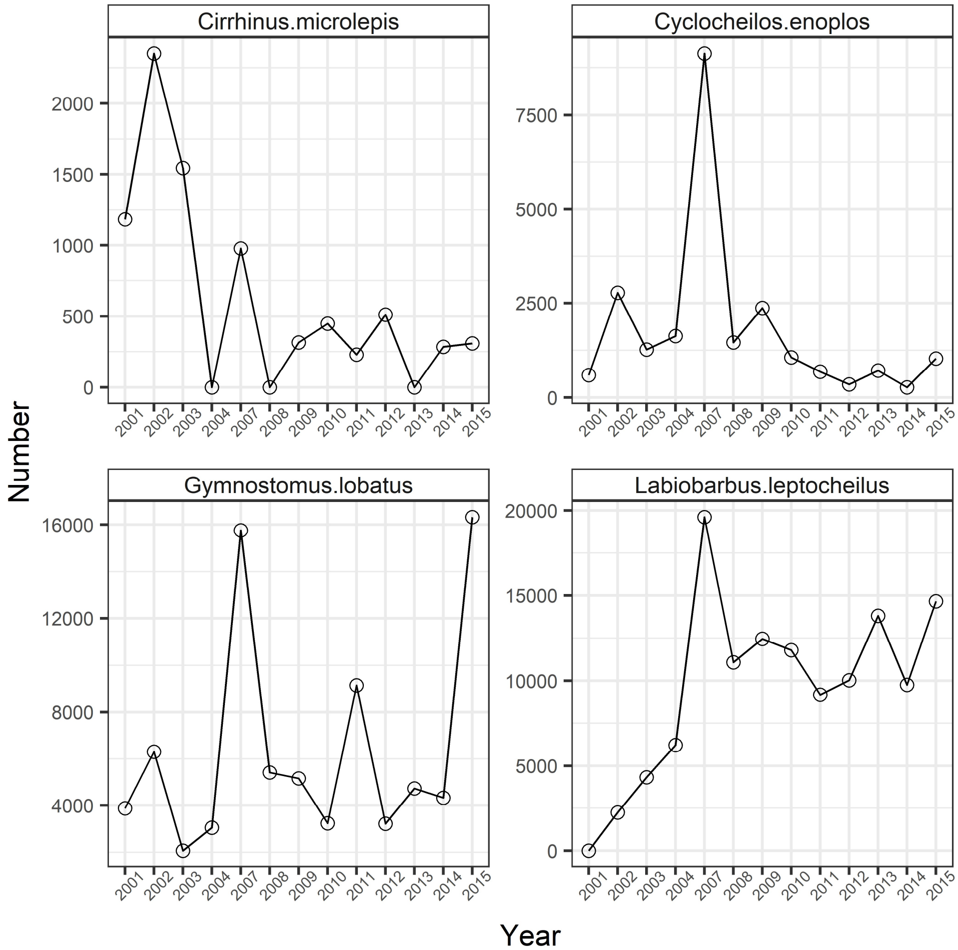
Over the 15-year assessment period from the fishing season of 2000/01 to 2014/15, the overall daily catch per dai unit fluctuated with no significant trend. However, out of 116 species studied, 78 percent showed decreasing catches over time. These were mainly the medium-to-large-bodied species that also tend to belong to higher trophic levels (Ngor *et al.*, 2018). In contrast, catches of some of the small-sized species appeared to be relatively stable or showed an increasing trend. Moreover, the study found a declining trend in species diversity (evenness index), particularly after 2008, and a decrease in individual fish weights and lengths for several common species of the fishery (Ngor *et al.,* 2018).

6.1.2 DATA COLLECTION ON LENGTH

Sampling takes place on a daily basis following a defined protocol (described by Halls *et al.*, 2013b). Sampling occurs on about 17 days each month; during the peak period, dais are sampled every day, and every second or third day during the low period (Halls *et al*., 2013b). The dais to be sampled are selected randomly, and 3–4 hauls are then sampled over a 12-hour period. However, during the seven days corresponding to the peak period each month, the number of sampled dais is increased. The number of samples are also doubled at this time, and cover a full 24-hour period. The volume of each haul, soak time for each haul, the number of hauls per day, and the species composition are recorded. From each haul, a sample of fish is sorted by species, weighed and counted. Individual length measurements are also taken for a number of species from the subsamples, including *Gymnostomus lobatus*, *Cirrhinus microlepis*, *Labiobarbus lineatus* and *Cyclocheilichthys enoplos* (Ngor and Van Zalinge, 2001), which are all common species that represent a large proportion of the dai catch and are the subjects of the present study. For the purposes of the analysis, data from 2001–2004 and 2007–2015 were used (Figure 3) (Ngor *et al.*, 2018). Key life-history parameters (e.g. L_∞, L_{mat}) were generally not available for these species.

Figure 3

Number of individuals of four fish species measured in random samples from the Tonlé Sap Dai fishery, 2001–2015 (no data for 2005 and 2006)



6.1.3 ANALYSIS

Life-history parameters were not available for the four current study species, and so an empirical indicator-based approach was chosen. State-space plots (Shephard *et al.*, 2019a) were used to present paired annual time series of a simple LBI ($L_{95\%}/L_{max}$) and relative abundance ($N_{species}/N_{total}$) for each of the four species in the total catch. The relative abundance indicator was standardized to the maximum observed annual value by species. These plots capture trends in each descriptor, and are ideally interpreted using expert elicitation.

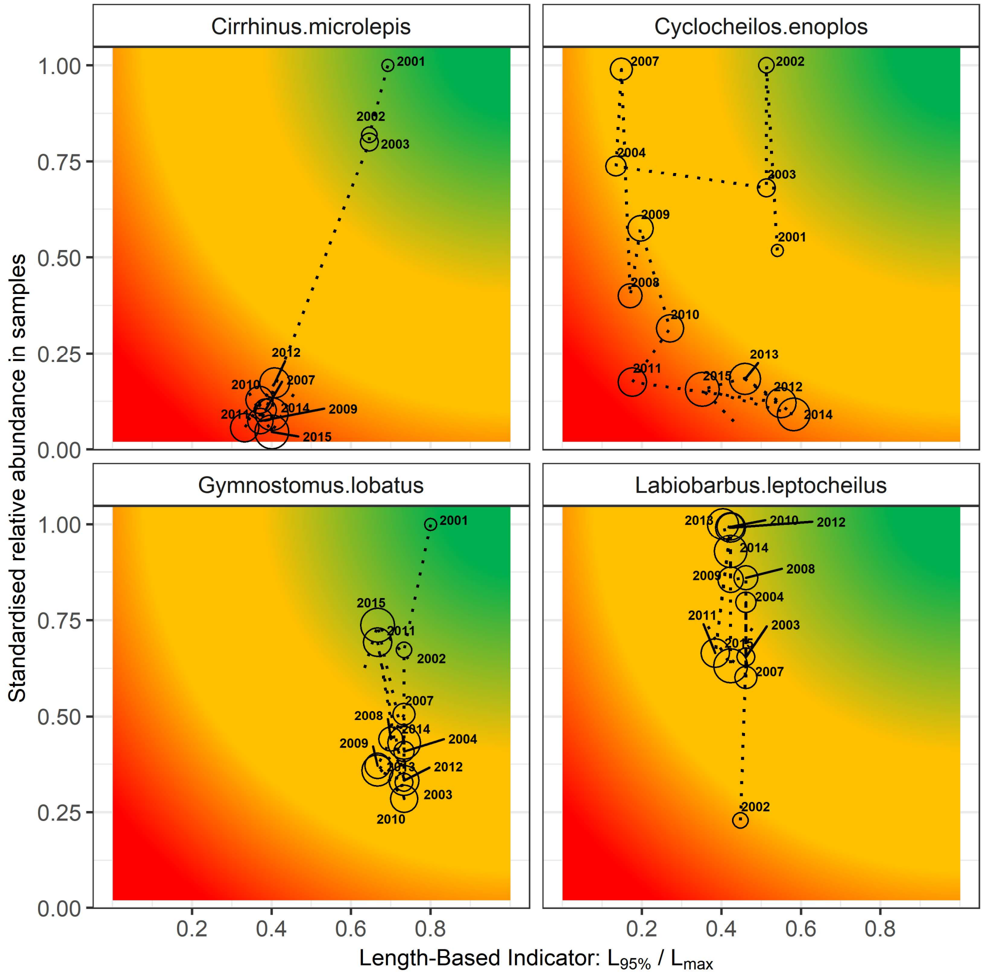
6.1.4 RESULTS

The plots seemed to provide a reasonable image of the temporal state of each tested Tonlé Sap species (Figure 4). One of the four species (*Cirrhinus microlepis*) showed a strong negative trend in both size structure and relative abundance, collapsing after 2003 with no evidence of subsequent recovery.

Cyclocheilichthys enoplos showed an interesting stock pattern, declining first in length structure and then in relative abundance, but showing some recent recovery in length. The other two species showed fairly stable length structure, with minor shifts in relative abundance in 2001 and 2002.

Figure 4

Time series of relative abundance and a length-based indicator for four fish species measured in random samples from the Tonlé Sap Dai fishery, 2001–2015



Notes: Relative abundance is the annual proportion of a species by number in the total catch of the four study species, standardized to the maximum observed value for that species. The colour scale is arbitrary, and simply indicates reference direction from good (green) to poor (red) state.

6.1.5 INTERPRETATION

The dai fishery data supported an empirical indicator approach to assessment, with lack of available life-history parameters precluding application of the LB-SPR. Indicator plots showed clear temporal patterns for two of the four study species, suggesting that a trends-based approach might be appropriate for monitoring this fishery. An important aspect of such an approach would be elicitation of expert data to inform interpretation of apparent indicator trends. For example, the small-scale mud carp (*Cirrhinus microlepis*) is listed as Vulnerable by the International Union for Conservation of Nature (IUCN), and considered to be under pressure from overfishing and dam building. This knowledge informs the very impaired state suggested by the state plots (Figure 3). The two small cyprinid species (*Gymnostomus lobatus* and *Labiobarbus leptocheilus*) are highly abundant and have similar population dynamics. In the current series, abundance and length structure for these species tended to fluctuate annually without any distinct trend.

It is not clear whether the non-selective dai fishery will impart curtailment of species size distributions, i.e. a length-based impact that can be captured by LBIs. Larger fish may decline because the cumulative probability of capture increases with age (and size), or because individuals on second or subsequent migrations to the lake will have run the gauntlet more often. It is also likely that other size-selective fisheries, e.g. traps and hooks, have an impact on some target species, and also that larger Mekong fishes may be disproportionally affected by barriers to spawning and feeding migration.

6.2 GOLIATH CATFISH, AMAZON RIVER (BRAZIL)

6.2.1 INTRODUCTION TO THE AMAZON SYSTEM AND FISHERIES

Figure 5

Dourada (*Brachyplatystoma rousseauxii*), one of the species of Goliath catfishes caught in the Amazon River, Pucallpa, Peru.

Key facts	
Name of the waterbody/river:	Amazon Basin
Type of waterbody/river or tributary river:	Major white-water rivers (Amazon, Solimões, Madeira, Purus). Major clear-water rivers (Xingu, Tapajós) Major black-water river (Negro)
Size of waterbody/size of river basin:	7 million km^2
Gear:	Dourada (*Brachyplatystoma rousseauxii*), piraíba/filhote (*B. filamentosum*) and piramutaba (*B. vaillantii*)
Total number of species present:	> 3 000 in the basin (200 fished commercially)
Target species:	Gillnets, longlines, driftnets and trawl nets
Total annual catch:	25 000
Number of fishers:	> 16 000
Management regulations:	In the estuary: area restriction for trawling, three-month closed season, limited number of vessels (trawling in pairs) and a minimum mesh size of

	100 mm in the codend In Colombia and Peru, minimum fish size
Data availability:	1999–2004 (Solimões/Amazon Rivers), 2009–2013 and 2017–2018 (Madeira River), 2012–2018 (Xingu River)

The Goliath catfishes of the family Pimelodidae (Figure 5) are large riverine catfishes, mostly occurring in the mainstream channels of large rivers with origin in the Andes and in the freshwater stretches of the Amazonian estuary.

The juveniles are found in the freshwater parts of the Amazonian estuary, where they inhabit open waters along the coast and bays, and a zone with strong currents caused by the tides. The Goliath catfishes ascend major rivers and tributaries to reach spawning grounds in the headwaters (Duponchelle *et al*., 2016).

The commercial catfish fishery has developed over the last six decades in the Amazon, driven by increasing demand from local, national and international markets, and this resource is now considered the primary source of income generation for Amazonian fishers (Fabré and Alonso, 1998; Barros and Ribeiro 2005; Doria *et al*., 2012). In 2005, it was estimated that about 16 000 fishers participated in this fishery, of which 50 percent were concentrated in the estuary where the only industrial fishery takes place (Barros and Ribeiro, 2005).

The industrial fleet uses trawls towed by two motorized vessels 17–29 m long with inboard engines of 165–565 hp (bottom pair trawl) (Batista, Isaac and Viana, 2004). The industrial fleet mainly targets young individuals of piramutaba (*Brachyplatystoma vaillantii*), but small douradas (*B. rousseauxii*) are also caught as bycatch (Jimenez, Asano Filho and Frédou, 2013). The small-scale fleet operates in the estuary as well as in the entire basin in Bolivia (Plurinational State of), Brazil, Colombia and Peru. These boats operate mainly along the Amazon mainstream, and in most large tributaries such as the Madeira, Purus, Branco, Japurá, Içá, Tapajós and Xingu Rivers. Small-scale fishing boats are motorized (outboard engine < 25 hp), and are equipped with insulated boxes to keep the fish refrigerated on ice, and the gear used are gillnets, mostly used as driftnets (80 percent of the catch in the Brazilian Amazon), or longlines (20 percent of the catch). They operate mainly in deeper parts of the river channels, and occasionally in shallower habitats in the floodplains. They target mainly dourada (*Brachyplatystoma rousseauxii*), piramutaba (*B. vaillantii*), piraíba (*B. filamentosum*), babão (*B. platynemum*), flamengo (*B. juruense*) and jaú (*Zungaro zungaro*).

The production of dourada and piramutaba from the industrial fleet averages about 3 000 tonnes per year. In the central Amazon, production is about 1 000 tonnes per year. In the high Solimões region, Fabré and Alonso (1998) and Fabré and Barthem (2005) estimated the total landings of all catfish at about 12 000 tonnes per year. In the Madeira basin (Bolivia [Plurinational State of], Brazil and Peru), the *Brachyplatystoma* total yield is about 179 tonnes per year. Reported catches of piraíba (*B. filamentosum*) in the entire basin are being compiled and average about 1 000 tonnes per year.

The main production peak occurs when the water level drops (Batista *et al*., 2012). Therefore, the average yield of the species depends on the hydrological river season and geographical region. In the estuary, the daily yield varies between 18 kg and 30 kg per fisher in the harvest period. The catch peaks occur sequentially along the river. The estimated daily mean yield of dourada varies between 6 kg and 30 kg per fisher, and for piramutaba it varies between 1 kg and 85 kg per fisher (Parente *et al*., 2005).

The dourada upstream migration starts in the estuary in the rainy season (June–July) when the juveniles are between 1.5 and 2 years old. The fish reach the region of Leticia, Colombia (2 970 km upstream from the estuary), in the low-water season (September and November) (Barthem and Goulding, 2007) about four years later (Alonso and Pirker, 2005). In the Madeira River, it was demonstrated that the dourada has homing behaviour (Duponchelle *et al*., 2016). They can reach almost 2 m in total length and 100 kg in weight. In the Brazilian portion of the basin, mainly young individuals below 5 years old were found, whereas older fish (> 5 years) were caught only in the Bolivian and Peruvian stretches, indicating that after migrating upstream to reproduce, adults remain in the headwaters (Hauser *et al*., 2018).

Piramutaba can reach 1 m maximum size and 10 kg. Similarly to dourada, mapping the presence of mature adults complemented by the seasonal and geographical variation in abundance and length of larvae and juveniles in river channels across the Amazon, Barthem and Goulding (2007) concluded that piramutaba also undertake large migrations, between the estuary (nursery < 40 cm in length) and the Andean headwaters, where larger individuals can be caught year-round.

Piraíba (*B. filamentosum*) is the largest catfish in the Amazon, with a maximum total length of more than 3 m (Santos and Jegu, 2004) and a weight of more than 150 kg. The species is mainly found along the bottom of the main river channels. Piraíba is the second most fished catfish in the commercial fishery in the Amazon region, and small individuals (known as "filhotes") are caught frequently. Nevertheless, unlike all other large Siluriformes, the species does not perform long migrations (Petrere *et al*., 2004).

Growth overfishing has been demonstrated for dourada and piramutaba (Alonso and Pirker, 2005) and is suspected for piraíba (Petrere *et al*., 2004). The piramutaba fishery is regulated by a minimum mesh size of 100 mm, and the number of industrial boats is limited to 48. In addition, there is a closed season (generally during the last two months of the year) for the industrial fleet, but there is a low level of compliance with these fisheries regulations (Klautau *et al.*, 2016). There are no management measures directed to the Goliath catfishes for the artisanal fleet in the Brazilian part of the basin. In Colombia, the minimum size is 85 cm for dourada, and 40 cm for piramutaba. In Peru, the minimum size for dourada is 115 cm (Vieira, 2005).

Overfishing and impacts caused by major infrastructure projects currently being planned for the region, such as hydroelectric dams and mining, are likely to affect the access of these species to their spawning grounds and directly impact the reproductive areas, and may therefore reduce their lifespan and compromise the status of their stocks (Barthem, Ribeiro and Petrere Jr, 1991; Barthem *et al*., 2017).

Fabré and Barthem (2005) proposed an integrated management plan for the Amazonian large migratory catfishes, taking into account the peculiarities of their life cycles and the socio-economic aspects of the fishery. However, their recommendations have not been reflected in the rules and regulations.

6.2.2 DATA COLLECTION

The length data were collected through several different research programmes from 1999 to 2018, and include the measurement of 5 673 dourada, 4 263 piraíba and 3 122 piramutaba sampled as far upstream as Iquitos, Peru, and as far downstream as Belém in the estuary in Brazil. A data set of dourada length records (year 1999) included samples from a large linear range of sites from the river estuary to Iquitos in Peru; these data may capture the upstream size gradient for this highly migratory species (Table 5).

Table 5

The data sets used for the LB-SPR assessment of the three species of Goliath catfishes: dourada, piramutaba and piraíba

Basin	Species	Place	Year	Period	No.
Estuary	Dourada	Landing sites. Belém and Mosqueiro (Pará State, Brazil)	1999	15–20 days in July–August	370
Amazon-Solimões	Dourada	Landing sites. Santarém (Pará State, Brazil);	1999	15–20 days in September	249
Amazon-Solimões	Dourada	Landing sites. Manaus (Amazonas State, Brazil)	1999	15–20 days in October	198
Amazon-Solimões	Dourada	Landing sites. Tefé, (Amazonas State, Brazil)	1999	15–20 days in October–November	185
Amazon-Solimões	Dourada	Landing sites. Leticia (Amazon Department, Colombia)	1999	15–20 days in November–December	174
Amazon-Solimões	Dourada	Landing sites. Iquitos (Loreto Department, Peru)	1999	15–20 days in December	212
Amazon-Solimões	Dourada	Landing sites. Alenquer, Almeirim, Curuá, Monte Alegre, Óbidos, Oriximiná, Prainha, Terra Santa (Pará State, Brazil)	2001–2004	March–November	905
Amazon-Solimões	Piramutaba	Landing sites. Alenquer, Almeirim, Curuá, Monte Alegre, Óbidos, Oriximiná, Prainha, Terra Santa (Pará State, Brazil)	2001–2004	March–November	580
Amazon-Solimões	Dourada	Landing sites. Santarém (Pará State, Brazil);	2001–2004	February–December	794
Amazon-Solimões	Piramutaba	Landing sites. Santarém (Pará State, Brazil);	2001–2004	February–December	365
Amazon-Solimões	Dourada	Landing sites. Parintins (Amazonas State, Brazil)	2001–2004	February, March, May, June, July, November	69
Amazon-Solimões	Piramutaba	Landing sites. Parintins (Amazonas State, Brazil)	2001–2004	May, June, July, August, November	33
Amazon-Solimões	Piramutaba	Landing sites. Itacoatiara, São Sebastião do Atumã, Manacapuru,	2001–2004	June, July, August, September	62

		Tabatinga (Amazonas State, Brazil)			
Madeira	Dourada	Landing sites. Porto Velho (city market), São Carlos (riverine community), Calama (riverine community), Teotônio (riverine community) (Rondônia State, Brazil)	2009–2013 and 2017–2018	January–December	2 017
Madeira	Piraíba	Landing sites. Porto Velho (city market), São Carlos (riverine community), Calama (riverine community), Teotônio (riverine community) (Rondônia State, Brazil)	2009–2013 and 2017–2018	May–November	1 194
Madeira	Piramutaba	Landing sites. Porto Velho (city market), São Carlos (riverine community), Calama (riverine community), Teotônio (riverine community) (Rondônia State, Brazil)	2009–2013 and 2017–2018	May–November	1 984
Madeira	Dourada	Markets. Porto Velho – fish market (Rondônia State, Brazil)	2009–2013 and 2017–2018	January–December	500
Madeira	Piraíba	Markets. Porto Velho – fish market (Rondônia State, Brazil)	2009–2013 and 2017–2018	May–November	241
Madeira	Piramutaba	Markets. Porto Velho – fish market (Rondônia State, Brazil)	2009–2013 and 2017–2018	May–November	98
Xingu	Piraíba	Landing sites. Belo Monte, Senador José Porfírio, Vila Nova, Vitória do Xingu	2012–2018	Monthly from April 2012 to October 2018	2 828

This case study focuses on three species of Goliath catfish: dourada (*Brachyplatystoma rousseauxii*), piramutaba (*Brachyplatystoma vaillantii*) and piraíba/filhote (*Brachyplatystoma filamentosum*). The Goliath catfish data provide a data-limited stock assessment case study for one of the most iconic and vulnerable freshwater systems in the world (Castello *et al.*, 2013). Fisheries on the Amazon contribute significantly to food security, but are threatened by deforestation (Castello *et al.*, 2018) and ongoing dam building (Petrere, 1989). There is also growth overfishing of many species (Batista *et al.*, 2018), and low compliance with fisheries regulations (Klautau *et al.*, 2016). Castello, McGrath and Beck (2011) concluded that fishery resources in the region appeared to be moderately fished, with some key target species showing typical signs of overfishing.

Two of the study species (dourada and piramutaba) show long-distance migrations from nursery grounds in the river estuary, up to spawning grounds in areas close to the Andes Mountains (Barthem *et al.*, 2017), and in the Madeira River it was demonstrated that the dourada has homing behaviour (Duponchelle *et al.*, 2016). That the nursery areas are situated so far downstream from the spawning grounds results in a systematic upstream increase in mean size, with important implications for size-based assessment. A sample of fish from further upstream will tend to have more, larger fish, and assessments may thus indicate better stock status (higher SPR) for these spatial components than for those downstream. This potentially misleading result must be accounted for in the sampling strategy.

6.2.3 ANALYSIS

The three Goliath catfishes are well studied, with several published estimates of the key life-history parameters available for each species (Table 6). These published estimates were used to support an LB-SPR assessment for each species. Catches were separated by fishing gear (where recorded) and river system to account for likely differences in fishery selectivity or spatial differences in fish life-history stage (due to ontogenetic migration). The predominant fishing gear (driftnet with belly) was assumed to show asymptotic selection, while longline selectivity was unknown, and so the GTG-LB-SPR approach (Hordyk *et al.*, 2016) was applied.

Table 6

Published estimates of life-history parameters for the study on Amazon Goliath catfish species

Species	L_∞	K	M	$L_{mat50\%}$	$L_{mat95\%}$	Location	Reference
B. rousseauxii	140.2	0.30	0.32 (Tay), 0.49 (Pau)	70.6	96.3	Amazon	Alonso, 2002
B. rousseauxii	102.8	0.57	-	73.0	-	Madeira Basin	Hauser *et al.*, 2018
B. rousseauxii	153.3	0.22	0.32–0.56	88.5	95.0	Caquetá, Columbi a	Cordoba *et al.*, 2013
B. rousseauxii	153.3	0.29	0.48–0.52	87.0	-	Iquitos, Peru	García Vásquez *et al.*, 2009
B. rousseauxii	176.0	0.08	0.54	-	-	-	Munoz-Sosa, 1996
B. rousseauxii	-	-	-	66.5	-	-	Barthem *et al.*, 2017
B. rousseauxii	132.0	0.33	0.35	-	-	-	Alonso & Pirker, 2005
B. filamentosum	221.0	0.11	0.22	-	-	-	Munoz-Sosa, 1996

Species	L_∞	K	M	$L_{mat50\%}$	$L_{mat95\%}$	Location	Reference
B. filamentosum	-	-	-	146 (F), 98 (M)	-	-	Gomez, 1996
B. filamentosum	-	-	-	86 (F), 80 (M)	161 (F), 106 (M)	-	Petrere *et al.*, 2004
B. vaillantii	110.5	0.13	0.3	-	-	-	Alonso & Pirker, 2005
B. vaillantii	-	0.10	-	42.0	64.0	-	Barthem & Goulding, 1997
B. vaillantii	77.3	0.22	0.5 (0.2–0.6)	-	-	-	Barthem, 1990
B. vaillantii	110.5	0.13	-	55.0	-	-	Pirker, 2001
B. vaillantii	77.5	0.27	-	-	-	-	Nogueira, 2015
B. vaillantii	77.2	-	-	-	-	-	Barthem & Petrere, 1995

Considering the range of reported life-history estimates (Table 6), a corresponding set of L_∞ and M/K values were tested for each species (Table 7). The SPR for each species was estimated for each study year, using each set of life-history values.

Table 7

Life-history parameter values used as inputs to the LB-SPR for each Amazon Goliath catfish species

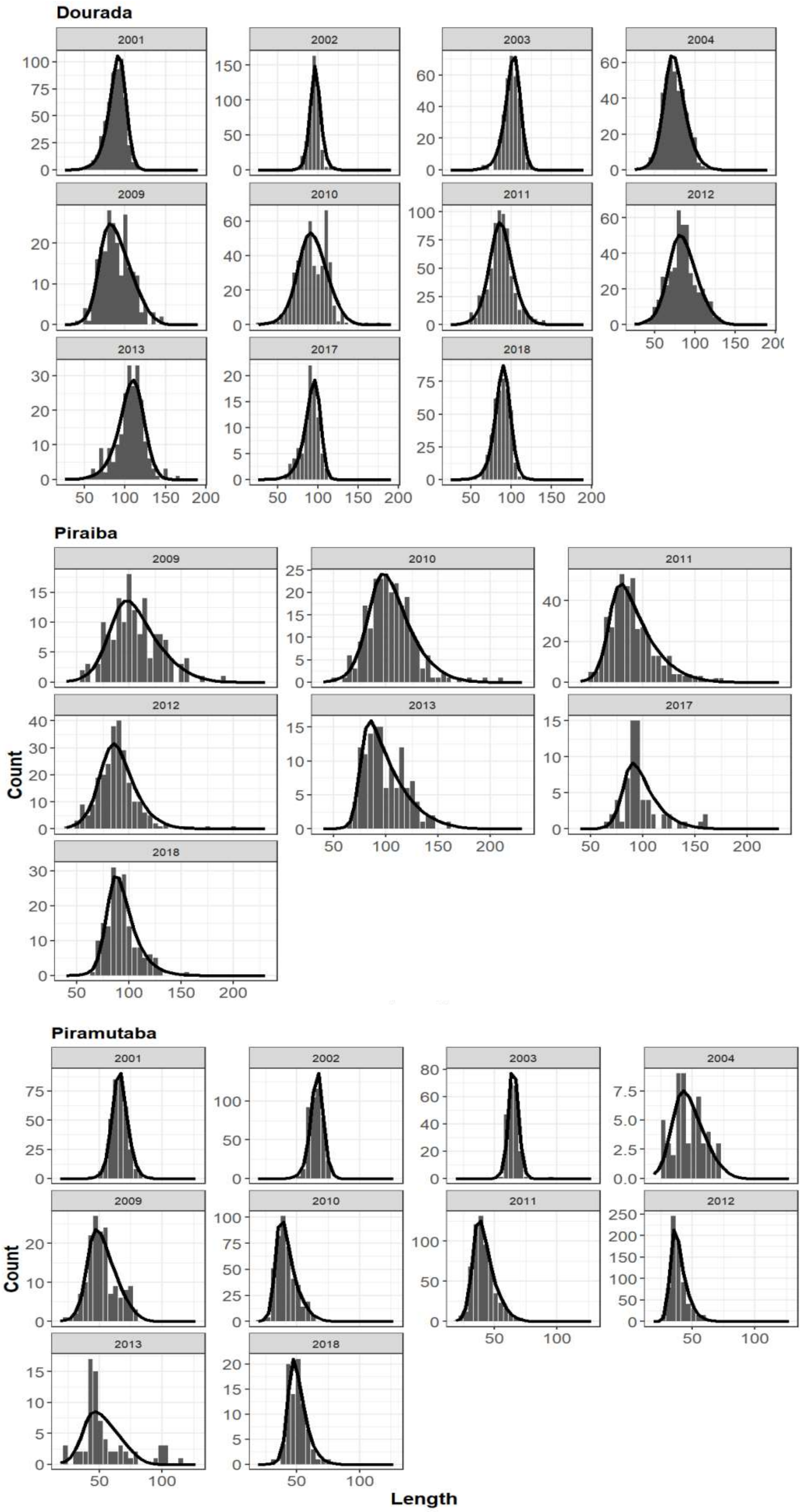
Species	Common name	L_∞	M/K
B. rousseauxii	Dourada	125, 135, 150	1.85, 2.0
B. filamentosum	Piraíba/filhote	175, 185, 195	1.90, 2.0
B. vaillantii	Piramutaba	80, 85, 90	1.85, 2.0

The additional dourada data (sampled from estuary to upstream) were used to highlight the potential effect on SPR estimates of sampling progressively upstream towards the spawning areas. A single L_∞ (135 cm) and M/K (1.85) were applied in this analysis to estimate the SPR for fish from each sampling site.

6.2.4 RESULTS

The LB-SPR model seemed to show good fit to the annual length data for each of three tested Goliath catfish species (Figure 6).

Figure 6


Dourada
2001
2002
2003
2004
2009
2010
2011
2012
2013
2017
2018
Piraiba
2009
2010
2011
2012
2013
2017
2018
Piramutaba
2001
2002
2003
2004
2009
2010
2011
2012
2013
2018
Count
Length

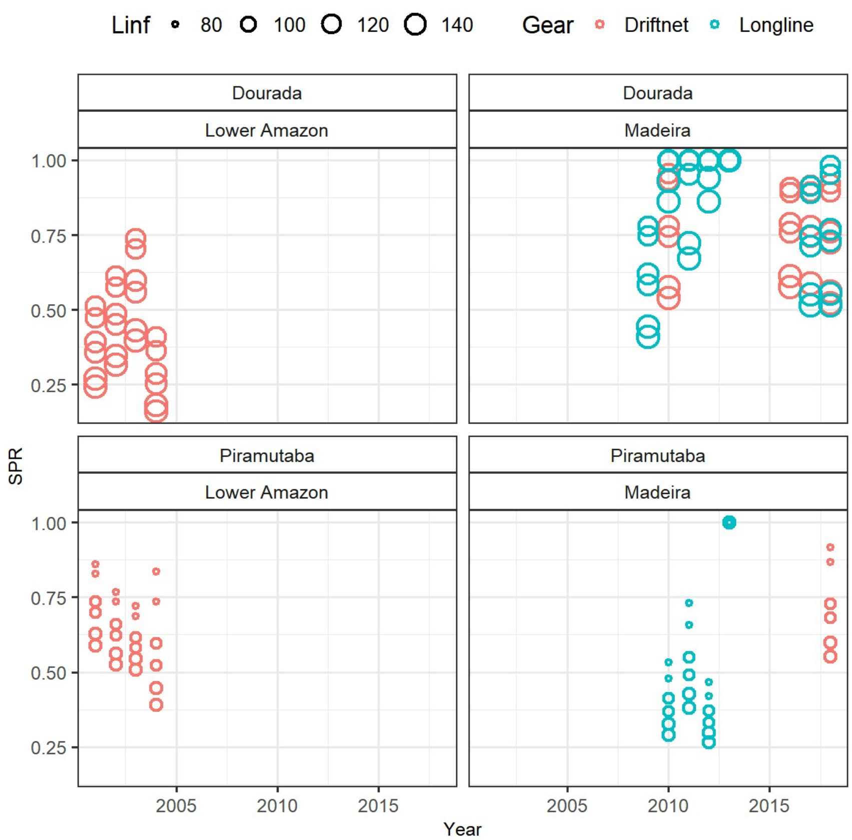
Annual length-frequency plots for the Goliath catfish species tested

Notes: The black lines are the fitted LB-SPR model. Note differing y-axis scales and small sample sizes in some years.

The SPR estimates for the three species studied showed a strong effect of input L_∞ values and a lesser effect of M/K. Both dourada and piramutaba showed a reasonable state for 2001–2004, with a possible subsequent decline for piramutaba (Figure 7a). State appeared to be better in the Madeira tributary than in the lower Amazon, although this may reflect the tendency for larger fish to move upstream. Piraíba showed declining state in the Madeira River, with almost complete absence of larger fish in the Xingu River (Figure 7b). This result concurs with previous evidence (Petrere *et al.*, 2004; Castello, McGrath and Beck, 2011), and more recent studies (Van Damme *et al*., 2019), and many anecdotal reports that the mean size of this species is declining in the Amazon system.

Figure 7a

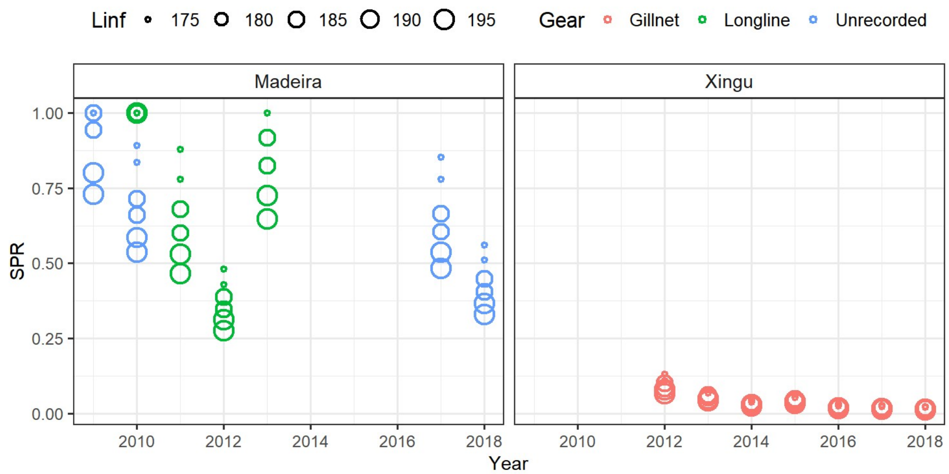
Estimates of spawning potential ratio for dourada and piramutaba, sampled in each of the lower Amazon main channel and Madeira tributary



Notes: Sampling gear (driftnet and longline) are highlighted. Different values were used for the input life-history parameters (Table 7). The size of the circles refers to L_∞ (L_{inf}, centimetres), which had the strongest effect on SPR estimates, while the M/K ratio had less influence (see input values in Table 7).

Figure 7b

Estimates of spawning potential ratio for piraíba (filhote), sampled in the Madeira and Xingu systems



Notes: Different values were used for the input life-history parameters (Table 7). Sampling gear (driftnet, longline or unrecorded) are highlighted. The size of the circles refers to L_∞ (L_{inf}, centimetres), which had the strongest effect on SPR, while the M/K ratio had less influence (see input values in Table 7).

The dourada samples from different Amazon locations in 1999 showed progressively greater SPR moving upstream (Table 8). The mean value (SPR = 0.38) was in the range of the overall value estimated for 2001, which was the next closest year having data (Figure 7a). This result reflects the tendency for greater mean length for this species at upstream sites, which may be rather unique to Amazon catfish, where the upstream migration takes so long that the fish grow markedly during this period. The case study does highlight the issue of spatial segregation of life-history components of a stock, and the need to consider this factor in length-based assessments, possibly by spatially stratifying sampling to collect an overall representative sample of the stock.

An increase in mean length for this species was also noted by Van Damme *et al.* (2019) in the upper Madeira River (Bolivia [Plurinational State of]), but was attributed to a blocking effect of upstream young migratory fish due to the San Antonio and Jirau dams. This perspective emphasizes that SPR analysis should be complemented with local expert knowledge to avoid misinterpretation of observed trends.

Table 8

Spawning potential ratio (SPR) estimates for dourada sampled at different sites on the Amazon system in 1999

Site	Number	SPR	Upstream (km)
Estuary	370	0.20	0
Santarém	249	0.34	570
Manaus	420	0.18	1 310
Tefé	185	0.41	1 910
Leticia	174	0.54	2 900

Site	Number	SPR	Upstream (km)
Iquitos	200	0.62	3 545
Overall	1 598	0.38	NA

Notes: Input parameters were L_∞ = 135 cm and M/K = 1.85. Note that the SPR estimate tends to increase further upstream from the estuary.

6.2.5 INTERPRETATION

Previous assessments of the state of key fish stocks in the Amazon system have typically been limited to trends in CPUE (e.g. Petrere *et al.*, 2004; Welcomme, Valbo-Jorgensen and Halls, 2014), to catch curves (Cordoba *et al.*, 2013) or to empirical indicators, including community size-spectra (Castello, McGrath and Beck, 2011; Fabré *et al.*, 2017; Doria, Lima, and Angelini, 2018). The current study may be the first to apply a data-limited model and assess stock state relative to an objective (SPR) RP.

An important finding is that current state differs markedly between the case study catfish species, even though all three are important commercial fishes. The state of piraíba/filhote is of particular concern, with different tested input values for L_∞ and M/K making little difference to the estimated SPR values. This species is probably being targeted below size at first maturity (Castello, McGrath and Beck, 2011), and the size structure of the population is clearly strongly impaired. Annual landings of piraíba "decreased drastically" from 1977 onwards (Petrere *et al.*, 2004). Piramutaba also showed a decline in state during the study period, and this may reflect high fishing mortality (F) in the trawl fishery targeting juvenile fish in the river estuary (Petrere *et al.*, 2004). Declines in both these species are associated with increasing pressure on dourada, and therefore the state of this stock should be closely monitored.

A second key issue is the tendency for mean length of dourada and piramutaba (and associated SPR estimates) to increase systematically upstream moving closer to spawning locations. This behaviour suggests that the SPR should be calculated from a sample collected from locations throughout the river channel to ensure a representative stock-level size distribution. Alternatively, a trends-based approach could be applied to separate spatial stock components, using an SPR calculated for specific sampling locations.

There may be many cases where different life stages of a targeted fish species are spatially separated, and careful sampling will be required to accurately represent the true stock size distribution. It will be important that local knowledge of the system and the life history of assessed stocks be carefully included in the overall assessment framework.

6.3 NILE TILAPIA, LAGO BAYANO (PANAMA)

6.3.1 INTRODUCTION TO THE LAGO BAYANO SYSTEM AND FISHERY

Figure 8
The capture of tilapia in Lago Bayano using Chinese trammel nets along the shoreline in combination with beating on the surface in shallow water.

Key facts	
Name of the waterbody/river:	Lago Bayano
Type of waterbody/river or tributary river:	Reservoir on the Bayano River
Size of waterbody/size of river basin:	350 km^2
Target species :	Nile tilapia (*Oreochromis niloticus*)
Total number of species present:	9
Gear:	Chinese trammel net
Total annual catch:	102 – 3 700 tonnes/year
Number of fishers:	1 200 (2007); 300 (2018)
Management regulations:	Restricted access, minimum mesh size 5 inches (12.7 cm)
Data availability:	2005–2018

Lago Bayano was formed in 1976 with the damming of the Bayano River for electricity generation. Nine fish species are present in the waterbody, with Nile tilapia (*Oreochromis niloticus*), which was introduced to the reservoir in 1980, supporting the only commercial fishery (Figure 8).

The fishery, which is only open to the members of the communities around the reservoir, initially involved more than 1 200 full-time fishers and a significant number of seasonal fishers. However, the number of fishers has declined because of lower demand for tilapia, triggering most of the intermediary businesses to shift their attention to marine products. In addition, a dramatic event occurred in 2011–12, when the electricity-generating company responded to high water levels by opening the reservoir floodgates causing enormous impact on the fishing community, with many fishers losing boats, engines and fishing gear. At the same time, the price of tilapia stayed very low, so many fishers could not afford to invest in new equipment and, therefore, left the fishery.

In the early 2000s, the total catch reached almost 3 900 tonnes; however, the fishery has experienced a decline, and in the last decade an average 863 tonnes have been landed annually. Daily catch has diminished from 139.1 kg/boat in 2009 to 95 kg/boat at present. The decline in the fishery is a result of falling demand, as intermediaries will now buy only 2–3 baskets of fish from each fisher (1 basket = 80 pounds [36 kg] of fish). Stock status is believed to have improved after the implementation of a management plan in 2009, which stipulates that only Chinese trammel nets with three layers of net with mesh sizes 5 inches (12.7 cm), 8 inches (20.3 cm) and 10 inches (25.4 cm) can be used, and only four net units are allowed per boat. The nets are set along the shore, and the fish are scared into the nets, where they become completely entangled. The management plan also establishes a three-month closed season. The Aquatic Resources Administration of Panama enforces compliance with the regulations established in the management plan, and also monitors catches and measures 100 fish twice a month in the open season.

The catch data from the years 2005–2007 and 2016–2018 were analysed. The trammel nets used in this fishery may show dome-shaped selectivity, and it was necessary to account for this possible pattern when estimating stock SPR from the catch length data, in order to correctly evaluate whether "missing" larger fish reflect size-based fishing mortality or gear selectivity. The extended GTG LB-SPR model (Hommik *et al*., 2020) was thus applied.

Tilapia is a well-studied species, and hence various gear-selectivity estimates were available in the published literature. The data suggested a normal distribution of lengths in the catch, and therefore normal selection parameters (0.274, 2.812) were taken from Hailu (2014).

The size-selection mode for the model assuming dome-shaped selection was estimated assuming a mesh size of 5 inches (12.7 cm). Alternatively, the inclusion of larger mesh sizes in the trammel nets may also make the gear effectively non-selective for the largest size-classes. To address this second possibility, the original GTG LB-SPR model (assuming logistic selection, Hordyk *et al.*, 2016) was also applied.

There are many published estimates of life-history parameters for *Oreochromis niloticus*, and this species shows strong phenotypic plasticity. A time series for Lake Victoria (Njiru *et al.*, 2008) provided a range of values that seemed consistent with the Lago Bayano data.

6.3.2 ANALYSIS

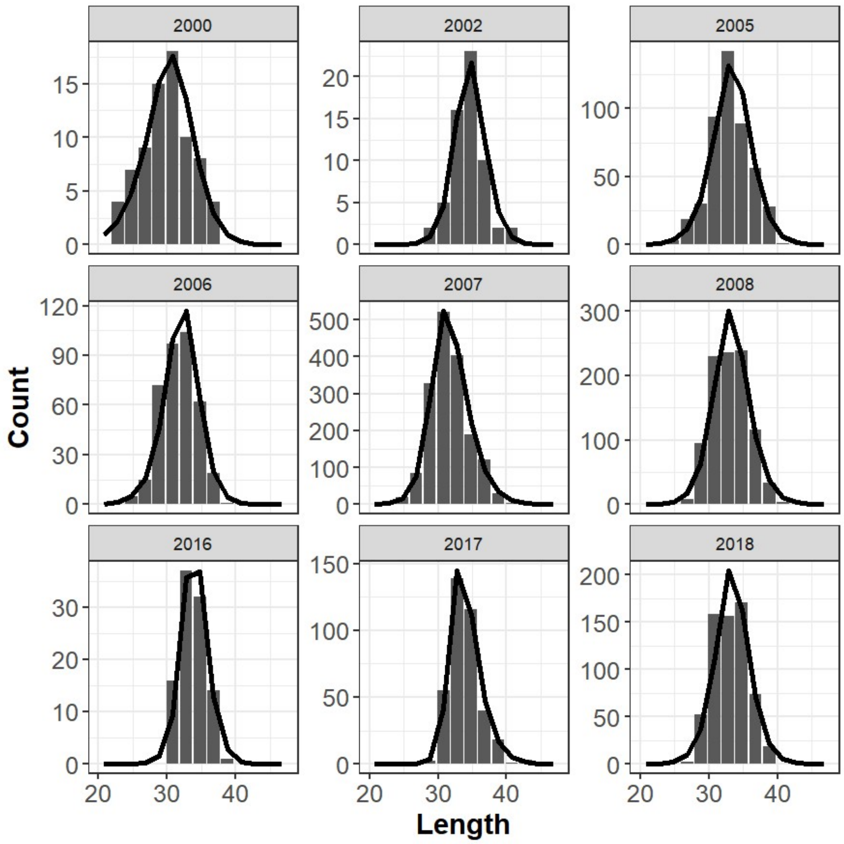
Based on the selectivity and life-history estimates above, a range of L_∞ (43 cm and 45 cm) and M/K (1.8, 2.0 and 2.2) values were tested using the dome-shaped model, while a fixed M/K = 2 was tested for the logistic model. This structure resulted in eight separate estimates of SPR (six dome-shaped and two logistic) for each of the study years. Sizes at 50 percent and 95 percent sexual maturity were fixed at 25 cm and 30 cm, respectively.

6.3.3 RESULTS

The LB-SPR model seemed to provide a good fit to the Lago Bayano tilapia data (Figure 9).

Figure 9

Annual length-frequency plots for the Lago Bayano tilapia samples

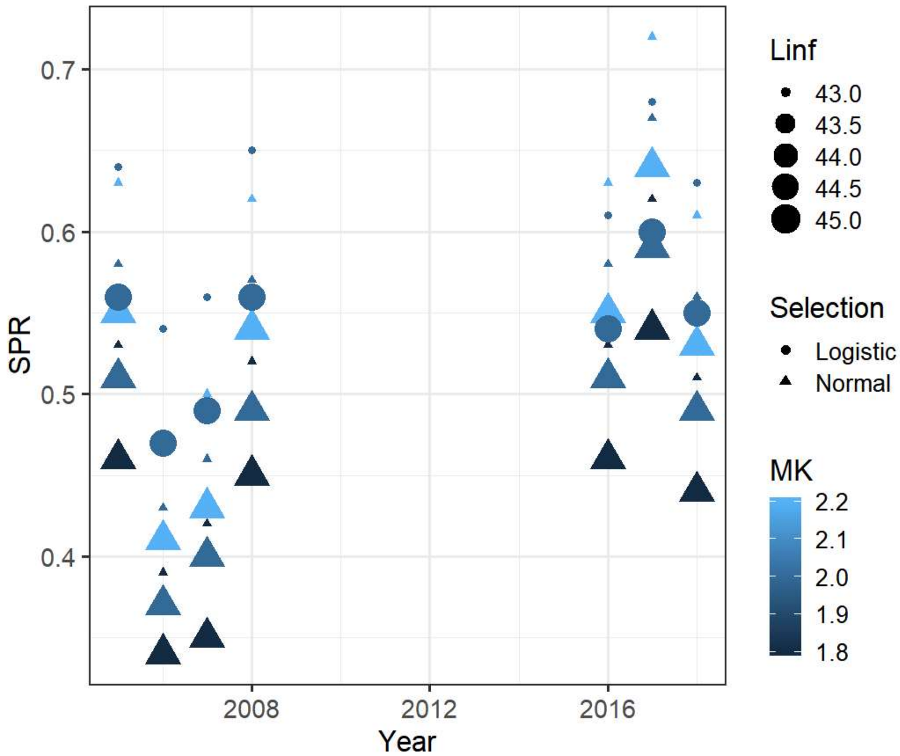


Notes: The black lines are the fitted LB-SPR model. Note differing y-axis scales.

Annual SPR estimates suggested that tilapia stock status had improved since the management plan was implemented, with values being consistently above a conservative sustainability reference point of SPR = 0.4. Estimates of SPR were typically similar or slightly higher for the model assuming logistic selection (Figure 10).

Figure 10

Estimates of SPR for tilapia in Lago Bayano, using different values for the input life-history parameters L_∞ (L_{inf}, cm) and M/K, and two different assumptions about gear selectivity (logistic and normal, i.e. dome-shaped)



6.3.4 INTERPRETATION

The data-limited GTG LB-SPR model can assess stock state relative to objective SPR RPs (Hordyk *et al.*, 2016). The model has been limited by the inherent assumption of asymptotic gear selection in assessed fisheries. The Lago Bayano tilapia data provide a case study for application of the recently extended GTG LB-SPR, which can accommodate dome-shaped selection (Hommik *et al.*, 2020). Selection parameters were already available, and therefore it was not necessary to conduct gear trials.

The LB-SPR model seemed to function well with the Lago Bayano tilapia data. Model plots suggested good fit to the data, and estimated SPR values were within a reasonable range and consistent between methods. The LB-SPR model assuming logistic selection tended to produce similar or greater estimates of SPR than the dome-shaped model. This contradicts the expectation (Hordyk *et al.*, 2015a) that the logistic model would underestimate SPR when confronted with data from a fishery having dome-shaped selection. A possible explanation is that the trammel-net gear is in fact non-selective for the available size range of tilapia, because the gear is operated actively by scaring fish into the net. Selectivity cannot be tested from the available data, but the similarity in SPR estimates between models suggests that this issue is not important for the current analysis.

6.4 SÁBALO, PARANÁ RIVER (ARGENTINA)

6.4.1 INTRODUCTION TO THE PARANÁ RIVER SYSTEM AND FISHERY

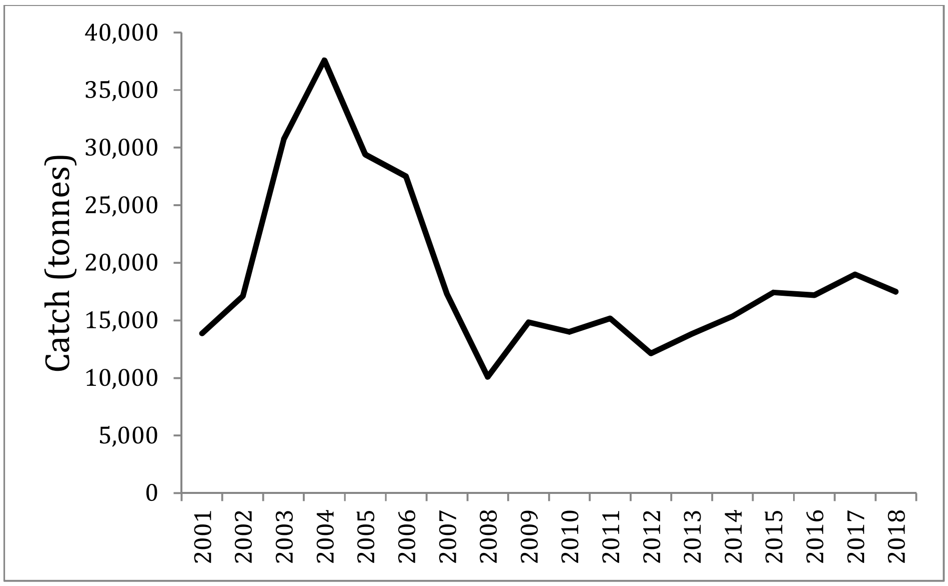
Figure 11
Sábalo fisher, Paraná basin.

Key facts	
Name of the waterbody/river:	Paraná River in Argentina
Type of waterbody/river or tributary river:	River
Size of waterbody/size of river basin:	3 million km^2
Gear:	Gillnet
Total number of species present:	
Target species:	Sábalo (*Prochilodus lineatus*)
Total annual catch:	Up to 40 000 tonnes/year (currently 15 000–20 000 tonnes/year)
Number of fishers:	3 000–3 500
Management regulations:	Catch quotas
Data availability:	2012–2017

In the lower Paraná basin, artisanal fishing is a traditional activity that provides most of the commercial catch within that region (Figure 11). The sábalo (*Prochilodus lineatus*) represents up to 60 percent of the fish biomass in the floodplain lagoons (Bonetto *et al.*, 1970; Tablado *et al.*, 1988) and is by far the main target (Quirós and Cuch, 1989; Baigún, Sverlij and López, 2003; Baigún, Minotti and Oldani, 2013). The sábalo exhibit different types of migratory movements adapted to cope with thermal regime and hydrological variability (Sverlij, Espinach Ros and Orti, 1993). The fishery has an annual catch regime. The most common gillnet mesh size used by fishers is 80 mm bar, which catches fish of 42 cm total length (mode size). If the fish size are smaller, some fishers will use 70 mm where the mode is about 38–39 cm. Fishing regulations are mostly based on gear restrictions and size limits, and depend on each province (Castillo, Baigún and Minotti, 2016). Since 2001, intense exportation activity has led to an increase in catch quotas reaching a peak of almost 40 000 tonnes per year, but they are currently managed at between 15 000 tonnes per year and 20 000 tonnes per year (Figure 12). Beyond the collection of catch statistics, some provinces and the State collect fishery information (catch and fish length) at a few landing ports, and periodically by experimental fishing.

Figure 12

Sábalo captures for export



Source: Ministerio de Agricultura, Ganadería y Pesca, Argentina, undated.

A comprehensive assessment of the stock up to 2009 suggested that status had declined following recent overfishing (Baigún, Minotti and Oldani, 2013). The current study used data from 2012 to 2017.

6.4.2 ANALYSIS

The sábalo data provide an interesting case in that they comprise length records from a set of experimental gillnets having mesh sizes covering the full selectivity range of the species (30–180 mm stretched mesh). This sampling gear is intended to be effectively non-selective, i.e. captures a representative sample of the stock size distribution. The approach is similar to many standardized sampling programmes for freshwater systems, e.g. for reporting under the European Union's Water Framework Directive (2000/60/EC). The GTG LB-SPR model (Hordyk *et al.*, 2016) was applied to assess the sábalo stock studied, on the assumption that the series of gillnet mesh sizes imparted logistic selectivity from some small size. This could bias the model estimate of F/M if the main commercial gear has different size selection to that of the survey gear, because LB-SPR infers relative fishing mortality by comparing the catch size distribution with a predicted "unfished" size distribution.

This application was complicated by the fact that the size distribution of the sábalo sample was bimodal in 2016 and 2017, with a clear length mode at about 25 cm in 2016 suggesting a strong cohort of fish becoming recruited to the gear. Sábalo recruitment as a periodic species is very sensitive to hydrological variation, and there can be clear differences in annual recruitment, leading to highly modal size structure. The potential issue is that the LB-SPR model provides a smooth "expected" size distribution that does not capture strong modality. Simulations in Hordyk *et al.* (2015a) suggest that the LB-SPR is reasonably reliable for bimodal size distributions, with a tendency to provide conservative results.

In the case of the sábalo case study, estimates of the life-history parameters (Baigún *et al.*, 2013) and gillnet selectivity (Doménico and Espinach Ros, 2015) were available from the literature. Length at 50 percent maturity for sábalo ($L_{mat50\%}$) is about 37 cm (Baigún, Minotti and Oldani, 2013). This $L_{mat50\%}$ value means that very few fish smaller than the 35 cm length mode will be sexually mature, and hence contribute to SPR. The data comprised standard length (SL) measurements for each individual sábalo, while Baigún *et al.* (2013) used total length (TL), hence a conversion equation was applied where TL = (1.209 × SL) + 1.057.

Based on the selectivity and life-history estimates (Baigún, Minotti and Oldani, 2013; Doménico and Espinach Ros, 2015), a range of L_∞ (63 cm, 65 cm and 68 cm) and M/K (1.5, 1.64 and 1.8) values were tested using the GTG LB-SPR model. This structure resulted in nine separate estimates of SPR for each of the study years. Sizes at 50 percent and 95 percent sexual maturity were fixed at 36 cm and 43 cm, respectively.

6.4.3 RESULTS

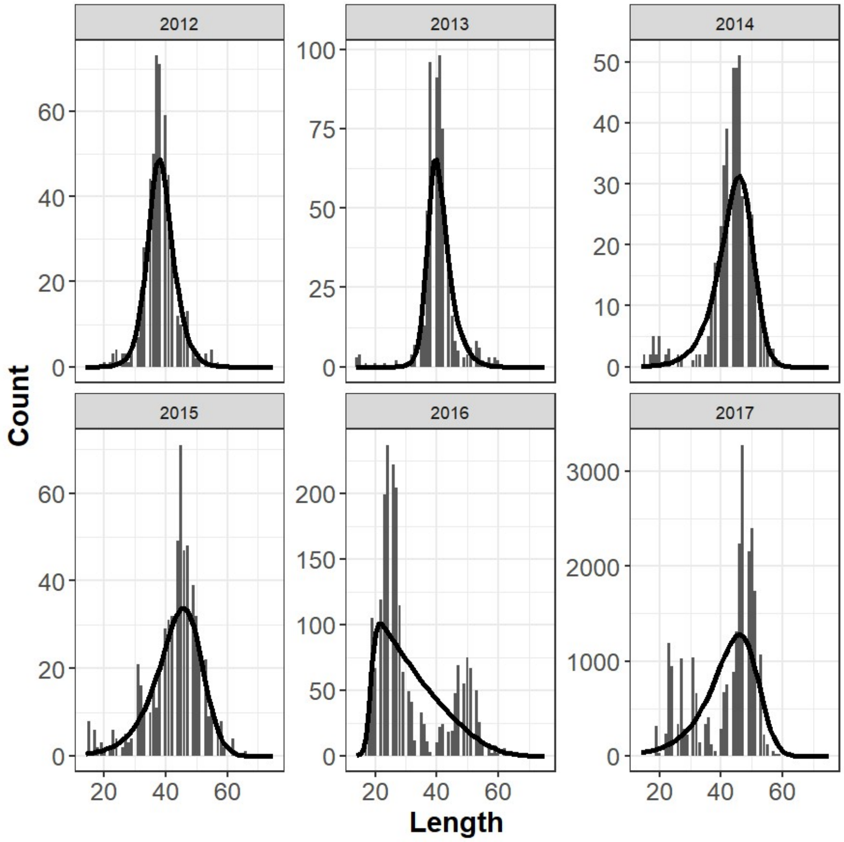
There was a clear displacement of the 2012 cohort (about 35 cm) to 2017, where it reached about 55 cm (Figure 13). There were problems with a relatively poor model fit in 2016 and 2017, due to the clearly bimodal length distribution, which may reflect the presence of a strong year class (20–25 cm) being recruited to the gear in 2016.

Encouragingly, the SPR estimates for these years were in the same range as the previous two years, and hence may be acceptable.

There is some evidence that this year class was rapidly fished, as the right tail of the larger mode was strongly curtailed at about 55 cm in 2017. Estimates of the SPR increased until 2014, and then remained at about 0.3–0.4 (Figure 14).

Figure 13

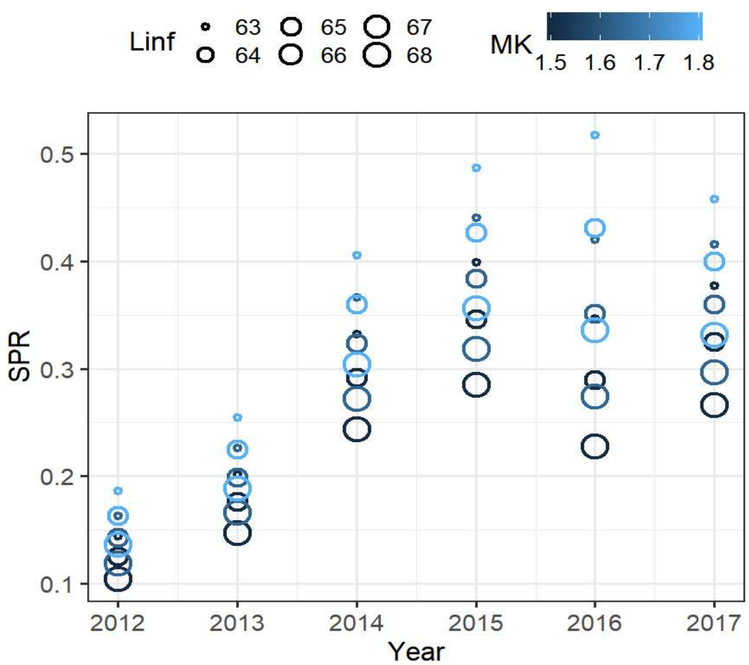
Annual length-frequency plots for the Paranà River sábalo samples



Notes: The black lines are the fitted LB-SPR model. Note differing y-axis scales.

Figure 14

Estimates of SPR for sábalo in the Paraná River, using different values for the input life-history parameters L_∞ (L_{inf}, cm) and M/K



6.4.4 INTERPRETATION

The size distribution of fish in the current study data includes individuals close to the von Bertalanffy L_∞, estimated at about 65 cm, although fish up to 70 cm were observed historically (Baigún, Minotti and Oldani, 2013). This observed size distribution suggests some loss of larger fish, but not serious overfishing.

Gillnets are typically assumed to show dome-shaped selectivity. However, the Paraná sábalo were sampled using a set of mesh sizes intended to derive a representative sample of the overall stock. In this case, the assumption of logistic selection probably holds, and so estimates of annual SPR were derived using the GTG LB-SPR model (Hordyk *et al.*, 2015a).

The estimates of SPR (about 0.3), suggest that the stock is fully fished. Notably, results shown in Baigún, Minotti and Oldani (2013) indicated that the SPR had declined to 0.2 by 2005, which was attributed to the uncontrolled exports that took place from 2001 to 2006. However, because the SPR mostly remained between 0.3 and 0.4 after 2014, some subsequent recovery is apparent. Such results suggest that the sábalo fishery is being fished at a maximum sustainable limit, and thus would be exposed to increased risk if hydrological scenarios were adverse to successful recruitment and juvenile survival in the floodplains. Strong flood pulses are required to ensure stock recovery following heavy fishing pressure, but fisheries management measures must be in place to safeguard sufficient megaspawner biomass during low-water years.

7. DISCUSSION

7.1 APPLICATIONS IN INLAND SMALL-SCALE FISHERIES

Beard *et al.* (2011) acknowledged that "there is an urgent need for rapid appraisal methods that empower local decision-making for small-scale fisheries in the developing world." This process will help attain the Sustainable Development Goals by supporting jobs and livelihoods, local food security and poverty alleviation (Chuenpagdee, 2019).

The aim of the current review has been to discuss and apply some accessible approaches to support low-investment monitoring and rapid assessment of inland fisheries, using available data rather than requiring new resource-intensive sampling programmes. While this low-tech approach may not satisfy the needs of large-scale commercial fisheries, it does but represent a tractable first step in management of numerous stocks that have real social, economic and ecological importance (Cooke *et al.*, 2016; Lynch *et al.*, 2016), mainly where fisheries data collection and assessment processes are less developed (Lorenzen *et al.*, 2016; Fitzgerald, Delanty and Shephard, 2018). The immediate priority is to establish some form of monitoring and management that is feasible and affordable within the socio-economic and governance constraints impacting the fishery (Dowling *et al.*, 2018). Moving towards management objectives, rather than waiting for improved assessments (Mahon, 1997), can support interim "pretty good yield" (Hilborn, 2010).

The review and case studies presented here make a case for the application of empirical indicators and an established length-based model (LB-SPR) for assessment of data-limited inland fisheries. These methods require only a sample of the size distribution of the catch, and can be used in conjunction with appropriate sustainability RPs and key biological parameters related to growth and mortality. Both empirical and model-based indicators will benefit from expert interpretation, which can be provided by local scientists, fishers and other stakeholders with insight into the history and trajectory of the fishery. Users in other systems can evaluate data availability, and then decide on appropriate methods on a scale from expert knowledge only, to empirical indicators (where length data only are available), and up to the LB-SPR (where length data and life-history parameter estimates are both available).

The methods have been previously tested on temperate recreational salmonid stocks, but this is the first application in commercial inland fisheries in a developing-country context. The current study did not conduct sensitivity testing of the methods, as this had been thoroughly explored previously (e.g. Hordyk *et al.*, 2015a, 2015b). Instead, the intention has been to present a set of case studies that can guide users implementing data-limited stock assessments in other similar fisheries worldwide. The case studies highlight several potential issues, limitations and solutions for the suggested methods. These are summarized (Table 9) and then discussed; each of these issues will require careful consideration, and there are some fishery types where alternative approaches will be more appropriate.

Table 9

Summary of potential issues and solutions

Issue	Problem	Limits to application	Possible solution
Small sample size	LB-SPR model fit.	Need at least 60–100 individuals (Babcock, Tewfik and Burns-Perez, 2018).	Additional sampling, or select a few abundant species for assessment.
Spatial issues	Some target fish species may have strong spatial segregation of life-history stages.	Length samples may not be representative of underlying population size distribution.	Spatial stratification of the sample.

Selectivity issues	Many inland fishery gears (gillnets, hooks and small traps) show dome-shaped selection.	Dome-shaped selection is not incorporated in the current LB-SPR.	A modified LB-SPR method is being developed (Hommik *et al.*, 2020). Selection parameters are derived from a selection experiment and provided to the modified model.
Bimodal distributions	Freshwater fish species may often show strongly modal size distributions due to large interannual fluctuations in recruitment.	Potential poor model fit using the LB-SPR model. May not be a serious issue (Hordyk *et al.*, 2015a).	Use an assessment model with an annual recruitment time-step that can capture strong peaks in recruitment, e.g. Fitzgerald *et al.* (2019).
Multispecies and multigear fisheries	A species may be taken by more than one gear type, and catches from these mixed gear types may not correspond to the selectivity of one gear type.	The modified dome-shaped LB-SPR requires a single set of selection parameters corresponding to the sampling gear.	Length samples should come from only a single gear, ideally the one responsible for most fishing pressure.
Phenotypic plasticity (limits borrowing of data from known cases)	Some species, particularly tilapia, can show strong system-specific differences in life-history parameters, e.g. maturation schedule.	The LB-SPR method requires reasonably accurate estimates of life-history parameters, and for many species, these values can be borrowed from other systems. This is more difficult for the highly plastic tilapia.	Where possible, borrow from other systems; otherwise, track size at maturity in the study system.
Monsoon drivers	Monsoonal fisheries are often highly seasonal as they target fish migrations driven by flood pulses.	The fishery may target different size or life-history components in different seasons. Samples from these subcomponents may not be representative of the whole underlying population.	Stratify sampling in space and also time, e.g. river sections, and important season, e.g. dry vs monsoon season.
Annual recruitment	Particularly in multispecies floodplain fisheries, there is a surge in annual-recruiting fish,	LB-SPR cannot be used for these fisheries that target only juvenile fishes as they return to the main river channel,	The method may still be applicable to larger, longer-lived species also caught in these fisheries,

Small sample sizes may be relatively tractable, as the LB-SPR can produce reasonable (if uncertain) estimates with as few as 60 fish (Babcock, Tewfik and Burns-Perez, 2018; Hommik *et al.*, 2020). Unknown (dome-shaped) selectivity in commercial gear (or gear types) can also be resolved if it is possible to undertake targeted scientific sampling using non-selective gear such as multimesh gillnets. Survey gillnets with a standardized range of mesh sizes can collect a non-selective sample that is representative of the underlying population size structure, and this approach was used in the current Paraná River sábalo case study. A problem with this is that the sampling gear may have different selectivity to the commercial gear, and so the model estimates of F/M may be incorrect, and of reduced value in interpreting trends in the SPR. Hommick *et al.* (2020) address this issue by accounting for differences between sampling and fishery selectivity.

An advantage of survey data is that they capture cohort trajectories and the strength of annual recruitment events. This information coupled with hydrological data could be important for anticipating management measures based on empirical LBIs. An alternative is to conduct selectivity experiments (or identify existing work) to determine the selection parameters of the commercial fishing gear from which samples are collected. This approach was taken in the Lago Bayano tilapia case study.

A multimodal stock size structure, which may occur in species with strong (environmentally driven) year classes, is a more difficult issue to address. Hordyk *et al.* (2015a) suggest that the LB-SPR model can still provide robust estimates of the SPR in this situation, and the current results for sábalo seem reasonable. One solution may be to use only data from the larger mode, which represents the most important spawners (i.e. the "big old fat fecund female fish" [BOFFF]).

Two of the Amazon Goliath catfish (piramutaba and dourada) demonstrate the potentially most awkward situation, which is systematic spatial heterogeneity in length structure. This is critical, as size-based methods make the basic assumption that the size distribution of the sample is representative of the assessed stock. In the current dourada case study (1999 data), the upstream trend of increasing mean size is reflected in greater SPR estimates farther from the Amazon estuary. However, the SPR averaged across all sites in this year is similar to estimates derived from samples pooled across several sample sites in proximate years. This result suggests that collecting samples from across the range of the species can provide an adequately representative sample, with the Amazon River being an extreme case.

7.2 USING DATA-LIMITED ASSESSMENT IN MANAGEMENT

An important consideration is how fishers and fisheries co-managers might respond meaningfully to negative changes in empirical or model-based indicators. Cooke *et al.* (2016) point out that inland fisheries management often "occurs in the absence of assessment or assessment occurs and is not directly linked to the fisheries management cycle or integrated into adaptive management or an ecosystem approach framework." This comment highlights the need for specified MPs that are explicitly linked to stock state (Butterworth, 2007), i.e. some form of "harvest strategy framework" for selection of indicators to determine state relative to RPs, and how and when management decision rules will be invoked (Dowling *et al.*, 2015; McDonald *et al.*, 2017).

There may not be capacity to control catch or fishing pressure in the majority of data-limited inland fisheries, but the use of size-based state indicators creates an obvious link to size-based technical measures, e.g. mesh size regulations and fish minimum size limits. Vasilakopoulos, O'Neill and Marshall (2016) and Prince and Hordyk (2018) reaffirmed that, when the size of first capture (L_c) for a fish population is sufficiently greater than the size of maturity (L_{mat}), both yield and spawning biomass can be maintained despite high levels of fishing pressure. This "rule of thumb" suggests that simple measures that shift the fishery size-selection curve to the right of the maturity-at-length given for a target species can achieve sustainability objectives (Ayllón *et al.,* 2019).

The LB-SPR case studies presented here have focused deliberately on such examples, where it makes ecological and management sense to undertake single-species assessments and potentially impose management regulations at this resolution.

Importantly, size limits may not make sense for targeted multispecies communities, e.g. tropical lakes or large river floodplains, where selective removal of large fish may not produce sufficient yield, and can induce trophic cascades (Kolding *et al.,* 2016). Size limits are also unlikely to work in these systems without an effective co-management system upholding the regulations. In this case, it would make sense to combine these single-stock indicators with community- or assemblage-level metrics that can monitor shifts in trophic structure, size distribution and species richness.

Management procedures are typically tested by simulation to confirm that they can be expected to achieve key objectives (Butterworth, 2007). Jardim, Azevedo and Brites (2015) used management strategy evaluation (MSE) to test a simple HCR, which adjusted future catch up or down when the mean length in the current catch is above or below the target ($L_{F=M}$), respectively. This HCR effectively reduced overall catch rate when fishery size selection moved towards smaller fish. This would be a useful tool in fisheries where there is creep towards smaller mesh sizes, and is an alternative to trying to enforce mesh size limits. The HCR was shown to recover the majority of a set of simulated fished stocks, but was typically not successful when L_c was well below L_{mat}.

However, to progress toward an ecosystem-based management approach for large floodplain rivers, environmental scenarios dictated by hydrological conditions and flood pulses should be considered in order to orient the HCR.

The extensive implementation and evaluation of size-based technical measures mean that further testing is probably not vital in the short term. A useful exercise might be to conduct MSEs implementing size-based technical measures (rather than catch limits) using a length-structured fish population/community operating model. An important addition for inland fisheries assessment could be to incorporate simulated trends in recruitment that might reflect decline in spawning success due to incremental habitat loss. Such studies could be informed by known hydrological proxies of recruitment success, e.g. flooded area, floodplain connectivity indices, and flooding time.

A strong advantage of size-based technical measures is that they are intuitive and transparent, supporting co-management and more explicit acknowledgement of social-ecological feedbacks (Nguyen *et al.*, 2016). It is easy to understand that the use of undersized mesh will probably result in recruitment overfishing and associated economic loss because fish do not have a chance to grow large (e.g. Mulimbwa, Sarvala and Micha, 2018).

Different inland fishing gear types have different selection profiles, and, in cases of declining stock state, there is scope to manage these (Ghulam Kibria and Ahmed, 2005), e.g. by restricting small traps or fine-mesh seines (McClanahan and Mangi, 2004). Some local groups have also implemented minimum size limits for targeted inland fishes successfully (e.g. Amarasinghe and De Silva, 1999).

However, an important exception to the assumptions of size-based fishing, and consequently to the utility of rule-of-thumb size-based measures, may occur in unregulated open-access fisheries targeting a broad multispecies fish community such as the African lakes and large river floodplains. In this situation, an EAFm co-managed by the fishing community is likely to be appropriate. The objectives would be to maintain sustainable fishery yield while preserving ecosystem structure and function.

There is some evidence that the size-spectrum slope, describing the distribution of $\log_2$ body mass across species, can be maintained by de facto balanced harvesting (Law, Kolding and Plank, 2015) implemented using non-selective (small-mesh) gillnets (Kolding *et al.*, 2016) or a varied balanced multitude of different fishing methods. The African lakes provide empirical examples of systems where overall biomass of demersal species has been depleted while maintaining the size spectrum of this assemblage (Kolding and van Zwieten, 2014). In this case, there may have been a shift towards a system dominated by small pelagic species. In this context, access restrictions or closures, rather than size limits, may be the most relevant management tool.

The appropriate form of co-management will depend on the nature of each system and existing user groups (Sen and Nielsen, 1996), and co-management can emerge spontaneously for collaborative problem-solving in fisheries (Galappaththi and Berkes, 2015). In the Tonlé Sap, co-management has been established to support community fisheries.

In severely impaired systems, radical restructuring of fishing patterns will be required (Tweddle *et al.*, 2015), and technical regulations typically fail (Hara and Njaya, 2016). Gillnet mesh-size regulations of the sort envisaged here are associated with user conflicts between Zambia and Zimbabwe, because of cross-border differences in management strategy for Lake Kariba (Bower *et al.*, 2019).

Indeed, size-based management may not be most productive in this system (Kolding *et al.*, 2016). In the context of such challenges, it is hoped that the visual indicator plots presented here will provide a tool for discussing stock status with users, and for highlighting the opportunity for appropriate size-based technical measures that can be locally implemented and cooperatively enforced.

7.3 SUMMARY

Inland fisheries support numerous communities, but these social-ecological systems are beset by severe and complex problems. A small part of the solution is appropriate quantitative or semi-quantitative methods to evaluate the state of target resources. Data-limited assessment tools used in marine fisheries can be successfully interpreted to fulfil this role in some important cases, where data availability improves from 1 to 3:

1. Expert knowledge is available from local stakeholders, including fishers, scientists etc. This knowledge can be used to infer and interpret shifts in stock status that might trigger co-management action.
2. Length and catch or CPUE data are available, or can be collected with little additional sampling effort. Empirical indicators can be applied using a reference direction approach that may be informed with expert knowledge of fishery and environmental events. In a fishery that catches multiple species, selecting a set of key indicator species may offer some insight into the overall state of the assemblage. There are promising signs that this could be used as a means to assess the state of a mixed-species fishery as shown by the results of the Tonlé Sap case study.
3. Length data and estimates of key life-history parameters are available. The LB-SPR model can provide useful information on the state of target stocks, relative to an objective SPR RP. This has been demonstrated here using the Amazon catfish case study. This new insight can then be used to inform co-management discussions, and could even be collected by stakeholders through co-management agreements. This scenario moves well beyond just reporting catch volume as an indicator of the state of a fishery.

Researchers can evaluate existing and potential monitoring and data availability in the systems for which they are responsible. The case studies presented here could then be used as a starting point for considering applicable size-based assessment approaches. Other similar methods available in the literature should also be considered and may be more appropriate in given cases. It should then be possible to make a suitable assessment of important fishery resources.

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Inland fisheries are often complex, spatially dispersed and difficult to monitor and their status is therefore difficult to assess. This publication reviews the applicability of empirical indicators and simple size-based models usually used in marine fisheries to existing data-sets from four important fisheries in respectively the Amazon Basin, Tonlé Sap River, Paraná River and Lago Bayano. The trends in stock state were interpreted by local scientific experts. These case studies discuss how a number of variables related to each environment or fishery influence the outcomes of the analyses. The review concludes that data-limited assessment methods developed for marine stocks, under the right conditions, may provide guidance for the sustainable management of important target species in inland fisheries. However, the methods tested are probably less applicable in non-selective fisheries where small species are preferred, or in river fisheries with extreme dependence on flood pulses. Important considerations include species life history, spatial distribution, environmental variability, and fishery sampling strategy.

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