FEATURE

From Amazon Catfish to Mekong Money Fish: Size-Based Assessment of Data-Limited Commercial Inland Fisheries

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Dai fishing on the Tonlé Sap River in the Mekong basin in Cambodia. Photo Credit: Peng Bun Ngor, Wonders of the Mekong Project

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Inland fisheries are often complex, spatially dispersed, and seasonal. A lack of monitoring can result in unreliable or incomplete catch data, suggesting a role for assessment methods based on population size structure. This paper evaluates and compares empirical size-based indicators and the length-based spawning potential ratio model as candidate tools for assessing data-limited commercial fisheries in inland systems. Case study applications are presented for a contrasting set of important fisheries in the Amazon Basin (Brazil, Bolivia, Colombia, and Peru), the Tonlé Sap River (Cambodia), Paraná River (Argentina), and Bayano Reservoir (Panama). These case studies were selected to explore the effects on assessment of factors including lack of life history information, spatial separation of life history stages, modality in population size structure of floodplain river fish, and fishing gear selectivity. An international workshop was organized to bring together experts from the study systems and elsewhere to discuss the results, and to highlight potential issues and caveats. It was concluded that length-based models may work well in cases where size-selective gears are used to target a few larger species with reliable life history parameter estimates. Empirical surveillance indicators are more flexible for integrating quantitative data with local expert knowledge in common data-poor situations. In general, size-based assessment can provide guidance for the sustainable management of target species in diverse inland fisheries.

INTRODUCTION

Inland commercial and artisanal small-scale fisheries are extremely important to numerous rural communities (Smith et al. 2005; Lynch et al. 2016), and make a critical dietary contribution in low food security regions (Kawarazuka and Béné 2010; McIntyre et al. 2016). However, developing countries often have limited investment in monitoring their complex subsistence fisheries (Bartley et al. 2015). This situation can result in unreliable catch estimates and poor understanding of the status of exploited stocks (Fluet-Chouinard et al. 2018) that are often vulnerable to collapse (Andrew et al. 2007).

Lack of information has limited the representation of inland fisheries in dialogue on livelihoods and food security (Funge-Smith and Bennett 2019), and management often occurs in the absence of appropriate assessments (Cooke et al. 2016). There is an urgent need for accessible and reliable appraisal methods that empower local decision making (Beard et al. 2011). Resource-intensive sampling programmes may be slow to establish, and may never be possible in some remote and complex inland systems. It is thus necessary to support assessment of fisheries that are likely to remain data-limited (De Graaf et al. 2015; Cooke et al. 2016).

Science and management ideas should be shared between commercial and recreational fisheries (Cooke and Cowx 2006), and across marine and inland systems (Cooke et al. 2014). Data-limited assessment methods from marine fisheries can be transferred to freshwater (Lorenzen et al. 2016; Fitzgerald et al. 2018), but the process, uncertainties, and outcomes must be critically confronted (Dowling et al. 2018). The diverse and highly decentralized nature of inland fisheries means that candidate monitoring and assessment approaches from the marine will require testing and interpretation before they can be applied transparently. It is vital to recognize the enormous social and ecological differences between marine and inland fisheries, including the mechanisms of anthropogenic pressures that threaten to degrade entire freshwater systems.

On-going research into assessment of data-limited fish stocks provides many different approaches to consider (e.g., review in Chrysafi and Kuparinen 2016). Catch-based methods are useful where there is reasonably standardized reporting of landings from an exploited stock. This is a rare situation in inland small-scale fisheries, especially in developing countries, where catch is often recorded inconsistently and from only a small fraction of numerous local landing sites. Correspondingly, national statistics reported to the Food and Agriculture Organization of the United Nations (FAO) probably underestimate inland fisheries catch (Funge-Smith and Bennett 2019).

Size-based methods do not require catch records, and data can be derived from fisheries-independent surveys, from fishers or from catch (Ticheler et al. 1998; Prince et al. 2015; Van Damme et al. 2019), although assessments may be biased when these data are not representative of the target stock. These approaches are frequently used to assess marine stocks where size-selective fishing mortality curtails the length structure of populations by removing larger individuals (Gulland and Rosenberg 1992), and of communities (Shin et al. 2005) by removing larger species (Welcomme 1999; Shephard et al. 2012). Angling also typically removes larger fish (Miranda and Dorr 2000; Arlinghaus et al. 2008) and is associated with shifts in population size distributions (Lewin et al. 2006).

Empirical length-based indicators (LBIs) are often used to measure and monitor progress towards sustainability (Garcia and Staples 2000). Empirical LBIs can be a good starting point for fisheries progressing towards management using simple models (Babcock et al. 2013; Bentley 2015). Length-based models can perform as well as catch-based methods in many scenarios, although the optimal assessment technique will depend on data availability and the biology of target species (Pons et al. 2020). These models can be applied for stocks where appropriate input life history parameters (e.g., growth and mortality rates) are available.

Models provide an opportunity to implement absolute management reference points (RP) for data-limited stocks. Reference points express some measure of the stock that relates to status and define desirable "target" levels or "limit" levels, which management attempts to avoid (Caddy and Mahon 1995). Size-based models use RP based on the population structure theoretically expected for an unfished stock. Management procedures based on relative abundance or mean length RP have consistently satisfied conservation performance metrics in marine fisheries (Geromont and Butterworth 2015; Sagarese et al. 2018). The relatively rare application of formal data-limited approaches in inland fisheries means that management using RP is much less prevalent in these systems (Welcomme 2001).

The goal of the current study was to evaluate the use in commercial inland fisheries of LBIs and a length-based model (The Length-Based Spawning Potential Ratio model [LB-SPR]; Hordyk et al. 2015a). These two approaches have undergone extensive technical evaluation elsewhere (see references below), and so the objectives were to identify types of inland fishery where they are most likely to be useful and to highlight key potential issues or caveats. We provide a set of case study applications in important fisheries systems in Asia and Central and South America.

Empirical Indicators

Length-Based Indicators track change in aspects of population size structure, and are typically estimated using fish lengths sampled from commercial or survey catch. Such "model-free" indicators (McDonald et al. 2017) are not typically data- or expertise-hungry (Geromont and Butterworth 2015) and can be derived for numerous important stocks (Chrysafi and Kuparinen 2016). They provide anything from robust assessment down to "a rough indication of the state of a fishery" (Lorenzen et al. 2016).

Single-species empirical LBIs are frequently used for marine stocks (Froese 2004; Cope and Punt 2009), and applications in freshwater recreational fisheries (e.g., Anderson 1976; Gabelhouse 1984) have been widely used for management. Applications of LBIs in commercial inland fisheries have typically focused on fish communities, where many species are harvested and managed together (Kolding and van Zwieten 2014). Assemblage-level LBIs function in some floodplain rivers (Welcomme 1999), when fisheries are size- and species-selective (Hallwass and Silvano 2016; Doria et al. 2018), and modify community size structure (Fabré et al. 2017; Van Damme et al. 2019) and species composition (Ngor et al. 2018). LBIs may be less informative if the fishery exploitation pattern approximates to balanced harvesting (Kolding and van Zwieten 2014; Kolding et al. 2016).

Froese (2004) suggested three LBIs, which track growth, maturation, and the presence of large fish in a population. These indicators were then integrated by Cope and Punt (2009) and have subsequently been applied to tropical reef fisheries (Karnauskas et al. 2011; Babcock et al. 2013, 2018), and some temperate inland stocks (Baigún et al. 2013; Fitzgerald et al. 2018; Shephard et al. 2018).

Empirical indicators can be used "operationally," invoking known pressure-state relationships and associated (frequently trends-based) RP to support effective decision making (Dowling et al. 2015; McDonald et al. 2017). More frequently, the lack of understanding of the dynamics of anthropogenic pressure and stock state make it difficult to establish meaningful management RPs. In this case, indicators may then take a "surveillance" role, providing complementary information (including warning signals) that informs science and management (Shephard et al. 2015). Surveillance indicators provide a flexible tool for monitoring change in inland fisheries (Shephard et al. 2019a). Interpretive surveillance plots track stocks in relation to broad expectations about state, e.g., that healthy stocks should have more large individuals. This represents a trends-based approach as commonly used in marine fisheries (e.g., Cotter 2009; Greenstreet et al. 2012). Observed trends in state can be related to likely starting condition, specified from data (e.g., Carruthers et al. 2014) and/or expert narrative (Pasquaud et al. 2012; Canales et al. 2018). Impacted stocks should show movement in a positive direction, while healthy stocks should not decline (Rochet et al. 2005).

Assessments using empirical indicators should be structured to integrate expert knowledge (Chrysafi et al. 2017), perhaps harnessing "data-less" knowledge (Johannes 1998) to interpret indicator trends (Shephard et al. 2019a, 2019b). Accessible metrics should be close to raw data and have few assumptions (Van Zwieten et al. 2011; Njaya 2018). Users could be local experts (Prince 2003) or co-management groups who need an approximate impression of state to inform "nudges" in behavior (Mackay et al. 2018).

LB-SPR Model

Empirical approaches should not mask the fact that "there is no substitute for better data" (Dowling et al. 2018). Where appropriate life history information is available (e.g., fish growth, maturity, and mortality rates), length-based models offer scope to assess state against objective RPs. There are many model options, which may be almost equally good. The length-based integrated mixed effect (LIME) model (Rudd and Thorson 2018) demonstrates similar performance to LB-SPR (Chong et al. 2020), but requires an estimate of natural mortality (M). Reliable estimates of this parameter are typically unavailable for the freshwater fishes of many developing countries. The LIME model may also be more suitable for assessments with time-series longer than a year (Chong et al. 2020). The LB-SPR (Hordyk et al. 2015a, 2016) was selected from available options because it has been evaluated as consistent and accurate among a set of data-limited, length-based stock assessment methods (Chong et al. 2020). It has minimal requirements for biological parameters, and is applicable in freshwater fisheries (Hommick et al. 2020).

Spawner Potential Ratio (SPR) is defined as the proportion of un-fished reproductive potential left in a stock at given fishing pressure (Goodyear 1993), and is commonly used to set fisheries RP. Management should set SPR to a value that protects against serious stock depletion to prevent recruitment overfishing. Goodyear (1993) recommended SPR targets of no less than 20–30%, based on observations of marine species that are pelagic at early life stages. The LB-SPR uses input estimates of the ratio M to growth rate k (M/k), and von Bertalanffy asymptotic length L_∞ to predict un-fished population structure. Inputs of the sizes at which 50% and 95% of the population mature ($L_{mat50\%}$ and $L_{mat95\%}$) then allow un-fished spawning potential to be estimated from "expected" numbers of fish at size (Hordyk et al. 2015b). The model uses maximum likelihood to find the values of relative fishing mortality F/M and selectivity-at-length that minimize the difference between observed catch size distribution and the expected distribution, and calculates the SPR.

The original version of LB-SPR made the assumption of asymptotic (trawl-type) selectivity in target stocks (Hordyk et al. 2016); the same important assumption is made in the length-based Bayesian biomass, another candidate model (Froese et al. 2018). In contrast, gillnet or hook gears more commonly used in inland fisheries typically show dome-shaped selection, in which larger individuals have a declining probability of retention in smaller mesh or hook sizes. This assumption is important, because in a fishery with dome-shaped selection, these models would assume that the "missing" larger fish in the catch had suffered fishing mortality rather than not been retained in the gear, and consequently estimate poorer stock state. A recent model extension now allows appropriate dome-shaped selection parameters to be input to LB-SPR (Hommick et al. 2020), providing new potential for application in many inland fisheries.

Length-based models are sensitive to values of the input life history parameters (Hordyk et al. 2015a, 2016). These values may be difficult to estimate reliably for specific stocks, but can be derived statistically from taxonomically-related species (Thorson et al. 2017) or sometimes derived from FishBase (fishbase.org).

The LB-SPR was initially applied to tropical reef fisheries (Prince et al. 2015), but has subsequently been implemented for several temperate stocks (e.g., ICES 2015). Babcock et al.

(2018) applied both empirical indicators and LB-SPR to a small reef fishery, where the methods produced similar state assessments. While SPR has been used as a RP for river fisheries including Sábalo *Prochilodus lineatus* in the Paraná River (Baigún et al. 2013) and Mississippi Channel Catfish *Ictalurus punctatus* (Slipke et al. 2002), the LB-SPR model has seldom been applied to inland fish stocks.

Selection of Case Studies

Acknowledging the value of ensemble approaches (e.g., Chong et al. 2020), we demonstrated single-species assessments using LBIs and LB-SPR, and compared estimates of stock state between methods. Case studies aimed to balance data availability with study objectives, where the intent was to evaluate how the two approaches performed in contrasting fishery types with differing data availability. We assumed that it would be informative to cover a range of fishery types (gears) and systems (rivers and lakes), as well as temperate and tropical locations, with different exploitation and management histories.

Inland fisheries in developing regions are more likely to be data-limited, and potentially more important for food security (Funge-Smith and Bennett 2019). We used case studies that addressed target fish stocks in the tropical Tonlé Sap (Mekong basin, Cambodia), Amazon basin (Brazil, Colombia, and Peru), and Lago Bayano reservoir (Panama), and the temperate Paraná River (Argentina). Existing data were supplied by local scientific experts, who participated throughout the study process. The LBIs and/or LB-SPR were applied depending on availability of data and supporting fish life history information.

The Mekong case study supported species-level LBIs only and allowed a comparison with previously published assemblage-level assessment(s) of state in this system (Ngor et al. 2018). The subsequent studies focused on fisheries targeting a broad size range of individuals from a small number of readily identified species, as these cases seemed most appropriate for size-based single stock analysis. The Amazon study considered three species of goliath catfish (Pimelodidae), and was used to directly compare LBI trends with time series of SPR estimated by LB-SPR. The single-species case studies for Sábalo in the Paraná River and Nile Tilapia *Oreochromis niloticus* in Lago Bayano provided opportunities to test how fishing gear type, input life history parameter values, and assumptions about gear selectivity affected state assessments from LB-SPR in very different freshwater systems.

All case study contributors, and other experts, subsequently participated in a face-to-face expert workshop held at the FAO (FAO 2020) in 2019. This workshop interpreted the results, highlighting and discussing potential issues and caveats. It provided invaluable conclusions and guidance related to interpreting length composition and biological parameters in different systems, and identified general issues for size-based assessment of data-limited inland fisheries.

CASE STUDIES

Dai Fishery, Tonlé Sap, Mekong River (Cambodia)

Introduction

The commercial *dai* (fixed bagnet) fishery takes place in the lower Tonlé Sap River (Ngor et al. 2018), a location unchanged for more than a century. The individual dai nets are currently anchored in 14 rows, with exclusive access to each anchoring location being auctioned biennially. The fishery takes place around October–March, as water recedes from the lake. The primary target is migratory fish that feed or spawn on the Tonlé Sap floodplain in the wet season before returning to the Mekong mainstream for dry season refuge. Larger fish tend to migrate in the beginning of this season (Ngor 2000). Daily catches may be up to 80 tons per *dai*, with a monthly peak in landings occurring 7–14 days after the new moon (Halls et al. 2013a).

Dai nets are unselective and retain up to 141 species, but catches are dominated by small-bodied Mud Carps, including the important food fish *Gymnostomus lobatus*, known as *trey riel* or "money fish." Overall, daily catch per *dai* (2000–2015) has fluctuated with no significant trend. However, 78% of 116 species studied show decreasing catches, with declines predominately among larger species (Ngor et al. 2018).

The Tonlé Sap is one of the world's most productive fisheries, and contributes significantly to food and nutrition security by supplying fresh and processed fish products, e.g., fish paste, *prahoc* (Halls et al. 2013b; Ngor et al. 2018). The system depends on the annual flood pulse (Arias et al. 2013), and so the current drive for large-scale hydropower is a significant threat as it can degrade entire ecosystems (Keskinen et al. 2015; Lima et al. 2020).

This case study supported calculation of a simple LBI and corresponding abundance indicator, allowing bivariate surveillance plots to be used for selected species. This visual approach is intended to help elicit expert knowledge that can help inform state assessment in fisheries where life history information is not available to parameterize models.

Data Collection

Catch sampling occurs on about 17 days each month. During the peak period (around 7 days), 6–8 hauls are sampled daily from each of a random set of *dais*. In the low period, sampling occurs every 2–3 days, with three to four hauls sampled over a 12-hour period (Halls et al. 2013b). Species composition is recorded for each haul, and a sub-sample of fish is sorted by species, weighed and counted. Individual length measurements are taken for a number of common species (Ngor and van Zalinge 2001), including the study species *Gerrardanthus lobatus*, *Cirrhinus microlepis*, *Labiobarbus leptocheilus* and *Cyclocheilos enoplos* (see So et al. 2019). The current analysis used data from 2001–2004 and 2007–2015.

Analysis

Life history parameters were not available for the multi-species Tonlé Sap *dai* fishery. We were not confident that estimates from other systems or time periods (possibly available from FishBase) would provide reliable inputs to a model such as LB-SPR, in which the outputs vary strongly with these parameters. We chose instead to apply only an empirical indicator approach that makes no specific assumptions about life history. Indicator surveillance plots were used to present paired annual time series of a simple LBI and a corresponding relative abundance indicator for each of the four species in the sampled catch. The LBI comprised the annual 95th percentile of observed species length $L_{95\%}$ as a proportion of observed maximum length L_{max} ($L_{95\%}/L_{max}$). This metric captures how population structure (essentially the predominance of larger individuals) deviates from a fixed threshold (the largest observed individual). The relative abundance indicator was defined as $N_{species}/N_{total}$, i.e., the proportion of a given overall annual catch (all study species) that was comprised of each of these four species. This indicator was standardized to the maximum observed annual value by study species.

Surveillance indicators are characterized by the absence of well-understood pressure-state relationships (Shephard et al. 2015). The indicators used for the *dai* fishery thus provide insight into the relative state of target stocks ("better or worse") but not a conclusive link to associated pressure(s). An important aspect of applying surveillance plots to the *dai* fishery was expert elicitation to inform interpretation of observed indicator trends; local scientific insight and the FAO expert workshop were invaluable.

Results

The Tonlé Sap study species showed contrasting temporal trends in abundance (Figure 1), and population size structure vs. relative abundance (Figure 2). Indicator surveillance plots revealed temporal patterns for *C. microlepsis* and *C. enoplos*. *Cirrhinus microlepis* showed a strong negative trend in both size structure and relative abundance, collapsing after 2003 with no evidence of recovery. *Cyclocheilos enoplos* showed a distinct pattern, declining first in length structure and then in relative abundance, with some recent recovery in length. The other two species showed fairly stable length structure, with minor shifts in relative abundance in 2001 and 2002.

Interpretation

The Smallscale Mud Carp *C. microlepis* is listed as "Vulnerable" by the IUCN, and considered to be under pressure from overfishing and dam building. Such recognition of seriously declining stock status makes this species a good case study, as it provides an independent evaluation against which to compare the current assessment. The very impaired state suggested by the state plots (Figure 2) affirms the IUCN listing, and is also consistent with previous assemblage-level assessments Ngor et al. (2018).

The two small cyprinid species (*G. lobatus* and *L. leptocheilus*) showed fairly similar temporal trends in the indicators, and can be considered to remain in good state. These resilient fishes form an important part of the protein yield in the fishery.

This result suggests that a trends-based approach, i.e., relative improvement or decline in the indicators, might be appropriate for monitoring such fisheries where life history parameters are not available to support modelling. Accessible indicator plots provide a useful format for combining different quantitative and semi-quantitative information with local expert knowledge to achieve a holistic image of fishery state. The key limitation with surveillance indicators remains, i.e., that the absolute state of the stock remains unknown and hence, links to anthropogenic pressures or critical ecological thresholds (or RP) cannot be reliably specified.

Goliath Catfish, Amazon River (Brazil)

Introduction

The Amazon goliath catfish (Pimelodidae) provided a data-limited stock assessment case study for one of the most iconic freshwater systems on Earth (Castello et al. 2013). Dourada *Brachyplatystoma rousseauxii* and Piramutaba *B. filamentosum* show long-distance migrations from nursery grounds in the estuary, up to spawning grounds close to the Andes (Duponchelle et al. 2016; Barthem et al. 2017). After spawning, adults remain in these headwaters (Hauser et al.

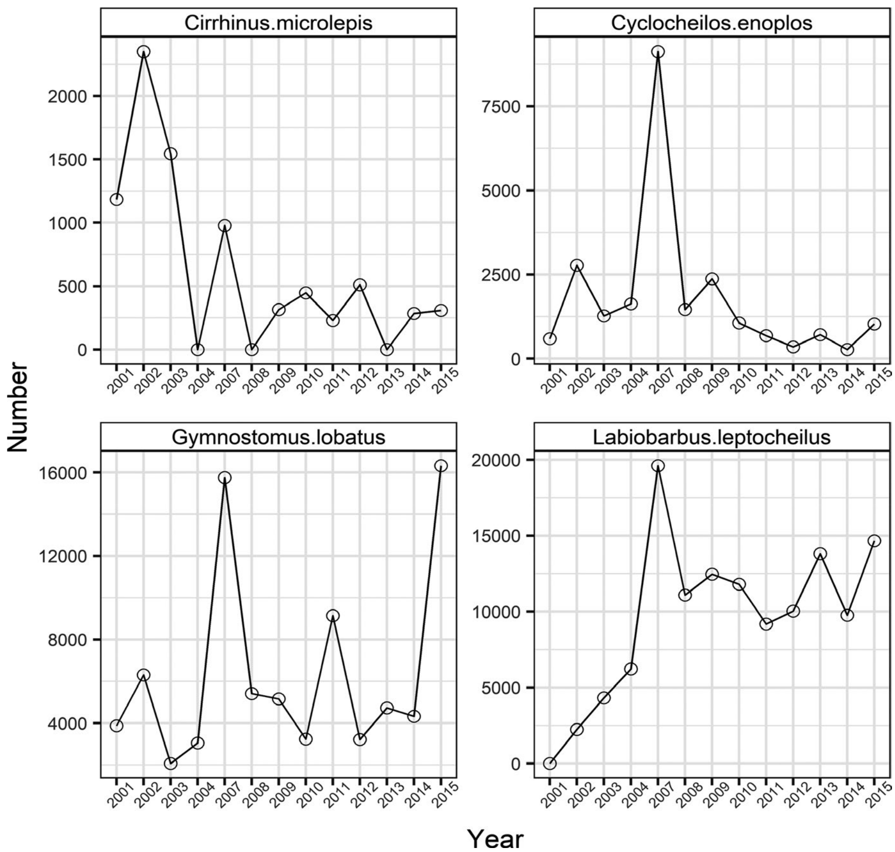

Figure 1. Number of individuals of four fish species sampled from the Tonlé Sap *Dai* fishery.

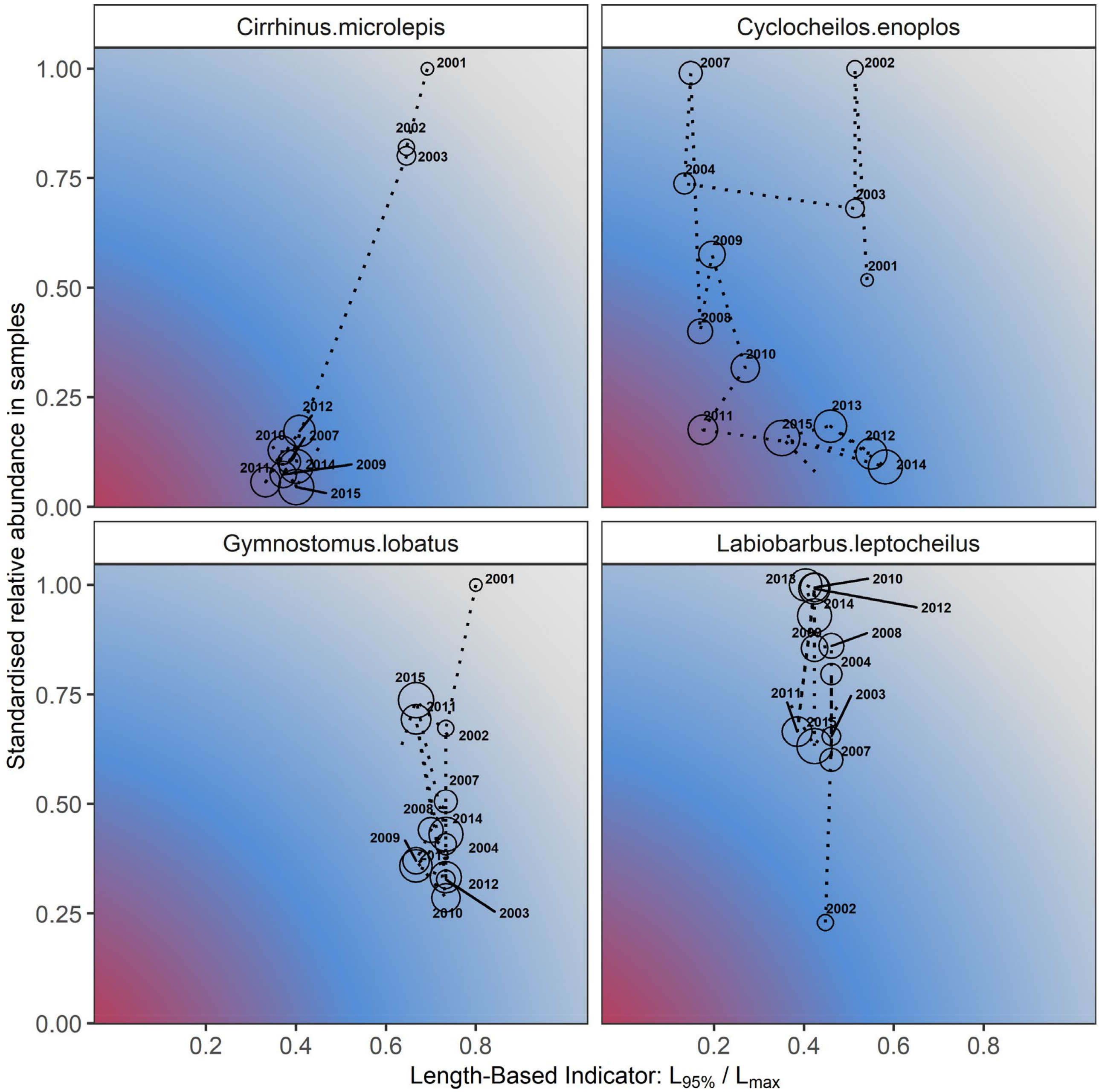

Figure 2. Time series of relative abundance and a length-based indicator for four fish species from the Tonlé Sap *Dai* fishery (2001–2015). Relative abundance is the annual proportion of a species by number in the sampled catch of the four study species, standardized to the maximum observed sample value for that species. The color scale is arbitrary, and suggests reference direction from good (light grey) to poor (red) state. Data points showing good or improving status should remain in or move towards light grey respectively.

2018). Piraíba (*B. vaillantii*, max length 3m) is the largest Amazon catfish; it is found along the main river channels and does not seem to make large-scale migrations (Petrere et al. 2004).

The commercial catfish fishery has developed to become a primary source of income for Amazonian fishers (Doria et al. 2012). Around 16,000 fishers participated in 2005, of which 50% were concentrated in the estuary, where the only industrial Amazon fishery takes place. The industrial fleet uses demersal pair trawls, and mainly targets juvenile Piramutaba, with a bycatch of small Dourada (Jimenez et al. 2013). The small-scale fleet operates throughout the Amazon basin, using drifting gillnets (80%) or longlines (20%).

Annual combined catch of Dourada and Piramutaba averages around 3,000 tons for the industrial fleet and 1,000 tons for the small-scale fleet, while catch of Piraíba is around 1,000 tons. Fish production peaks when the water level drops (Batista et al. 2018), thus depending on hydrological season and geographic region. Catch peaks occur sequentially along the river (Parente et al. 2005).

Fisheries on the Amazon contribute significantly to food security, but are threatened by deforestation (Castello et al. 2018) and on-going dam building (Petrere 1989; Doria et al. 2018). Fishery resources appear to be moderately exploited, with some key species showing signs of overexploitation (Petrere et al. 2004; Castello et al. 2011). Fisheries regulations exist (e.g., Vieira 2005), but compliance is poor (Klautau et al. 2016).

A simple LBI and the LB-SPR model were both applied to this case, and the results were compared visually for each study species. This comparison was intended to explore how well an LBI could track state in the absence of a model-based assessment.

Data Collection

Length data were collected through several different research programmes from 1999 to 2018, and include 5,673 Dourada, 3,122 Piramutaba, and 4,263 Piraíba sampled between the estuary and headwaters (lower Amazon, Xingu River, and Madeira River). The huge distance between estuarine nursery areas and headwater spawning grounds results in a systematic upstream increase in mean fish size. This trend has important implications for size-based assessment of Dourada and Piramutaba, because a sample of fish from further upstream will tend to have larger individuals, and so assessments may suggest better state than for downstream. Dourada length records (year 1999) included fish from a large linear range of sites, allowing evaluation of this upstream size gradient.

Analysis

The LB-SPR fits an estimated size-selection curve to input length data, and so model outputs will be biased if sampled fish come from fisheries with different gear selection profiles. Catches were thus separated by fishing gear (where recorded) and river system, to account for likely differences in fishery selectivity or spatial differences in life history stage (due to ontogenetic migration). The predominant fishing gear (drift net with belly) was considered to show asymptotic selection, while longline selectivity was unknown. Published estimates of key life history parameters were available for the three catfish species (Table S1, Online Supplementary Material). This may be typical of significant commercial target species, which tend to be relatively well studied compared to less valuable species within an exploited assemblage.

Time series of the same simple univariate LBI ($L_{95\%}/L_{\infty}$) as applied for the *dai* fishery (see above) were calculated for each study catfish species, using the mid-range L_{∞} value subsequently tested in the LB-SPR model (Table 1). The LB-SPR assessments were then undertaken, assuming logistic selectivity in the commercial gears from which the samples were collected (and noting that this assumption may lead to bias in results from the longline fishery if this gear actually imposes a different selection pattern). A set of L_{∞} and M/k values were tested (Table 1) to estimate annual SPR for each species. Model fit was evaluated from plots (observed vs. fitted size distribution) that are provided as a standard output in the LB-SPR package in R. The LBI and LB-SPR results were compared visually to evaluate how well annual LBI trends matched corresponding SPR estimates for each of the three catfish species.

The additional Dourada data (sampled from estuary to upstream) were used to highlight the potential effect on SPR of spatial differences in sampling site. Here, a single input value was applied for each of L_{∞} (135) and M/k (1.85).

Table 1. Life history parameter values used as inputs to the LB-SPR model for Amazon catfish.

Species	L_{∞} (cm)	M/k
Dourada	125, 135, 150	1.85, 2.0
Piraíba	175, 185, 195	1.90, 2.0
Piramutaba	80, 85, 90	1.85, 2.0

Results

The LBI time series for each catfish species showed contrasting trends in $L_{95\%}/L_{\infty}$, with fairly stable state for Dourada, but apparent declines for Piraiba and Piramutaba (Figure 3). The LB-SPR model showed good fit to annual length data for each of three catfish species. The SPR estimates showed a strong effect of input L_{∞} values and a lesser effect of M/k. Time series of SPR corresponded quite closely to the LBI results (Figure 4). Dourada again showed fairly stable trends, with SPR consistently >0.5, especially in the Madeira River, although this may partly reflect upstream movement of larger fish from the main channel. Piramutaba seemed to be in decline in the lower Amazon. Piraíba showed declining state in the Madeira River, and almost complete absence of larger fish in the Xingu (Figure 4). Estimated trends in state were very similar between the LBI and LB-SPR approaches (compare Figures 3, 4).

Dourada from different Amazon locations in 1999 showed progressively greater SPR moving upstream, with an outlying result for Manaus (Table 2). 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 4).

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 et al. 2014), catch curves (Córdoba et al. 2013), or to empirical indicators, including community size-spectra (Castello et al. 2011; Fabré et al. 2017; Doria et al. 2018). The current study may be the first to apply a data-limited model, potentially allowing stock state to be evaluated against an objective (SPR) RP that expresses the ratio between observed spawning potential and expected unfished potential.

The state differed markedly among the case study species, even though all three are important commercial fishes. Piraíba is of particular concern, with different 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 et al. 2011) and population size-structure is strongly impaired. Landings of Piraíba “decreased drastically” from 1977 onwards, while Piramutaba also showed a decline in the lower Amazon, and this may reflect high *F* in the estuarine trawl fishery (Petrere et al. 2004).

Importantly, apparent trends in catfish populations were very similar between the LBI and the more data-hungry LB-SPR approach. This result highlights the value of simple length-based metrics for the assessment of data-limited inland fish stocks. However, it should be remembered that LBIs do not have associated management RP, while the LB-SPR approach provides outputs that can be compared to an absolute SPR RP (e.g., 30%; Goodyear 1993) that has been used to support management in marine fish stocks.

Mean length of Dourada increased systematically upstream, with a corresponding increase in estimated SPR. This is assumed to reflect ontogenetic migration of large fish, although Van Damme et al. (2019) suggested an influence of diminished upstream migration of small individuals due to dams. One solution to such spatial heterogeneity

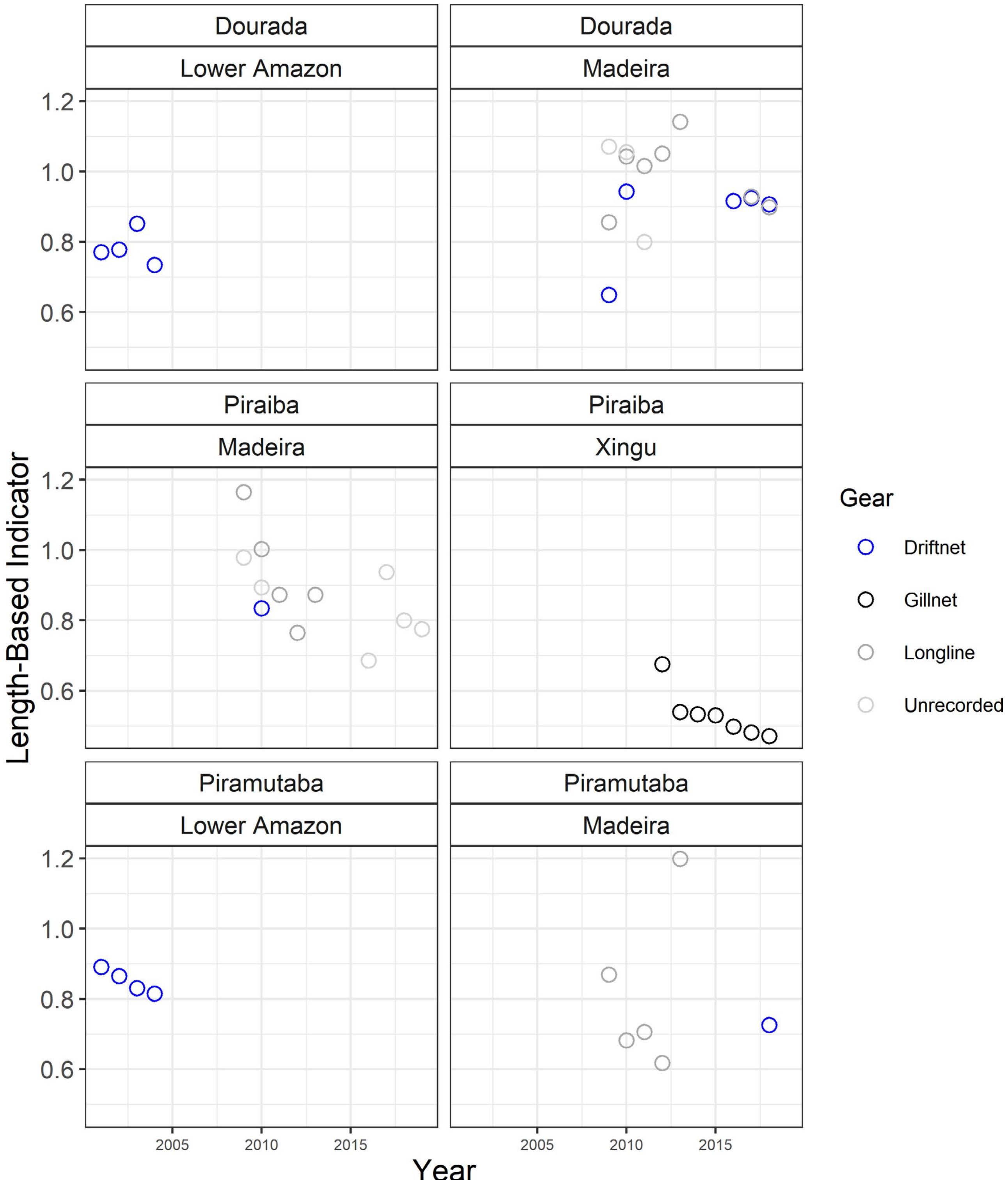

Figure 3. Time series of a length-based indicator ($L_{95\%}/L_{\infty}$) for each of the three study Goliath catfish species. Results are given by river system and sampling gear. Values around 1.0 may imply a healthy size distribution where the largest fish have observed lengths around the von Bertalanffy L_{∞}.

in size structure may be to calculate an average SPR from a fish sample collected throughout the river, to ensure a representative population size distribution. Alternatively, a trends-based approach could be applied to surveillance SPR series for specific index sampling locations along the channel.

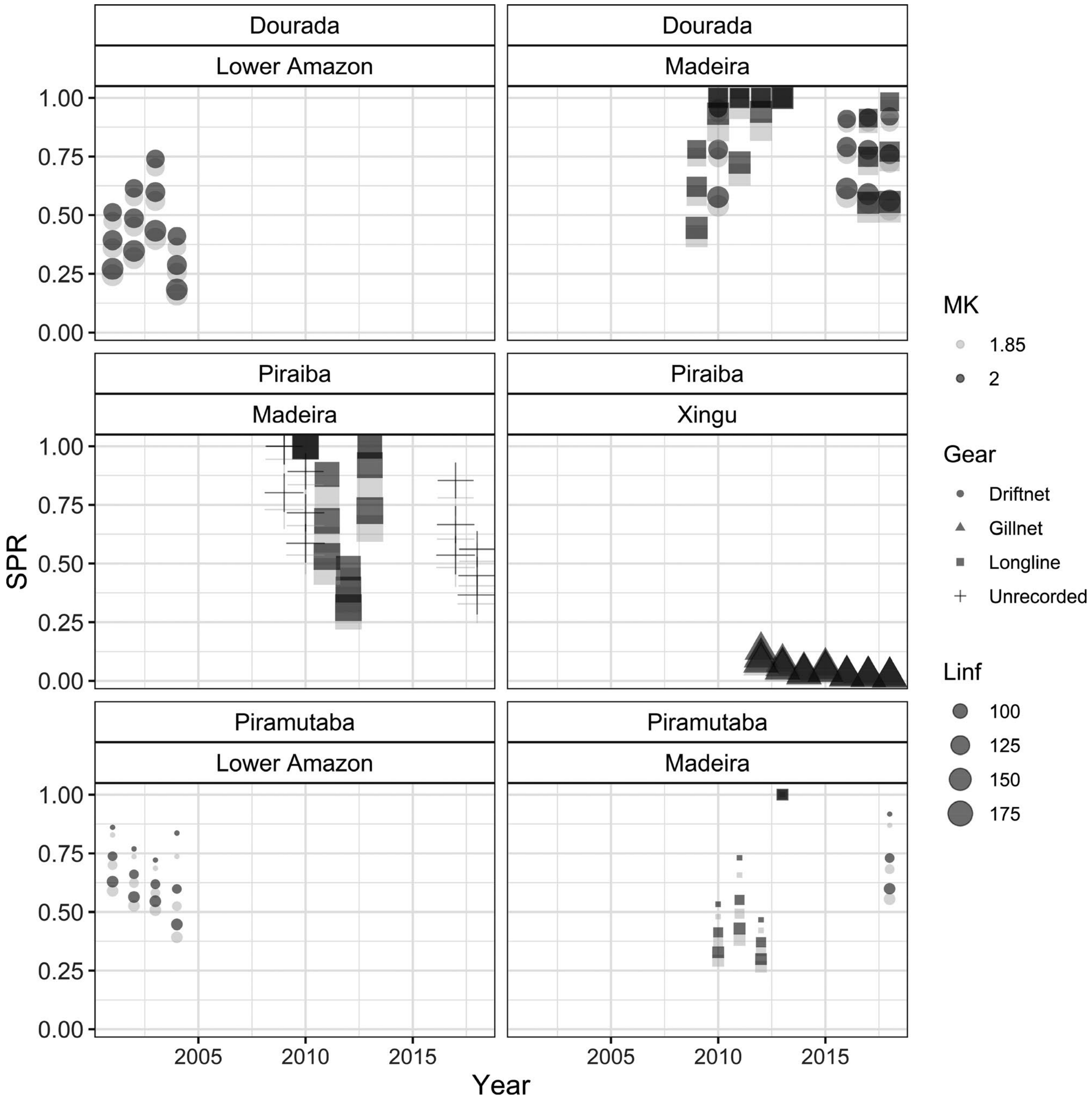

Figure 4. Estimates of Spawning Potential Ratio (SPR) for Dourada, Piramutaba, and Piraiba, sampled in each of the lower Amazon main channel and Madeira and Xingu tributaries. Different values were used for the input life history parameters (Table 1): circle shading refers to M/k (MK), and circle size to L_∞ (Linf, cm).

Nile Tilapia, Lago Bayano (Panama)

Introduction

Lago Bayano was formed in 1976 with the damming of the Bayano River for electricity generation. Nine fish species are present; Nile Tilapia *Oreochromis niloticus* was introduced to the reservoir in 1980 and supports the only commercial fishery. This fishery is open only to local communities, and initially involved fewer than 1,200 full time and many seasonal fishers with annual catch reaching almost 3,900 tons in the early 2000s. Reduced demand for tilapia led to a subsequent decline in participation, with catches falling to around 863 tons; intermediaries now buy only 2–3 basketfuls of fish per fisher, per day. There was a dramatic event in 2011–2012, when the hydropower company responded to high water levels by opening the reservoir flood gates. Fishers lost boats and equipment, while the price of tilapia stayed very low, so many operators left the fishery.

Stock status is believed to have improved after the implementation of a management plan in 2009. The plan stipulates that only trammel nets with three layers of net having mesh sizes 5, 8, and 10 inches can be used, and four nets are allowed per boat. The nets are set along the shore, and fish are scared into them by beating the water. The management plan also establishes a 3-month closed season (July–Sept). The administration enforces compliance with management regulations, monitors catch and measures 100 fish twice a month in the open season.

Table 2. Spawner Potential Ratio (SPR) estimates for Dourada sampled at different sites on the Amazon system in 1999.

Site	N	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
Iquitos	200	0.62	3,545
Overall	1,598	0.38	

The trammel nets used in this fishery may show dome-shaped selectivity, i.e., gillnet and hook type (Millar and Holst 1997). This selection pattern is common in inland fisheries, which frequently use passive gears, and has recently been incorporated into the LB-SPR model (Hommick et al. 2020). The Lago Bayano case study provided an opportunity to evaluate how much the different assumptions of logistic (trawl type) or dome-shaped selection influenced tilapia assessment results.

Analysis

Catch data from 2005–2007 and 2016–2018 were analyzed. The extended LB-SPR model (Hommick et al. 2020) was applied. The data suggested a normal distribution of lengths in the catch, and so normal gillnet selection parameters (0.274, 2.812) for Nile Perch *Lates niloticus* were taken from Hailu (2014), for a size selection mode assuming a mesh size of 5 inches (127mm). The inclusion of larger mesh sizes in the trammel nets may allow the gear to retain the largest available size classes, and so the original LB-SPR model (assuming logistic selection; Hordyk et al. 2016) was also applied for comparison.

A time series for Lake Victoria Nile Tilapia (Njiru et al. 2008) had similar length structure to the Lago Bayano stock, and was consequently used to provide an appropriate range of values for input life history parameters. Two L_∞ (43 and 45cm) and three M/k (1.8, 2.0, and 2.2) estimates were tested using the dome-shaped model. A single M/k = 2.0 was tested for the logistic model, with the intention of allowing a simple comparison between SPR estimates from the two selectivity assumptions. This structure resulted in eight separate estimates of SPR (six dome-shaped and two logistic) for each of the study years. Sizes at 50% and 95% sexual maturity were fixed at 25 and 30cm, respectively (Njiru et al. 2008).

Results

The LB-SPR model provided good fit to the Lago Bayano tilapia data, with L_∞ having a stronger effect than M/k on SPR estimates. Annual SPR estimates suggested that stock state has improved since the management plan was implemented, and SPR is now consistently>0.4. Estimates of SPR were typically similar for the two tested selectivity assumptions (Figure 5).

Interpretation

The Lago Bayano tilapia data provide a case study for application of the recently extended LB-SPR, which can accommodate dome-shaped selection (Hommick et al. 2020). Selection parameters were already available from a similar stock (Hailu 2014), and so it was not necessary to conduct trials to estimate the selection profile(s) of the gear for the target species, i.e., the proportion of individuals of given size classes that are retained (e.g., Millar and Fryer 1999).

The LB-SPR model assuming logistic selection produced SPR estimates that were similar to those from 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, because the logistic model assumes that "missing" large fish have been caught, rather than escaping the gear and remaining in the population. A possible explanation for this result in Lago Bayano is that the largest mesh size of the trammel net gear retains all individuals up to some size at least as large as the largest fish in the population, such that selection is effectively logistic across the size range of tilapia extant in the population.

The tilapia case study seems to fulfil the requirements for robust and useful application of a size-based stock assessment model. The fishery targets one species using a single regulated gear type of known selectivity. Size-structure of the population is easily available from catch and reliable life history parameter estimates are available. It makes sense in this case to relate model SPR estimates to an appropriate management RP.

Sábalo, Paraná River (Argentina)

Introduction

Sábalo is the main target species (Baigún et al. 2003, 2013) in the lower Paraná basin and represents up to 60% of the fish biomass in the floodplain lagoons (Tablado et al. 1988). Sábalo exhibits different types of movement including trophic, thermal, and reproductive migrations adapted to cope with seasonal regimes and hydrological variability (Sverlij et al. 1993). Provincial fishing regulations are mostly based on gear restrictions and size limits (Castillo et al. 2016).

Intense export activity since 2001 led to an increase in catch, reaching an annual peak of almost 40,000 tons in 2004. A quota was introduced in 2006, limiting catch to 15,000–20,000 tons to fulfil export demand, but there is not reliable scientific evidence that this level is sustainable. In addition to these export catch statistics, some provinces and the state collect local fishery information (e.g., fish length and weight) in a few landing ports. There is periodic experimental fishing, which provided the length data used for the current case study. An assessment of the stock up to 2009 suggested declining state following over-exploitation triggered by intense fishing for export (Baigún et al. 2013). These earlier data were not available for the current analysis (2012–2017), with around 400–600 individuals measured in the first 4 years, increasing to more than 2,000 in 2016 and more than 20,000 fish in 2017.

The Paraná is a large and extremely variable floodplain system, where fish population dynamics, especially recruitment, respond strongly to the prevailing hydrological regime. A similar pattern can be expected in other neotropical floodplain environments. In contrast, LB-SPR assumes relatively stable demographic state and a smooth population size distribution. This case study evaluated how the model might cope with assessment of an important commercial and subsistence stock in a floodplain river.

Analysis

The Sábalo data comprised length records from 2012–2017, obtained from a set of experimental gillnets having mesh sizes (30–180mm) expected to capture a representative sample

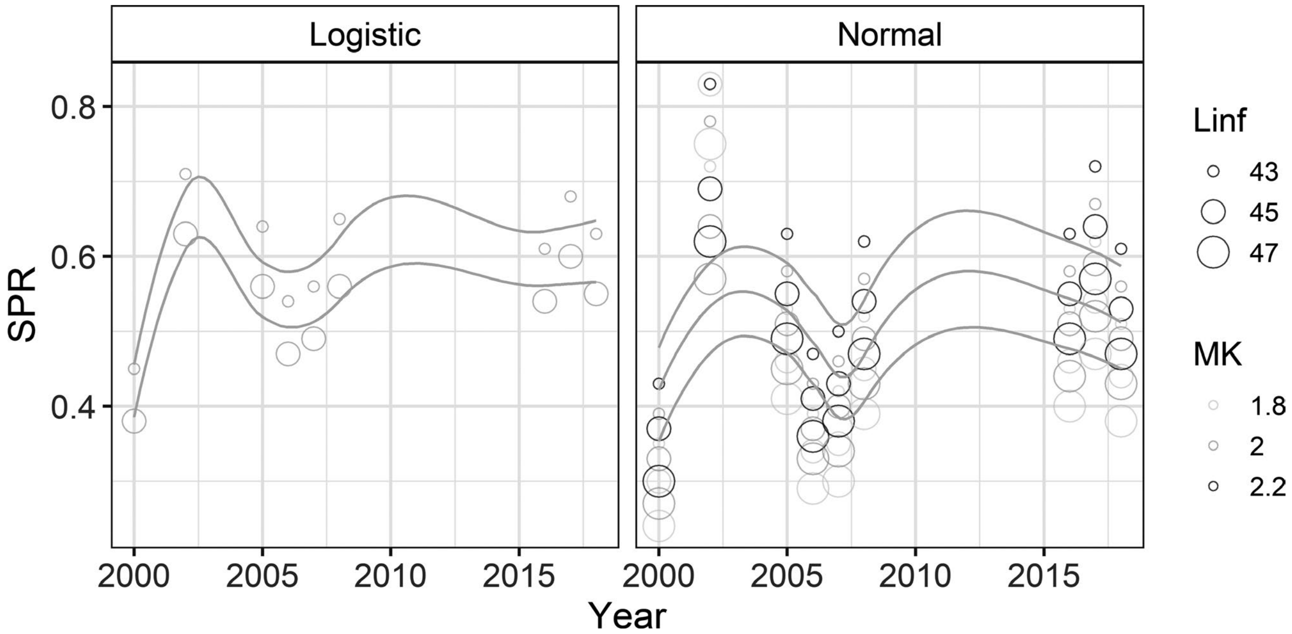

Figure 5. Estimates of Spawner Potential Ratio (SPR) for tilapia in Lago Bayano, using different values for the input life history parameters L_∞ (Linf, cm) and M/k (MK, see above), and two different assumptions about gear selectivity (Logistic and Normal, i.e., dome-shaped). A separate smoother is fit to the series for each input value of L_∞.

of the complete stock size distributions. The LB-SPR model was applied, but acknowledging that output estimates of F/M might not be very informative because the exploitation pattern of the sampling nets would differ from the commercial gears that could be expected to impose change on population length structure. This is relevant because LB-SPR infers relative fishing mortality F/M by comparing the sample size distribution to a predicted "un-fished" size distribution, and here the sample was not taken from the gear imposing M.

Published estimates of life history parameters (Baigún et al. 2013) and gillnet selectivity (Dománico and Espinach Ros 2015) were available. The current Sábalo data comprised individual standard lengths SL, while Baigún et al. (2013) used TL, hence a conversion was applied where TL = 1.209 × SL+1.057. A corresponding range of L_∞ (63, 65, and 68cm) and M/k (1.50, 1.64, and 1.80) values were tested. This resulted in nine separate estimates of SPR for each study year. Sizes at 50% and 95% sexual maturity were fixed at 36 and 43cm, respectively.

Results

Estimates of SPR showed an apparent positive trend until 2014, and then remained around 0.3–0.4 (Figure 6). As with the other LB-SPR case studies, the greatest SPR estimates were derived using the smallest input for L_∞. Standard model output plots of observed and predicted length distribution indicated that the model showed good fit in all years, except for 2016 and 2017, when the Sábalo length sample showed a bimodal distribution (Figure 7).

Interpretation

The current data included individuals close to L_∞ (65cm), although fish up to 70cm were observed historically. This similarity between current and historical state implies that the population is probably reasonably healthy. Baigún et al. (2013) found that SPR had declined to 0.2 by 2005, which was attributed to uncontrolled Sábalo exports from 2001–2006. Some subsequent recovery is now apparent, but the stock may remain vulnerable in hydrological scenarios, i.e., low water years, that are adverse to successful recruitment and juvenile survival.

The Sábalo data were collected using experimental fishing instead of commercial catch records. This survey sampling gear is designed to provide a precise and representative

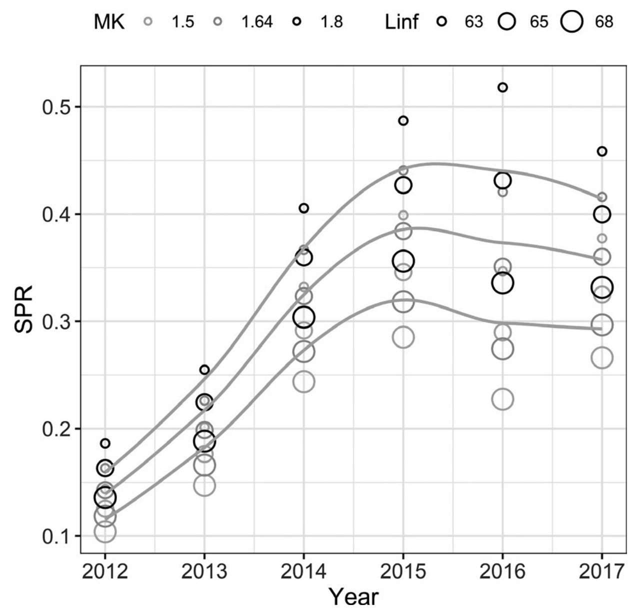

Figure 6. Estimates of Spawner Potential Ratio (SPR) for Sábalo in the Paraná River, using different values for the input life history parameters L_∞ (Linf, cm) and M/k (MK, see above). A separate smoother is fit to the series for each input value of L_∞.

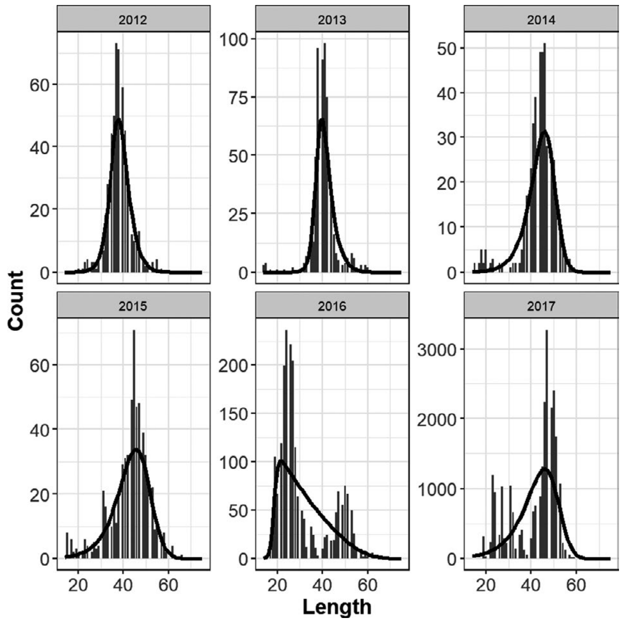

Figure 7. Model fit plot for the Length-Based Spawning Potential Ratio model assessment of Parana Sábalo. The bimodal length-distribution in 2016–2017 reflects environmentally driven recruitment pulses.

impression of population length structure during the study years, and thus allowed consideration of the effect of modal peaks in length on model SPR estimates. LB-SPR fits a smooth "expected" size distribution that does not capture the sort of strong peaks in length structure as were observed for Sábalo in 2016–2017 (Figure 7). The discrepancy in model fit may introduce bias in state assessments, although simulations suggest that LB-SPR is reasonably reliable for bimodal size distributions, with a tendency to provide conservative results (Hordyk et al. 2015a).

Flood events can periodically enhance recruitment (Winemiller and Rose 1992) and trigger strong Sábalo cohorts that support periods of greater catch. Management measures should safeguard biomass during intervening low water years. Strong flood pulses and floodplain access may be required to ensure stock recovery if heavy fishing pressure during dry periods depletes stocks. Hydrological cycles must be considered when using size-based methods to monitor state of fish populations in floodplain systems, and appropriate RP or RP ranges may require some investigation. It might be useful for such assessments to combine LBIs and/or a size-based model with metrics that track environmental conditions.

DISCUSSION

Rapid appraisal methods are needed to empower local management decision making in inland fisheries (Beard et al. 2011). Monitoring and management must be feasible and affordable given on-going socio-economic and governance constraints (Mahon 1997; Dowling et al. 2018). It is not clear whether more effective monitoring can effectively mitigate anthropogenic pressure (Allison and Mills 2018). However, accessible stock assessment approaches that can capitalize on diverse and imperfect data must be part of the solution.

Lorenzen et al. (2016) undertook a theoretical review of stock assessment approaches that might be applicable in inland fisheries. Prominent issues identified were unreliable catch data, lack of sampling infrastructure, and problems with applying classical age-based models in tropical regions where fish ageing can be difficult. They concluded that these systems "pose challenges, but also opportunities for assessment that are different from and more diverse than those encountered in large-scale marine fisheries." Some subsequent analyses have focused on the use of data-limited length-based approaches that can use representative samples of inland fish population size distributions to inform on target stock state (e.g., Fitzgerald et al. 2018; Shephard et al. 2019; Hommick et al. 2020).

The current study explored the application of empirical LBIs and an example model (LB-SPR) to support assessment of some globally significant inland fisheries. The results were interpreted by experts with local and international perspectives on freshwater fisheries science and management. Several general criteria emerged that should be considered when deciding which type of size-based assessment could be applied to a given fishery. This process will require careful evaluation of fishing gears and catch composition, the biology and life history of target species, and the ecosystem (Figure 8). Key fishery types can be categorized according to these criteria, with the appropriate assessment tool expected to differ among systems (Table 3).

Local Knowledge and Surveillance Indicators

Elliott et al. (2019) used the Mekong system to develop and implement an integrated monitoring strategy to address the need for improved fisheries data. They proposed that a participatory approach could combine different data sources to reliably characterize the fishery. The current Tonlé Sap case study demonstrated the flexibility of empirical surveillance indicators, and the ability of these metrics to elicit local expert interpretation. Surveillance plots proved to be an intuitive tool for informing such participatory stock evaluations. Assessment based on indicator trends can still be demanding and expensive (Dowling et al. 2008), but there are probably many inland fishery situations where a simple combination of surveillance metrics and expert narrative may be the only available option (Table 3; Figure 8).

This empirical approach could be enhanced by including additional layers of information, e.g., local ecological knowledge, market sampling, and environmental records, into a holistic image of the fishery. It might be useful to formalize a framework that integrated local knowledge and limited data in this way; some means of estimating the uncertainty around such assessment outcomes would support management decision making.

Length-Based Indicators and Opportunities for LB-SPR

The Amazon catfish case study provided an opportunity to compare a simple LBI with a length-based model, LB-SPR. Notably, trends in the LBI and SPR series were extremely similar for each of the three tested catfish species. This result demonstrates potential for using appropriate LBIs when life history estimates are not available to parameterize models. The long-term declining LBI trends evident for Piraiba and Piramutaba might be sufficient to raise management concern, even without invoking a model-based management RP.

Data availability, along with characteristics of the fishery and the ecology of target species, may place the Amazon catfish at the limit of where LB-SPR can provide a reliable assessment. The current results gain confidence from the use

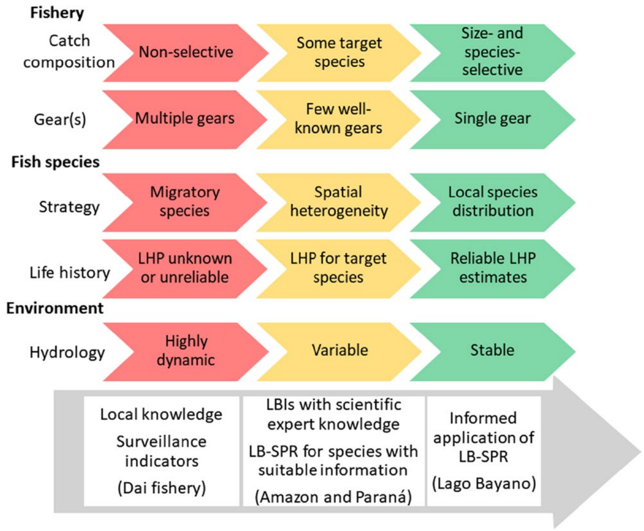

Figure 8. Criteria to be considered when selecting appropriate data-limited assessment approach. Data-availability and system equilibrium increases moving from red to green arrows. LBIs = length-based indicators, LB-SPR = Length-Based Spawning Potential Ratio model, LHP = Life History Parameters.

of parallel empirical indicators and the close involvement of local experts. More naïve application of length-based models could easily produce outputs that were biased because of failure to meet assumptions about fisher's behavior, gear selection, stock structure and fish biology etc.

Informed Application of LB-SPR

Careful use of data-limited models can allow stock state to be evaluated relative to absolute management RPs. An LB-SPR model informed by accurate life history inputs can thus indicate not just whether stock state shows a positive or negative trend, but whether or not it is objectively healthy. The three LB-SPR case studies highlighted potential issues, limitations, and solutions that are likely to be broadly relevant to the application of data-limited models in inland fisheries.

Practical and economic challenges in sampling some inland fisheries mean that sample size is a basic concern. LB-SPR can produce reasonable (if uncertain) estimates with as few as 60 fish (Babcock et al. 2018; Hommick et al. 2020), but larger samples are more informative. The current LB-SPR case studies focused on important commercial species in exploited assemblages, as these can be relatively well understood.

The LB-SPR model and other available data-limited size-based models, such as LIME (Rudd and Thorson 2018), have fairly accessible requirements for input life history parameters. Even so, these may not be available, (e.g., the Tonlé Sap), and some species can show system-specific differences in these parameters. A useful approach may be to borrow parameters from other systems, or statistically from taxonomically related species (Thorson et al. 2017). Caution should be used, since fish life history rates may differ among systems, e.g., Sábalo across rivers of the La Plata basin (Sverlij et al. 1993; Baigun et al. 2019). Selection of appropriate values for life history parameters can be strongly informed by on-going collaboration with local scientific experts. The length-based Bayesian biomass model (Froese et al. 2018) does not require input life history parameters, but still assumes that gear selectivity is asymptotic.

Gear selectivity parameters can be input to LB-SPR (Hordyk et al. 2016), and these parameters can now be dome-shaped (Hommick et al. 2020); see Lago Bayano tilapia. An alternative is to use standardized sampling gear, e.g., multi-mesh gillnets; see Paraná Sábalo. Note that when the sampling gear has different selectivity to the commercial gear, LB-SPR estimates of F/M may be incorrect. Hommick et al. (2020) touched on this issue by considering the component of the sampling selectivity profile that was likely to correspond to size-selective removals in a recreational fishery.

Recruitment and M may not be at equilibrium in floodplain river stocks and multi-modal size structure can emerge (see Paraná Sábalo). This may lead to biased (Chong et al. 2020), but acceptable SPR estimates (Hordyk et al. 2015a). It is speculated that such variability could be anticipated by estimating a likely SPR range linked to environmental conditions, with expected state (RP) dependent on the ambient hydrological regime. It might also be adequate to use only data from larger length mode(s), which represent the most biologically "important" spawners.

The Lago Bayano tilapia provides a case study where LB-SPR seems highly appropriate as an assessment and management tool (Table 3; Figure 8). The fishery targets one species using a single regulated gear type of known selectivity. Size structure of the population is easily available from catch. It may be possible to define a species-specific SPR RP for tilapia, which may be quite low given the high fecundity and resilience of this species.

CONCLUSIONS

Inland fisheries support numerous communities, but these social–ecological systems are beset by wicked problems, including higher-level anthropogenic pressures such as dam building, disconnection, and pollution. Due to their dispersion, accessibility constraints, and administrative limitations, appropriate quantitative or semi-quantitative methods are required to evaluate the state of many data-limited inland fishery resources. Stock assessment techniques from marine fisheries show potential but the case studies reveal how the nature of inland systems creates additional issues and challenges that should be considered when implementing size-based assessment methods in broad categories of inland fishery type (Table 3; Figure 8).

A key factor is the dynamic nature of many inland fisheries; see Paraná Sábalo. Flood pulses strongly influence fisheries performance in floodplain rivers (Halls and Welcomme 2004; Castello et al. 2015; Rabuffetti et al. 2016). Target fishes can exhibit a periodic life history strategy to cope with flow variability, while abundance and assemblage structure change with the flood cycle (Winemiller and Jepsen 1998). There also may be systematic life history migrations, e.g., Amazon and Mekong species.

In response to environmental cycles, fisheries may follow an annual sequence of target species and/or locations. Fishers may operate several gears with differing selectivity, possibly in different locations or at periods of a seasonal cycle. This situation is exemplified by floodplain fisheries that target diverse assemblages of juvenile fish as floodwaters retreat towards the main channel. Size-based assessment is probably not meaningful in such fisheries that tend to use non-selective gears, and retain all catch.

Table 3. Issues and potential for application of size-based assessment methods to major classes of commercial fishery. LHP = life history parameters, LBIs = length-based indicators, LB-SPR = Length-Based Spawning Potential Ratio model.

Fishery types	Nature of the fishery	Issues for size-based assessment	Applicable size-based methods
Floodplain/wetland, developing country. Static gears, fixed fence traps.	Commercial and artisanal. Multiple (usually migratory) species (e.g., "money fish") available in short season: often targeted as juveniles and all retained.	Strong annual recruitment pulses related to hydrology. LHP can change with hydrological conditions. Fisheries are not typically species- and/or size-selective, and may vary across seasons.	Size-based methods may not be appropriate as fishing does not curtail size distributions. Could rely on local expert knowledge.
Large river, developing country. Cast nets, static gears, seine nets, trawls.	Commercial and artisanal. Mixed species: larger migratory (e.g., goliath catfishes) and smaller local species targeted by specific gear, season or location.	Multi-species non-selective fisheries, and target fisheries for larger valuable species. May be strong impacts from other anthropogenic pressures, e.g., dams. Some LHP available for important target species, but parameters may not be at equilibrium due to strong environmental variability.	Assemblage-level LBIs may capture shifts in species composition. Need to consider environmental and other anthropogenic drivers of population structure. LBIs and LB-SPR for larger target species, e.g., catfishes. Separate by gear and location. Could use a range of LHP estimates.
Large African rift lake, developing country. Static gears, light-attraction, trawls, seines.	Commercial and artisanal. Large economic species (e.g., Nile Perch) and small pelagics targeted by specific gear, season or location.	Small pelagic fisheries and small-mesh gears are not size-selective. Target fisheries for Nile Perch may be size-selective and LHP may be available.	Size-based methods probably not appropriate for small pelagics. LBIs and LB-SPR for larger target species, e.g., Nile Perch.
Large reservoir, developing country. Light-attraction lift nets, static gears.	Commercial and artisanal. Introduced target species (e.g., Nile Tilapia) and small pelagics targeted by gear, season or location.	Differing selectivity among fishing gears. LHP may be available for target species.	LBIs and LB-SPR for larger target species, e.g., Nile Tilapia. Incorporate local expert knowledge. Separate by fishing gears and seasons.
Anadromous delta fishery, developing country. Static gears, bagnets, castnets.	Commercial and artisanal. Highly seasonal anadromous species (e.g., Hilsa and Ayerawaddy Shad).	Size-selective target fisheries with LHP likely to be available.	LBIs and LB-SPR for larger species targeted with size-selective gears. Incorporate local expert knowledge. Separate by fishing gears and seasons.
River, developed country. Traps, longlines, bag nets, fyke nets.	Primarily commercial. Limited number of food species targeted (e.g., eel, salmon and shads).	Differing selectivity among fishing gears. Size-selective target fisheries with LHP likely to be available.	LBIs and LB-SPR for important target species. Separate by fishing gears and seasons.
High-latitude lake(s). Gillnets and longlines.	Subsistence, commercial and recreational (e.g., salmonids, Northern Pike and whitefish).	Size-selective target fisheries with LHP likely to be available.	LBIs and LB-SPR for important target species.
Inland sea, developed country. Gillnets, longlines and trawling.	Primarily commercial. Limited number of food species targeted (e.g., kilka).	Target fisheries with differing selectivity among gears. LHP likely to be available.	LBIs and LB-SPR for larger species. Separate by fishing gears and seasons.

In the situation of heterogeneous fisheries, it may be necessary to sample spatial and temporal components separately to capture overall stock state. Alternatively, trends in size structure at index sites could also be used for a reference direction indicator approach. Sets of (quantitative and expert) fish stock and environmental indicators may support more flexible and holistic assessment. LB-SPR may be more suitable for fish stocks in stable lakes and regulated rivers, where fisheries may target a small number of well-studied species, for which life history parameters are available.

An associated issue for inland fisheries is the importance of external anthropogenic pressures. The Amazon catchment experiences deforestation, pollution, and construction of dams and waterways (Castello et al. 2013). Hydropower dams represent a primary issue for the Amazon and Mekong systems as these structures can disrupt migratory connectivity for target species (Anderson et al. 2018) and seriously impair fisheries (Petrere 1989; Doria et al. 2018; Lima et al. 2020). The relevance to size-based assessment methods is that these pressures may impose (possibly unexpected) changes in fish population size structure, e.g., if barriers to migration impair recruitment or somehow diminish abundance of mature individuals. Size-based methods may still provide useful information on stock health, but pressure-state relationships could be unclear.

These issues re-emphasize the need for local understanding of specific fisheries prior to designing and conducting an assessment, and also in interpreting results (particularly for surveillance indicators). The most informative and robust method will change depending on fishery characteristics and information (Figure 8). This insight can come from local expert scientific or ecological knowledge, which is critical to a holistic assessment process. Many fisheries are quantitatively data-limited, but inland systems may require an extended definition of the term when little is known about the social–ecological framework of the fishery.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study may be available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.

Supplementary Material AFS