Received: 6 October 2022 | Revised: 24 October 2022 | Accepted: 27 October 2022

DOI: 10.1111/fme.12604

Fisheries Management and Ecology

WILEY

ARTICLE

Community-based monitoring, assessment and management of data-limited inland fish stocks in North Rupununi, Guyana

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Funding information

EU Sustainable Wildlife Management Programme; Fonds Français pour l'Environnement Mondial; European Union; French Development Agency; United Nations; Wildlife Conservation Society; Centre for International Forestry Research

Abstract

Inland fisheries are important for food security in communities around the world, especially in developing countries. In North Rupununi, Guyana, the state of exploited stocks is poorly understood, and fishery monitoring and assessment are challenging because diverse fishing gears and target species are distributed across a heterogeneous landscape. This complexity created an opportunity for community-based monitoring (CBM) to support data-limited assessment. Standardised CBM was established for the North Rupununi as part of a new inland fisheries management plan initiated by indigenous community groups with support from the government. Quantitative length-based assessments undertaken for target stocks suggested moderate levels of exploitation consistent with local perception. Our study highlights that local experts and community participants with different levels of training can collect accurate biodiversity data. Further development of CBM is important in North Rupununi. We recommend using local ecological knowledge indicators to track spatial and temporal patterns in exploitation and fish stock status.

KEYWORDS

Fisher's ecological knowledge, floodplain fisheries, indigenous Makushi, LB-SPR, length-based indicators, rainforest

1 | INTRODUCTION

Inland fisheries are critically important for food security, by providing a local and affordable protein and micronutrient source for millions of people, especially in developing regions (Funge-Smith & Bennett, 2019). Freshwater ecosystems and fishes are correspondingly likely to be a significant element in achieving UN Sustainable Development Goals (Lynch et al., 2020). In the Amazon River basin alone, inland fisheries that yield around 450,000t of fish each year contribute substantially to regional diets (Junk et al., 2007). However, such systems experience complex anthropogenic pressures, including habitat destruction linked to mining, logging and agro-industry, which can cause rapid biodiversity loss (Albert et al., 2021). Some target fish stocks now show long-term overexploitation (e.g. Isaac & Ruffino, 1996; Petrere et al., 2004), although higher-level pressures such as hydroelectric dams (Santos et al., 2018) are generally more important drivers of fish community state (Welcomme et al., 2014).

Managing the harvest of freshwater species is important for both food security and reducing biodiversity loss (Tickner et al., 2020). An accurate understanding of inland fisheries social-ecological systems

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[Correction added on 23 November 2022, after first online publication: Contributing author 'Cynthia Watson' has been corrected to 'L. Cynthia Watson'.]

is central to sound policy development (Aminpour et al., 2020), with sustainability being linked to knowledge of fishery state relative to management targets, and of likely social-ecological responses to management decisions (Lorenzen et al., 2016). Fish stock assessment seems to be key (Hilborn et al., 2020) by allowing managers to predict rather than react with actions to institute management procedures, such as setting catch regulations and initiating enhancement or restoration measures, even in data-limited systems (Sun et al., 2020). However, formal state assessment is relatively unusual in inland fisheries systems (Fitzgerald et al., 2018; Lorenzen et al., 2016) because dispersed and heterogeneous patterns of exploitation, sales and consumption make the collection of representative data difficult (Graaf et al., 2015; Bartley et al., 2015). In many inland systems, such as floodplain rivers, the relative abundance of fish species and life history stages seasonally fluctuate, with corresponding shifts in exploitation patterns (Mosepele et al., 2022).

Stock assessments in marine fisheries often use catch or landings records when other information is not available. Catch data are problematic in complex inland fisheries with diverse users and many small landing sites because records are unlikely to represent the true extent of fishery removals (Lorenzen et al., 2016). Data-limited "catch-only" models have been applied in a few inland systems (Fitzgerald et al., 2018; Musinguzi et al., 2021), but maybe poor classifiers of stock status (Free et al., 2020) unless good prior information is available (Sharma et al., 2021).

Assessment methods based on fish population size distributions (e.g. length records) can be more informative in such systems (Pons et al., 2020) and are less reliant on regular monitoring. Length-based stock assessment assumes that size-selective fishing removes larger individuals (Shin et al., 2005) and species (Shephard et al., 2012; Welcomme, 1999), thereby leading to curtailed fish population size distributions in exploited systems. Empirical length-based indicators (LBIs) work by comparing summary statistics for observed length distributions to appropriate state reference points (Froese, 2004; ICES, 2015) or may act as trend-based surveillance indicators (Shephard et al., 2015). The basic principle of length-based models (LBMs) is that observed lengths can be compared to a theoretical "expected" population size distribution characterised by life history theory for an unexploited population. Therefore, a difference between observed and expected length distributions expresses fishing pressure and fishing gear size selection. Examples of LBMs used in inland systems include the length-based spawning potential ratio (LB-SPR, Hordyk et al., 2015) model in the Brazilian Amazon (Shephard, Valbo-Jorgensen, et al., 2021) and the length-based Bayesian biomass (LBB) model in Lake Edward, East Africa (Musinguzi et al., 2021).

Appropriate data for length-based assessments can be obtained by sampling commercial landings or from fisheries-independent surveys (Shephard, Valbo-Jorgensen, et al., 2021), without a need for overall removals from a target stock. However, the collection of representative data may not be practical for researchers across extensive, complex and poorly resourced inland fisheries, where local knowledge is paramount (Valbo-Jørgensen & Poulsen, 2000). Community-based monitoring (CBM) provides an alternative solution in such small-scale fisheries (Humber et al., 2017; Oviedo & Bursztyn, 2017), with an increasing role in supporting local food systems (Lowitt et al., 2020) and food security (Lam et al., 2019). Local user communities often already monitor patterns in fish abundance and catch as part of their fishing practices, and this insight can be captured as quantitative indicators (Thompson, 2018; Shephard, Valbo-Jorgensen, et al., 2021).

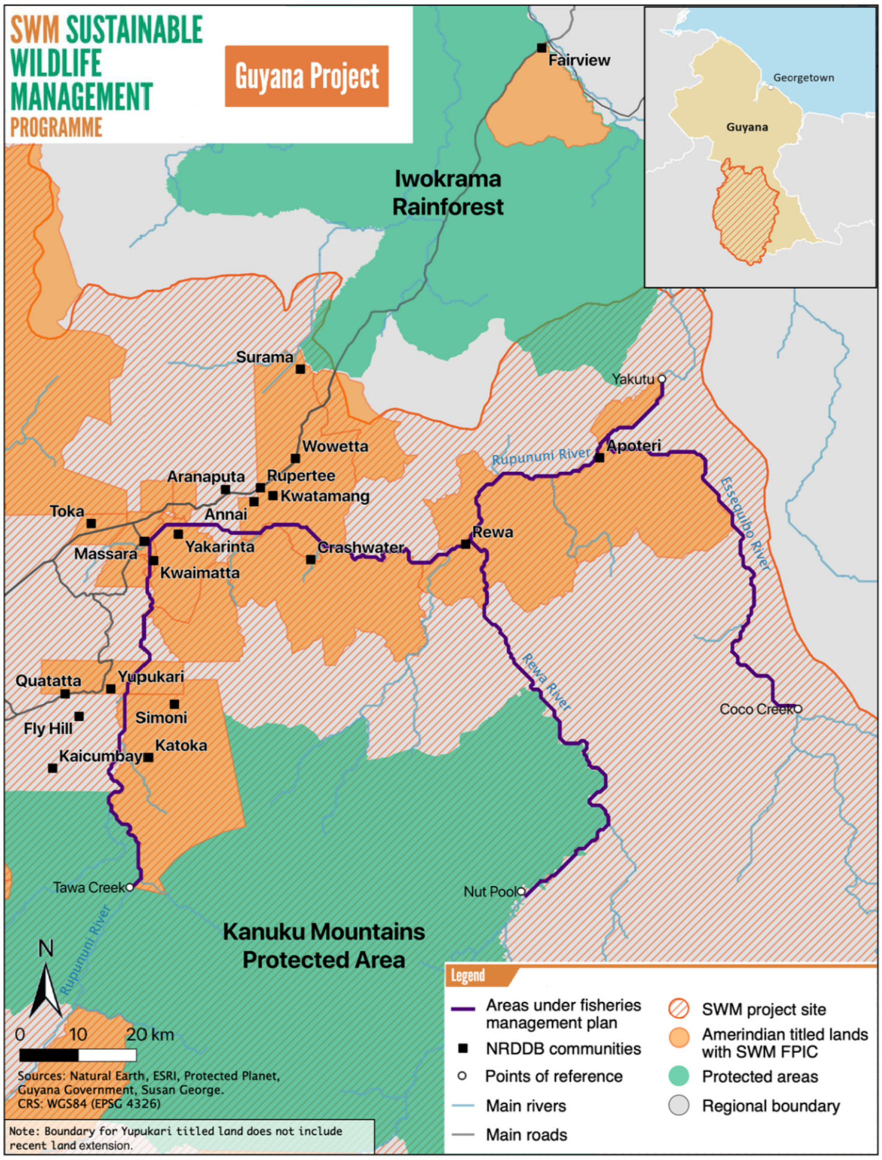
The North Rupununi is a biodiverse region of southwest Guyana (Figure 1). Fishing is a very important component of food security in the region, but the state of target stocks has not been formally evaluated. In 2018, the North Rupununi District Development Board (NRDDB), an umbrella organisation representing Indigenous Makushi communities, implemented a pilot study for inland fisheries monitoring and management. This initiative emerged from local concern about fisheries sustainability as regional development made community natural resources more accessible to exploitation by external actors. Such development can dismantle enduring social-ecological management principles (Ostrom, 1990), especially defined boundaries and graduated sanctions (Arantes et al., 2022), that have traditionally maintained balance. The primary aim of the North Rupununi pilot study was to develop baseline assessments of ecological state for important target fish stocks. This understanding would inform an updated fisheries co-management plan that could help Makushi communities monitor and regulate their fisheries in a changing social-ecological environment. The NRDDB requested technical support from the Guyana Department of Fisheries (Ministry of Agriculture) and an EU project (Sustainable Wildlife Management, SWM) to develop the plan and to provide a legislative framework.

In this case study, we describe (a) the process involved in developing a standardised CBM protocol for target fish stocks in the North Rupununi, and (b) quantitative length-based assessments for key target species with a spawning potential ratio (SPR) state indicator calculated for selected stocks using the LB-SPR model (Hordyk et al., 2015). We discuss the role of CBM in supporting the assessment and management of data-limited fisheries across Guiana Shield freshwater systems. Assessments based on local ecological knowledge (LEK) indicators will become an important part of the future management process, but we focus now on CBM and length-based state indicators. This work should be relevant to other CBM initiatives for small-scale inland fisheries elsewhere in the developing world.

2 | METHODS

2.1 | Study area and communities

The North Rupununi has a network of ponds and waterways, including large rivers that flood extensive areas of wetland during the rainy season. Local communities in this district rely heavily on wetland resources for their subsistence activities (Mistry et al., 2008),



Sources: Natural Earth, ESRI, Protected Planet, Guyana Government, Susan George.
CRS: WGS84 (EPSG 4326)

Note: Boundary for Yupukari titled land does not include recent land extension.

FIGURE 1 Map of the North Rupununi District Development Board fisheries management area, stretching across 20 indigenous communities around the Rupununi, Rewa and Essequibo Rivers of southwest Guyana.

with fish representing 60% of animal protein in the diet of Makushi communities (Luzar et al., 2012) and contributing primary income for 29% of households (Henfrey, 2002). Despite the social and economic importance of this sector, inland fisheries in Guyana have remained unregulated under national law and mostly under no form of institutional management. Traditional management and enforcement structures in some communities connected to the NRDDB remain somewhat effective in remote areas, but are insufficient to maintain sustainable exploitation as systems become more open access (e.g. close to roads and logging developments). A key problem is the wider use of efficient modern gears, such as monofilament gillnets, and an enhanced capacity to transport fresh fish to external markets.

This fluid situation is common in the neighbouring Amazon region and has led to initiatives that capitalise on traditional community-based management (Lopes et al., 2019) that invokes social memory (Mistry et al., 2014). A first significant attempt at developing a bottom-up inland fisheries management plan in Guyana in 2011 was in association with a previous international development project. Makushi community members at the time accepted plans for fishing licenses and a catch recording programme for all types of fishing activity. However, the communities quickly realised that licensing and reporting would be too onerous for subsistence fishers, while peer enforcement also seemed unworkable in practice, so the 2011 management process faltered.

In 2018, with support from the SWM, a new work plan was developed to implement a fisheries management plan with a focus on monitoring and awareness raising. Work conducted by NRDDB in conjunction with village councils increased governmental interest, as the Fisheries Department prepared to develop inland fisheries regulations and a strategic plan. In 2022, the need to revise the Fisheries Management plan became imminent to better specify co-management responsibilities among village councils, NRDDB and the Fisheries Department, and to ensure integration with fisheries regulations under development. In addition, an economic analysis of the fishery value chain was initiated to explore possibilities for internal funding and to reduce dependency on project funding to implement the fisheries management plan.

2.2 | Fish monitoring surveys

The new NRDDB fisheries monitoring programme, the first in Guyana that involved close coordination with 20 member communities in the North Rupununi and with the Guyana Department of Fisheries, aimed to develop a standardised CBM programme for fish and focused on providing data to support quantitative assessments for key target stocks. Such a programme is expensive and time-consuming, and so aimed to evaluate current stock status and establish baselines for subsequent semi-quantitative monitoring based on LEK. The programme emphasised the involvement of local fishers and their knowledge of the Rupununi social-ecological system.

Standardised fish monitoring surveys were conducted by the NRDDB in May 2021 (as river levels rose at the onset of the rainy season) and in each October and November 2020 and 2021 (as river levels receded at the onset of the dry season). Survey times were selected to capture information related to fish spawning and recruitment and were informed by community LEK. Upcoming surveys advertised on community radio asked village leaders to nominate two fishers to work with the team in local areas. Community researchers from six villages were not typically paid but contributed as a community, with 26 people trained in fish monitoring methods to participate in the first two surveys. Local insight into these fishers was extremely useful in fish identification and optimal use of local fishing gears and selection of appropriate fishing sites in the North Rupununi region. Most survey sites were known to village councils as good fishing locations or were familiar to regional researchers from previous fisheries patrols.

The same sites were sampled across all three survey periods, but the CBM strategy was allowed to be "context-specific, iterative and adaptive" (Pollock & Whitelaw, 2005). Standard scientific gillnets were the main survey gear in 2020, while a set of local gears were used for both surveys in 2021. This change in gear type was intended to catch larger fish and to match the survey more closely with corresponding subsistence and artisanal fisheries. Local gears were fished according to common practices understood from LEK, such as handlines for Peacock bass (*Cichla ocellaris*) in the morning and cadel (mid-water longlines) in the afternoon and at deeper water sites targeting catfishes. Fishing gear, site and time were recorded for each survey "haul" (fishing event). Each fish caught was identified to species where possible and measured in length (cm) and weight (g). Survey data provided length distributions for the abundant fish species to potentially support length-based assessment.

The development and implementation of the monitoring programme was a community-led process. Local knowledge and experience were used to evaluate and modify the survey to better represent habitats and fish populations targeted by local fishers. This iterative process produced recommendations for future surveys, including understanding and insight useful to other community groups initiating similar programmes elsewhere.

2.3 | Fish stock assessments

Observed contrasts in season and gear over surveys, and some extreme weather conditions, were considered by local researchers to have influenced species and size distributions of catches. Therefore, the three survey datasets were considered separately for the assessment of fish population state. Considerable species richness was evident in both surveys, with 100 fish species recorded in 2020 and 50 in 2021, but only a few marketable species had more than 50 individuals in either year (Table 1). Simulations by Hordyk et al. (2015) showed that the uncertainty of SPR model estimates increased as the sample size falls below 100 individuals, so length-based assessment methods were applied to any commercially important species with at least 50 individual length records (Table 1).

A reliable LBI ($L_{max5\%}$, ICES, 2015) was first estimated for each of the most abundant species. The $L_{max5\%}$ was calculated as the ratio of the mean length of the largest 5% of fish in the survey sample to the von Bertalanffy theoretical mean maximum length L_∞ (See explanation below, Table 2). A proposed threshold for good state is

TABLE 1 Number of individuals (N) of the most abundant target fish species (N > 50) in North Rupununi District Development Board fish monitoring surveys of the Rupununi, Rewa and Essequibo Rivers of southwest Guyana in October 2020, May 2021 and November 2021

Number of individuals				
Species	**Common name**	**Oct 20**	**May 21**	**Nov 21**
Ageneiosus inermis	Dawalla	216	54	220
Ageneiosus ucayalensis	Duck catfish	NA	195	NA
Boulengerella Cuvieri	Swordfish	NA	NA	88
Cichla ocellaris	Peacock bass	55	NA	169
Hydrolycus armatus	Black-tail Biara	281	53	123
Hydrolycus tatauaia	Characin	82	NA	NA
Piaractus brachypomus	Red pacu	NA	59	NA
Pygocentrus nattereri	Red piranha	354	NA	186

TABLE 2 Life history parameter estimates used for assessment of the most abundant target fish species ($N > 50$) in North Rupununi District Development Board fish monitoring surveys of the Rupununi, Rewa and Essequibo Rivers of southwest Guyana in October 2020, May 2021 and November 2021. L_∞ and k are from the Von Bertalanffy growth equation, L_{m50} and L_{m95} are the lengths at 50% and 95% maturity, respectively, A_{mat} is the age at maturity, A_{max} is longevity (y) and M is mean natural mortality from a set of published estimators

Species	L_∞	k	L_{m50}	L_{m95}	A_{mat}	A_{max}	M	References
Ageneiosus inermis	73.7	0.25	35	45	NA	9	0.52	Camargo et al. (2015); Sa-Oliveira et al. (2015)
Ageneiosus ucayalensis	38	0.54	15	21	2	NA	0.89	Camargo et al. (2015); Oliveira et al. (2017); Ref $L_\infty = 33.7$
Boulengerella Cuvieri	78	0.36	40	50	NA	NA	0.61	Mendes et al. (2017); Fonseca (2021); Camargo et al. (2015)
Cichla ocellaris	83	0.18	25	30	2	NA	0.64	Holley et al. (2007); Jepsen et al. (1999)
Hydrolycus armatus	85	0.15	35	50	NA	11	0.38	Camargo et al. (2015). Reference $L_\infty = 93.7$
Hydrolycus tatauaia	85	0.15	35	50	NA	11	0.38	Camargo et al. (2015). Reference $L_\infty = 93.7$
Piaractus brachypomus	64	0.6	30	45	7	28	0.47	Guerreiro et al. (2013); Loubens and Panfili (2001)
Pygocentrus nattereri	23.6	0.67	12	15	1	7	1.37	Duponchelle et al. (2007)

$L_{max5\%} > 0.80$ (ICES, 2015), but this varies with exploitation pattern and fish life history (Miethe et al., 2019). Lower values may be appropriate for migratory species (Shephard et al., 2018).

Estimates of spawning potential ratio (SPR) for selected North Rupununi fish stocks were obtained using the LB-SPR model (Hordyk et al., 2015). SPR is defined as the lifetime reproductive output per recruit of a fished population, divided by the output per recruit if the population had never been fished (Goodyear, 1993). SPR expresses how fishery removal of sexually mature individuals impairs overall productivity (e.g. spawning stock biomass). The LB-SPR model uses maximum-likelihood methods to estimate values of relative fishing mortality (F/M) and selectivity at length (fishing gear selection pattern) that minimise the difference between observed (fitted catch) and expected (modelled from life history) length distributions. The LB-SPR model then calculates SPR for comparison to a value representing good state, which varies with life history (e.g. SPR = 0.20 to 0.40; Mace & Sissenwine, 1993; Slipke et al., 2002).

The expected length distribution was derived by LB-SPR using input estimates of L_∞ and M/k, and SPR was calculated using input estimates of mean lengths at which 50% (L_{m50}) and 95% (L_{m95}) of a given population become sexually mature, to specify components of the population size distribution likely to contribute to the recruitment of juveniles. LB-SPR uses L_∞ as an input, and values for Von Bertalanffy k, natural mortality M, L_{m50} and L_{m95} for a given population (Table 2). Estimates of these life history parameters (LHP) should ideally be derived for the specific population being assessed (Hordyk et al., 2015). However, this process is frequently impractical for data-limited populations, so general estimators (Kenchington, 2014) or statistical approaches (Thorson et al., 2017) are often used. Values may also be taken from similar or nearby populations of the same fish species (Shephard, Valbo-Jorgensen, et al., 2021). Indirect approaches to obtaining proxy LHP are risky because parameters such as L_∞ and M/k can vary greatly among populations and strongly influence LB-SPR, thereby possibly inducing misleading estimates of ecological state.

Published sources of LHP parameters (L_∞, k, L_{m50} and L_{m95}) were used for each study species for North Rupununi survey stocks (Table 2). These values were used to derive a composite (mean) estimate of M for each assessed species (Table 2) using methods collected by Cope and Hamel (2022), to be used as the input to LB-SPR. Asymptotic length L_∞ was the LHP that most influenced estimates of SPR because it constrains the expected number of large fish. To explore the sensitivity of outcomes to error in L_∞, SPR was estimated for selected North Rupununi fishes using $L_\infty \pm 5\%$ (Table 2). Sensitivity was interpreted by comparing the percentage difference in the output (SPR) in relation to the 5% change in the input (L_∞). Where SPR changed proportionally more than L_∞, this was taken to indicate that the assessment was strongly sensitive to the input estimate of L_∞.

Selectivity-at-length in the LB-SPR model (Hordyk et al., 2015) assumed that the predominant gear in the fishery had asymptotic (trawl-type) size selection (i.e. all individual fish larger than an asymptotic length were retained). However, dome-shaped selection was more likely for NRDDB survey gears (gillnets and hooks), in which some larger individuals were probably not retained (e.g. by a smaller hook or static gear mesh sizes). Dome-shaped selectivity can be implemented in LB-SPR (Hommik et al., 2020), but requires input gear selectivity parameters that were not available for our assessed species, so we conservatively assumed asymptotic selection (Hordyk et al., 2015).

The LB-SPR model can be fit using an R package (Hordyk, 2019) or an online app (http://barefootecologist.com.au/lbspr), but we used a new (currently unpublished) application that was recently developed at Inland Fisheries Ireland (IFI) and includes estimates of uncertainty (95% confidence intervals) for SPR. Confidence intervals for SPR are derived by propagating standard errors (variance–covariances) of maximum-likelihood estimates of log-transformed F/M, length-at-50%-selectivity LS_{50} and selectivity "slope" (LS_{slope}) parameters from the inverse of the Hessian matrix through to SPR (a function of F/M, LS_{50} and LS_{slope}) using the delta method,

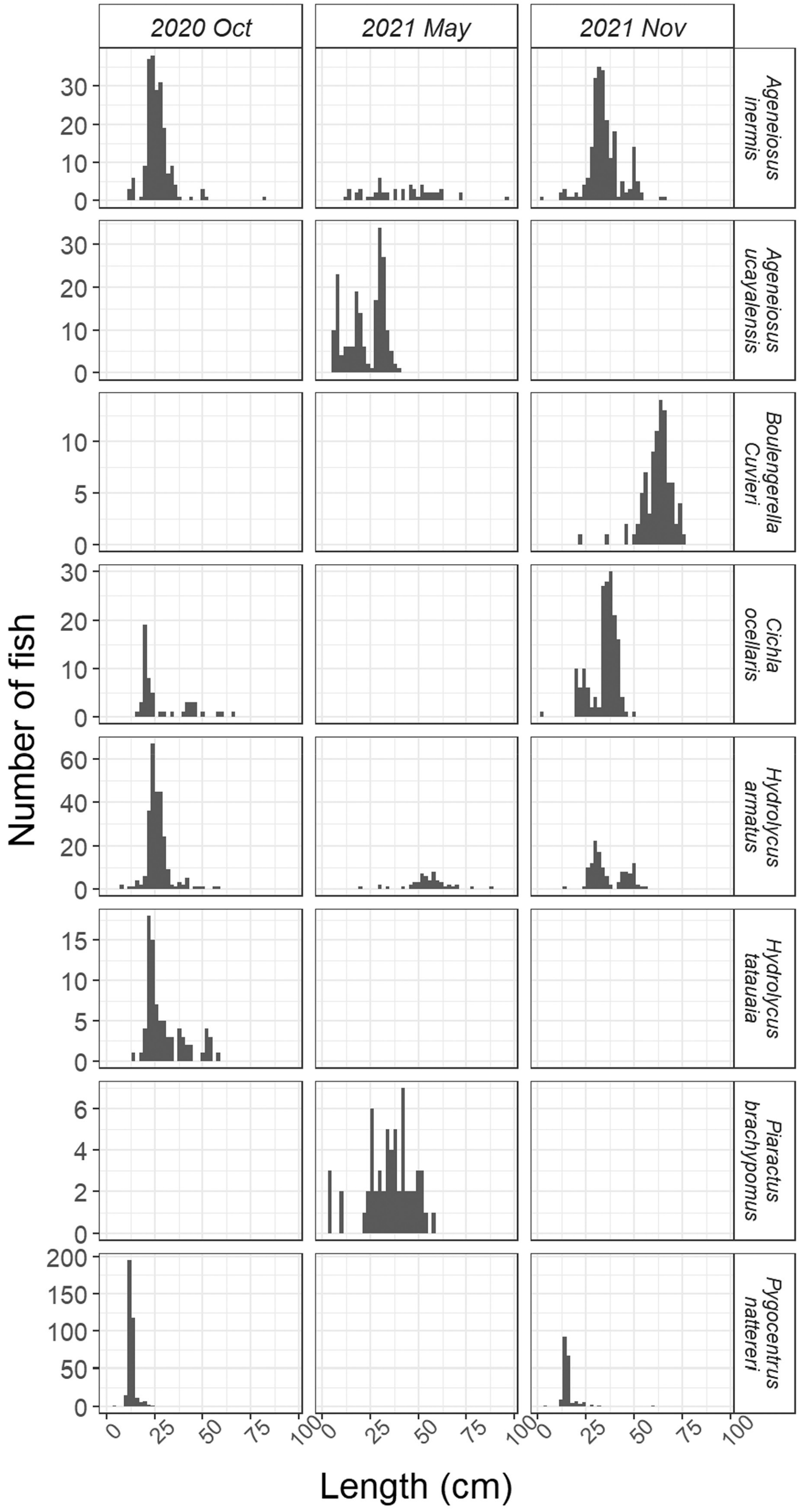


FIGURE 2 Length distribution of *Ageneiosus inermis*, *Ageneiosus ucayalensis*, *Boulengerella Cuvieri*, *Cichla ocellaris*, *Hydrolycus armatus*, *Hydrolycus tatauaia*, *Piaractus brachypomus* and *Pygocentrus nattereri* caught in North Rupununi District Development Board fish monitoring surveys of the Rupununi, Rewa and Essequibo Rivers of southwest Guyana in October 2020, May 2021 and November 2021.

a first-order approximation of variance for "derived" quantities that depend on other estimated statistical parameters. The new application also provides output plots that describe model fit, observed and expected size distributions of assessed populations and diagnostic plots that express if key model assumptions were likely to have been violated and results can be considered reliable.

3 | RESULTS

3.1 | Fish monitoring surveys

The most abundant species of fishery importance varied among sampling periods (Table 1). The NRDDB monitoring surveys generally caught fewer fish in the upper Rupununi than in the upper Rewa and Essequibo catchments where larger Makushi communities resided. Survey catches (species composition and population size distributions) also differed strongly between seasons and years. Length–frequency distributions from surveys in May and November 2021 were more multi-modal than in October 2020 and included larger individuals of several species (Figure 2). Changes in gear type and survey season prevented comparison between 2020 and 2021. Most fish sampled in 2020 were caught in standard scientific gillnets, whereas most fish sampled in 2021 were caught in local gears (cadel and handlines). According to community experts, differences in catch predominantly reflected differences in size and species selectivity between survey gillnets and artisanal commercial fishing gears. Gillnets had smaller meshes and were set close to the surface, where smaller fish were expected. Seasonal effects related to fish growth and recruitment may also have caused differences in catches (e.g. the greater abundance of small juvenile fish in May or of larger migrating fish in October–November).

Community discussion during survey development highlighted important issues that led to decisions about future surveys. The first requirement identified was to standardise the annual monitoring period. Surveys conducted as river levels recede were preferred, by catching more large fish with easier access to sample sites due to dry season conditions. This season was also the period when benthic-feeding fish were in prime condition from foraging in flooded landscapes (Oliveira et al., 2006). However, different seasons and water conditions may support different fishers and livelihoods, so a standard protocol should be open to other local voices. The second requirement identified was to standardise survey gears. Local fishing gears used in 2021 were more informative for monitoring the North Rupununi fish community. Using commercial gear for surveys also has advantages for size-based stock assessment because the survey selection pattern (size and species) is expected to match gears that imposed the most fishing pressure. This correspondence simplified estimates of size-selective fishing mortality for assessed species using LB-SPR. Other decisions discussed among community researchers referred to standardising fishing effort for each survey site and gear type because fishing gears were used according to local knowledge, such as site characteristics or time of day. The number of fishing events for each gear type (e.g. number of cadel lines, number of handline fishers, etc.) should now be fixed for each site.

The NRDDB recognised that maintaining fish monitoring in the future would require a reduced survey programme that could be implemented sustainably with only local and national funding. For example, sites may need to be surveyed quantitatively at multi-year intervals, interspersed with monitoring perceived trends based on LEK. Community researchers proposed that a streamlined survey could exclude the Essequibo River and concentrate on the more populated Rupununi and Simoni systems. One suggested approach was to identify key "sentinel" sites that were expected to have relatively low or high fishing pressure, which would be surveyed more frequently. Rewa is considered to have a strong conservation ethic, while Apoteri is relatively isolated and sheltered from intense fishing. In other regions, overfishing is a concern (e.g. the Essequibo River and tributaries between Kurupukari and Rockstone, outside of the NRDDB Fisheries Management Area, experience hunting and fishing pressure to support mining and logging industries). Nutrient classification of different systems (e.g. whitewater vs. blackwater rivers) could also be considered.

3.2 | Fish stock assessments

Species surveyed represented a range of life histories and maximum sizes, and therefore were potential indicators of the ecological state of the broader fish community. The LBI suggested moderate-to-good state for all species, while SPR from the LBM was much more variable (Table 3). Model fit was generally acceptable for LB-SPR, with diagnostic plots not suggesting strong reasons for rejecting results. An exception was *Ageneiosus inermis* in May 2021, where the assessment showed wide confidence intervals and an unreliable outcome, probably reflecting the small sample size (Table 1). Therefore, assessment outputs for this species were not used (Table 3, Figure 3). For other species, assessments tended to indicate a better state for 2021 than 2020, except for *Cichla ocellaris* (Table 3, Figure 3). Sensitivity analysis indicated that ±5% variation in L_∞ generally resulted in >5% change in SPR, indicating strong sensitivity to input estimates of this LHP. Such sensitivity has implications for reliably inferring fish population state using LB-SPR and points to the need for accurate population-level estimates of LHP (Table 3).

The contrast in survey catches between years was exemplified for *H. armatus*, which was the only species sufficiently abundant to be assessed in all three surveys. The state for this population was poor (<0.2) in October 2020, good (>0.4) in May 2021 and moderate (0.2–0.4) in November 2021 (Table 3). This outcome reflects large differences in length–frequency distributions among surveys, with larger fish (assumed to indicate a better state) being much more prevalent in local fishing gears used in 2021 (Figure 2). As expected, estimates of SPR were generally larger when the input value of L_∞ was smaller (Table 3), which highlighted the potential for bias if input LHP estimates borrowed from other stocks did not match the growth of the assessed stock.

4 | DISCUSSION

The NRDDB pilot programme is a collaboration among local communities, multi-disciplinary scientists and the national government that successfully established a standardised fish monitoring survey for the North Rupununi, tested several available sampling gears and

TABLE 3 Mean length of the largest 5% of fish sampled divided by the mean maximum length L_∞ ($L_{max5\%}$), minimum landing size (MLS), fishing mortality (F), spawning potential ratio (SPR), SPR at +5% L_∞ and State for *Ageneiosus inermis*, *Ageneiosus ucayalensis*, *Boulengerella Cuvieri*, *Cichla ocellaris*, *Hydrolycus armatus*, *Hydrolycus tatauaia*, *Piaractus brachypomus* and *Pygocentrus nattereri* caught in North Rupununi District Development Board fish monitoring surveys of the Rupununi, Rewa and Essequibo Rivers of southwest Guyana in October 2020, May 2021 and November 2021

Species	$L_{max5\%}$	MLS	F	SPR	SPR $L_{\infty+5\%}$	SPR $L_{\infty-5\%}$	State
Ageneiosus inermis	0.64	20	1.33	**0.038**	0.030	0.057	Poor
Cichla ocellaris	0.74	20	0.24	**0.487**	0.361	0.536	Good
Hydrolycus armatus	0.54	20	1.41	**0.023**	0.018	0.028	Poor
Hydrolycus tatauaia	0.57	20	0.42	**0.156**	0.127	0.197	Poor
Pygocentrus nattereri	0.83	10	3.10	**0.217**	0.178	0.268	Poor-Mod
Ageneiosus inermis	1.09	20	NA	**NA**	NA	NA	NA
Ageneiosus ucayalensis	1.13	25	1.04	**0.751**	0.640	NA	Good
Hydrolycus armatus	0.93	20	0.21	**0.716**	0.612	0.850	Good
Piaractus brachypomus	0.86	20	0.65	**0.214**	0.164	0.282	Poor-Mod
Ageneiosus inermis	0.72	20	0.72	**0.185**	0.149	0.234	Poor-Mod
Boulengerella Cuvieri	0.96	NA	1.44	**0.679**	0.581	0.797	Good
Cichla ocellaris	0.54	20	10.5	**0.263**	0.228	0.305	Moderate
Hydrolycus armatus	0.61	20	0.31	**0.273**	0.223	0.339	Moderate
Pygocentrus nattereri	1.19	10	1.13	**0.515**	0.425	0.640	Good

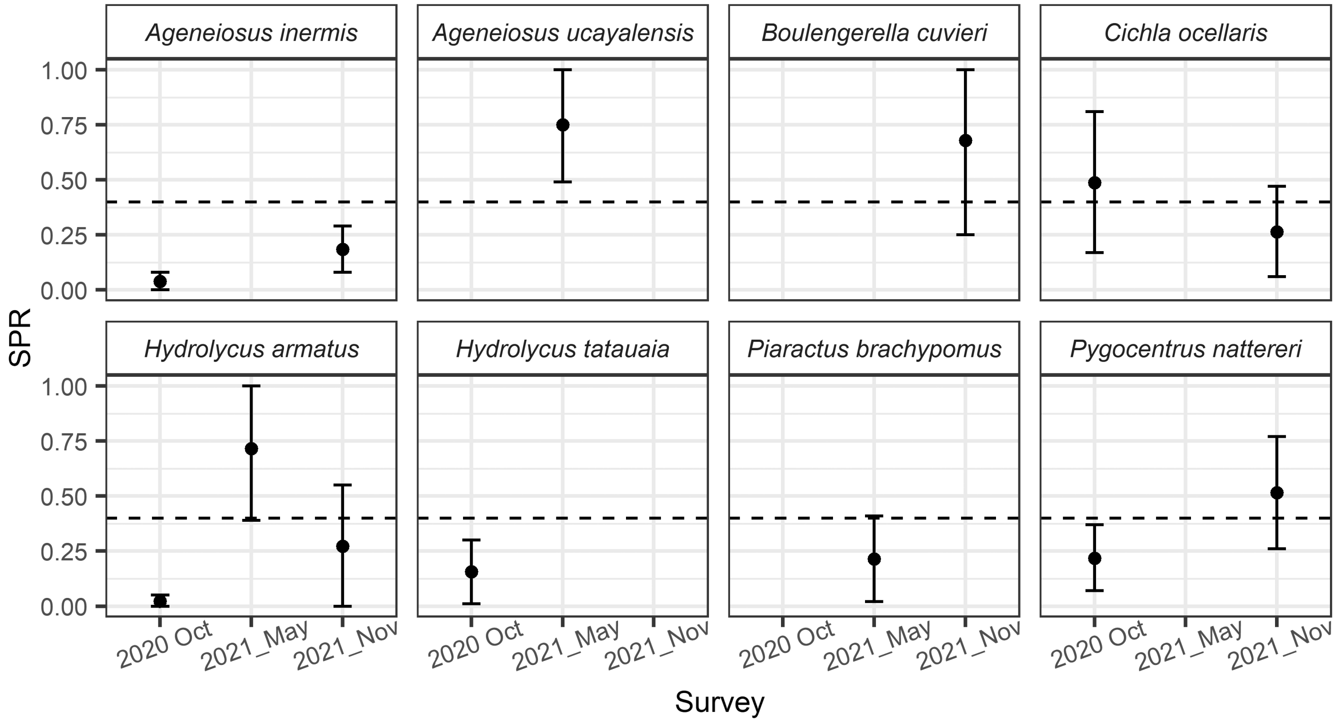


FIGURE 3 Spawning potential ratio (SPR ± 95% confidence intervals) for *Ageneiosus inermis*, *Ageneiosus ucayalensis*, *Boulengerella Cuvieri*, *Cichla ocellaris*, *Hydrolycus armatus*, *Hydrolycus tatauaia*, *Piaractus brachypomus* and *Pygocentrus nattereri* caught in North Rupununi District Development Board fish monitoring surveys of the Rupununi, Rewa and Essequibo Rivers of southwest Guyana in October 2020, May 2021 and November 2021. The dashed line depicts a good state reference point at SPR = 0.40.

targeted a wide range of sites. The survey was effective in catching most of the abundant fish species and including species important to local fisheries and livelihoods. Quantitative data provided a baseline for the fishery state for future application of accessible trends-based indicators based on LEK. Local social-ecological initiatives are extremely important to the sustainable management of inland fisheries (Nguyen et al., 2016). Previous work in tropical wetlands supports the use of knowledge and skill of fishers in resource monitoring and management to bridge knowledge systems among stakeholders (Castello et al., 2009).

4.1 | Community-based monitoring

Our study highlights an example of successful CBM, in which a combination of local experts and community participants with different levels of scientific training collected data that described shifts in biodiversity (Holck, 2008). The monitoring programme is closely linked to the development and implementation of the new inland fisheries management plan for the North Rupununi initiated by the NRDDB, who requested help from the government and the SWM project, including the establishment of appropriate legal authorities and rights (Ratner, 2006). Such grassroots participation in monitoring and the broader management plan reflect strong incentives for self-interested local conservation measures. Makushi communities perceive that their fisheries systems are experiencing increased pressures from commercial fishing, mining and logging, as well as potential changes in flood intensity linked to climate change. They also recognise that addressing this external forcing will require traditional regulation to be framed in national legislation through a more formal and transparent co-management structure. The new management plan is currently being revised (2022) in an inclusive consultation process.

The community-based monitoring and management system for North Rupununi fisheries must be practically and economically sustainable after external project support ends. Current village leadership is committed, with a strong interest in wildlife conservation, but some conditions must be established. The first element is to develop local monitoring and assessment capacity. Several young community members have already been trained to collect and curate relevant data. These individuals have developed and operated the monitoring survey very successfully and are willing to conduct basic data analysis. A complementary programme of fishery monitoring will be initiated by the NRDDB in 2022, using semi-quantitative state indicators based on simple LEK questionnaires (Shephard, Ryan, et al., 2021). This approach will allow for a broader set of social-ecological indicators that are meaningful and applicable at the local scale (Boyd & Charles, 2006). The information will be relatively cheap and easy to collect and will track annual trends in fishery state relative to the quantitative monitoring and assessment baselines established in the current study. This dual approach means that the more complex length-based assessments need only be updated at longer intervals. The communities will also undertake mandatory catch recording in the commercial fishery to provide a parallel monitoring series. The national fisheries department and ongoing environmental NGO programmes in the region (e.g. WWF) can also oversee and provide guidance as needed. Vital local coordination and communication (Murshed-e-Jahan et al., 2009) will be provided by the NRDDB.

Such knowledge co-production locates ownership of the assessment process at a very local level and minimises costs, but ongoing local funding will still be required. The most likely revenue sources are a levy on sport fishing and ecotourism, with successful examples in the Amazon (Freire et al., 2016), and potential to highlight "flagship" recreational species (Gupta et al., 2014). New license fees will also be imposed on local and regional commercial fishers as mandated in the new management plan. Some communities already operate thriving tourist businesses, which mainly serve relatively affluent international visitors. Both income streams will be collected by village councils and allocated across fisheries management and other local development projects.

A long tradition of CBM and management of fisheries in the neighbouring Amazon region has attempted to formalise co-management regimes (Castro & McGrath, 2003). These "fishing accords" often reflect the role of artisanal fishing as part of a portfolio of activities, including shifting agriculture, small animal husbandry and cattle raising (McGrath et al., 2004). Such bottom-up structures can protect fish populations even in cases of strong external pressures (Pinho et al., 2012). The effort required to enforce these agreements is justified by maintaining productivity at a level where catching fish does not encroach excessively on other activities (Schons et al., 2020). The sooner communities adopt such institutions, and the stronger the institutions they adopt, the more likely they are to sustain target fish stocks (Basurto & Coleman, 2010).

However, successful decentralised management is very challenging in inland fisheries because of their social-ecological dynamics and frequent problems with enforcement (Ocampo-Diaz et al., 2022). An important issue is the use of community data by decision-makers, and possible barriers to linkages between local communities and legislators or policymakers (Conrad & Hilchey, 2011). Sustainable small-scale fisheries in the North Rupununi likely depend on cross-scale linkages between local stakeholder groups and higher-level governance (Cudney-Bueno & Basurto, 2009) to leverage external support. Access to the Rupununi by fishers from the Amazon system further suggests that community initiatives will need to be combined with a transnational element for successful fisheries management (Goulding et al., 2019).

4.2 | Fish stock assessments

Survey length distributions were used to derive an empirical and a model-based state metric for each of eight abundant North Rupununi fish species of fishery interest. These baseline assessments provided scope for conclusions about the impact of fisheries in the region and to track future change using LEK and periodic quantitative updates. Length-based methods are not expected to capture higher-level ecosystem pressures such as pollution and climate change, so broader monitoring of the ecological state will also be necessary.

Uncertainty in input life history parameters and relatively small sample sizes (<100 individuals for some stocks) limit conclusions on the state of the North Rupununi fish community. The very poor population state suggested by the 2020 data probably reflects the selection for smaller individuals by scientific gillnets. In contrast, 2021 data included more large individuals, so the estimated state was more positive. In addition, evaluating the selectivity of local fishing gears, especially the assumption of asymptotic selection, is not currently possible. An important limitation is a lack of life history parameters estimated directly from surveyed fish stocks (i.e. input values for L_∞, k and M were derived from published estimates for similar populations), which could bias assessment outcomes if inappropriately high L_∞ values underestimate SPR because the LB-SPR model assumes an "expected" (unfished) population size distribution that includes more large fish than are recorded in the observed length data (Hordyk et al., 2015). Input estimates of M/k also inform the expected size distribution and hence can bias outputs. Ideally, stock-specific estimates of L_∞ and M/k would be estimated, which would produce more accurate estimates of F/M and SPR. Modelling growth from length-at-age data requires a year of monthly sampling for tropical systems where lack of clear annual growth increments complicates age estimation from scales or otoliths.

The NRDDB monitoring programme could also be extended to include LBM assessments over multiple years. Other length-based assessment models (e.g. LIME; Rudd & Thorson, 2018) can use time series of length data to track temporal change, although data quality and model performance may be more important than time series per se (Carruthers et al., 2014). Additional models would support an "ensemble" approach (Free et al., 2020) as more data become available. Data could also be pooled across survey periods (once the survey is standardised) to increase the number of individuals and support LB-SPR assessment of important but less abundant species.

The advantages of increasingly complex assessment models must obviously be balanced against local technical capacity and resources, and the potential for tracking fishery state using empirical and semi-quantitative LEK indicators. Limited resources are likely to mean that fish monitoring surveys only occur periodically, and so survey-based indicators (e.g. CPUE and length distributions) will only be available at an intermittent temporal resolution. A parallel surveillance series may come from reporting of commercial catch under the new North Rupununi management plan. These quantitative data could complement annual LEK surveys of fishery and broader ecological state, with the potential for an ecosystem-based framework in which management responds to a range of information.

Despite limitations, our study contributed to filling a knowledge gap about exploited fish stocks in the Guiana Shield. Relatively few formal state assessments are available for fish stocks in the region, with more knowledge of the bordering Amazon system (e.g. Shephard, Ryan, et al., 2021; Castello et al., 2011; Isaac & Ruffino, 1996; Petrere et al., 2004). In Guyana, the previous focus has been on *Arapaima gigas* (Castello, 2001; Watson et al., 2021), and to our knowledge, the broader fish community has not yet been assessed. Our results suggest that stocks in the North Rupununi are not yet strongly overfished, although evidence of loss of larger individuals is consistent with size selective exploitation. This conclusion matches reasonably well with local knowledge of the fishery. Fisher's LEK from the North Rupununi suggests that fish stocks near more remote communities are still relatively healthier than those closer to access roads. Larger and more desirable species (e.g. Dawalu (*Ageneiosus inermis*) and Red pacu (*Piaractus brachypomus*)) in these vulnerable areas have been reported by Makushi community members to be reduced in mean size, concordant with size-based assessment.

The moderate state of Rupununi fish stocks contrasts with the Amazon, where some stocks have been declining for decades (Bayley & Petrere, 1989; Petrere et al., 2004) and key species show clear signs of overexploitation (Shephard, Valbo-Jorgensen, et al., 2021; Castello et al., 2011). Our tentative conclusions about current stock status did not consider possible local depletions (e.g. close to fishing communities or regions with intense mining or logging). Future efforts to track state in specific locations could be supported by identifying indicator species, which could include important commercial fishes and species with vulnerable life history or other biodiversity interest (e.g. high trophic level and larger fishes, including Arawana *Osteoglossum bicirrhosum* and Peacock bass). A broader ecosystem approach would include empirical fish community indicators. The current $L_{max5\%}$ indicator refers to individual species, but can evaluate change at the assemblage scale (e.g. shifts in size distribution or maturation schedule that often follow size-selective fishing pressure; Trenkel & Rochet, 2003).

A significant issue that is not explicitly addressed in our study is the local understanding of the fishery state, and how it is perceived to have changed in recent decades (Bender et al., 2014). The current scientific assessments could be productive to consider more explicitly in the context of LEK, especially from indigenous experts (Davis & Wagner, 2003). Numerous examples of how this could be done are available, but reproducible methods are better for expressing LEK as semi-quantitative state indicators (Shephard, Ryan, et al., 2021) that can be interwoven with numeric metrics (e.g. LBIs, to produce more holistic impressions of fishery state). Such a multi-stranded exercise could include an evaluation of how fishing overlaps with terrestrial hunting, and whether changes in bush-meat hunting or burns adjacent to wetlands are likely to change pressure on fish populations. Important patterns could also be elicited regarding social-economic changes in fishing communities.

[Correction added on 23 November 2022, after first online publication: the reference citation has been corrected to read as 'Shephard, Ryan, et al., 2021' in this version.]

ACKNOWLEDGEMENTS

This work would not have been possible without the active participation of North Rupununi fishers and indigenous communities, and the precious contributions of the North Rupununi District Development Board (NRDDB). The research presented in this paper was funded by the European Union under the Sustainable Wildlife Management Programme, an initiative of the Organization of African, Caribbean and Pacific States (OACPS), with co-funding from the French Facility for Global Environment and the French Development Agency implemented by the Food and Agriculture Organization of the United Nations (FAO), the French Agricultural Research Centre for International Development (CIRAD), the Wildlife Conservation Society (WCS) and the Centre for International Forestry Research

(CIFOR). This work is also part of the Bushmeat Research Initiative, under the CGIAR research programme on Forest, Trees and Agroforestry partnership. In Guyana, the programme is implemented with the Guyana Wildlife Conservation Management Commission, the Fisheries Department, the NRDDB and village councils.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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How to cite this article: Shephard, S., Edwards, K., George, S., Joseph, E., James, S., David, O., Persaud, A., Watson, L. C., & Van Vliet, N. (2023). Community-based monitoring, assessment and management of data-limited inland fish stocks in North Rupununi, Guyana. *Fisheries Management and Ecology*, *30*, 121–133. https://doi.org/10.1111/fme.12604