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Assessment of exploited fish species in the Lake Edward System, East Africa

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Summary

The unknown status of inland fish stocks hinders their sustainable management. Therefore, increasing stock status information is important for sustainable inland fisheries. Fisheries reference points were estimated for five exploited fish species (11 stocks) in the Lake Edward system, East Africa, which is one of the most productive inland water systems. The aim was to ascertain the status of the fisheries and establish reference points for effective management. The reference points were based on four linked stock assessment approaches for data-limited fisheries. Estimates showed poor stock status with the stocks defined as either collapsed, recruitment impaired or overfished. However, higher catches could be obtained under sustainable management. Estimates of maximum sustainable yield (MSY) and supporting biomass (B_{msy}) are provided for 10 of the stocks as targets for rebuilding plans. The immediate target of management should be rebuilding biomass to B_{msy}. Applicable measures include shifting length at first capture to the length that maximizes catch without endangering size structure and biomass, and livelihood diversification out of fisheries.

KEYWORDS

data-limited fisheries, fish, Lake Edward, reference points

1 | INTRODUCTION

The paucity of information on the status of inland fisheries limits their consideration in major policy processes such as the Sustainable Development Goals (Cooke et al., 2016; UN General Assembly, 2015). Consequently, these fisheries do not benefit from associated management targets, leading to increased threats (Cooke et al., 2016; Youn et al., 2014). Improving available information is vital for sustainable inland fisheries (FAO, & MSU, 2015).

Fish stocks assessments support more effective fisheries management. These assessments are urgent in Sub-Saharan Africa where inland fisheries contribute significantly to livelihoods but are poorly managed. Inland fisheries in the region support livelihoods for over 4.9 million people (De Graaf & Garibaldi, 2014), but are threatened by stock depletion (Marshall, 2015). Management is scarce and where it occurs, it proceeds with unreliable guidance (Cooke et al., 2016).

Stock assessments provide fisheries reference points (FRP), the benchmarks on which the status of fish stocks is measured (ICES, 2017). Common FRP include: maximum sustainable yield (MSY), the target for sustainable exploitation of fish stocks; fishing mortality rate at MSY (F_{msy}), a limit beyond which exploitation becomes unsustainable; fishing mortality rate relative to F_{msy} (F/F_{msy}); biomass that supports MSY (B_{msy}); and current biomass relative to B_{msy} (B/B_{msy}). Caddy and Mahon (1995), Hilborn and Stokes (2010), ICES (2017) and Pew Charitable Trusts (2016) provided detailed accounts of the common FRP. However, FRP are rarely used to guide management of inland fish stocks due to data deficiency and the lack of appropriate stock assessments (Cooke et al., 2016; Lorenzen et al., 2016).

Stock assessment methods have developed simultaneously for data rich and data-limited fish stocks (Hilborn, 1992). The data rich methods, which utilize more data about the stock, are preferred, and

TABLE 1 Fish species assessed and their ecological and fishery aspects. Resilience and Length at 50% maturity (L_{m50}) are adopted from FishBase (Froese & Pauly, 2019). Fisheries importance is based on annual catches from the water bodies (NaFIRRI, 2018). Gillnets and longlines are the main fishing gears. Selectivity of these gears is envisaged to be sigmoid, a variant of the general bell-shaped selectivity for the gears because multiple hook sizes and mesh sizes are used, and small individuals are not caught and capture is expected starting from L_{m50}

Scientific name (common name)	Habitat	Length at first maturity (L_{m50})	Resilience (population doubling time in years)	Fecundity (range)	Fisheries importance
Mormyrus kannume (Elephant snout fish)	Demersal; inhabits near shore and offshore habitats in lakes, spawning in rocky areas	–	Medium (1.4–4.4)	1,393 and 17,396 (Okedi, 1970)	Relative composition in catches is 5.3%, 2.4% and 3% in lakes Edward and George and the Kazinga channel respectively
Protopterus aethiopicus (Marbled lungfish)	Demersal; inhabits nearshore vegetation fringes associated with rivers and open waters	70	Low (4.5–14)	468–8,422 (Witte & de Winter, 1995)	Responsible for most of the catch in Lake George (35.2%), and the second most important in Lake Edward and the Kazinga channel
Oreochromis niloticus (Nile tilapia)	Benthopelagic; restricted to near shore and shallow waters of <20 m depth (van Oijen, 1995)	25	Medium (1.4–4.4)	735–1,050 (Natugonza et al., 2015)	Previously, the most important commercial fish species, but its relative importance has reduced due to overexploitation. It is now the third most important in Lake Edward after Semutundu and Marbled lungfish
Clarias gariepinus (North African catfish)	Benthopelagic; prefers shallow and swampy areas in lakes and rivers	30.8	Medium (1.4–4.4)	5,000–192,000 (Witte & de Winter, 1995)	Comprises 13% of the catch in Lake Edward, 17.3% in Lake George and 11.4% in the Kazinga channel
Bagrus docmak (Semutundu)	Benthopelagic; in lakes, widespread in both shallow and deep water	30	Medium (1.4–4.4)	25,000–100,000 (Dadzie & Ochieng-Okach, 1989)	The most important in catches from Lake Edward (33.5%) and the Kazinga channel (40.2%) and the second most important in Lake George (18.1%) after Marbled lungfish

for a longtime, stock assessment agencies restricted assessments to data rich stocks. The increasing need of sustainable exploitation of all stocks has resulted into improvements in data-limited methods, addressing earlier criticisms such as the failure to adequately incorporate prior knowledge and the biology of stocks, conduct sensitivity analysis, and Monte-Carlo testing. These methods are becoming widely applied globally (Le Quesne et al., 2013).

This study aimed to determine FRP in the Lake Edward system, East Africa, one of the most productive inland water systems (Beadle, 1981), using stock assessment methods for data-limited fisheries. The system has the Kazinga Channel and lakes Edward and George as its main water bodies (Figure S1). Lake George and the Kazinga channel are within Uganda while Lake Edward is shared by Uganda and the Democratic Republic of the Congo (DRC). Decru et al. (2020) provided a detailed account of the features of the system. The waterbodies support fisheries with annual combined catches of 21,000 tonnes, supporting 22,000 fishers in Uganda and the DRC (Bassa et al., 2014; Lubala et al., 2018). Only five of eight commercial fish species were assessed in this study due to data limitations (Table 1). The assessed fish species are responsible for >80% of the catches in each of the waterbodies (NaFIRRI, 2018). The wide application of the data-limited stock assessment methods justified their application in this assessment. In addition, only length frequencies, catches, and catch per unit effort (CPUE), a measure of relative abundance were available for the stocks assessed, data that were not adequate for data rich methods.

The major FRP determined for the stocks assessed were MSY, B_{msy}, B/B_{msy}, F_{msy}, F/F_{msy}, and current biomass relative to unfished biomass (B/B_0). The MSY, F_{msy} and F/F_{msy} were determined to demonstrate to managers, the limits below or beyond which fishing is sustainable or unsustainable. The B_{msy}, B/B_{msy}, and B/B_0 were determined to demonstrate the degradation or rebuilding potential of the stocks, and as targets of rebuilding or maintaining the stocks at optimal levels. The B_{msy}, which is an absolute number, is particularly important as it can easily be understood by managers.

Our assessment is the first to provide FRP for the system. Fisheries management in the system is not effective, as depicted in the declining CPUE (Bassa et al., 2014; Lubala et al., 2018). The FRP are envisaged to stimulate effective management and provide a basis for evaluation. Our assessment responds to calls to assess data-limited fisheries and develop responsible inland fisheries (FAO, 2020; FAO, & MSU, 2015).

2 | MATERIALS AND METHODS

2.1 | Approach

From a fisheries perspective, the assessed species were assumed to form distinct stocks within the waterbodies. In Lake Edward, all species were assumed to form subpopulations in the eastern, Ugandan side of the lake, with little exchange with the western subpopulation in the DRC; also the DRC fishers were assumed not to fish in Uganda and vice versa. While there is no evidence of the actual existence of separate stocks, we assumed restricted exchanges because the assessed species dominantly use nearshore, shallow and vegetated fringes as habitats (Table 1). Nile tilapia (*Oreochromis niloticus*), one of the most important species for fisheries, is restricted to shallow habitats of <20 m (van Oijen, 1995), while North African catfish (*Clarias gariepinus*) was found to predominantly use vegetated fringes in Lake Edward (Mbalassa et al., 2015). Because only catch data for Uganda were used, the generated FRP apply only to Uganda.

The FRP were based on four stock assessment methods for data-limited fisheries: Length-based Bayesian Biomass (LBB; Froese et al., 2018a), abundance-based maximum sustainable yield (AMSY; Froese et al., 2019a), catch-based maximum sustainable yield (CMSY), and a Bayesian Schaefer Model (BSM; Froese et al., 2017). The LBB is a Bayesian model, considering prior knowledge on the stock, while the AMSY, CMSY, and BSM are mixed Bayesian and Monte Carlo methods. These methods are user friendly with open source software, facilitating easy application to the fish stocks of interest. Also, the methods have fewer data needs compared to similar methods such as length-based model (Hordyk et al., 2015) and the Length-based Integrated Mixed Effects model (Rudd & Thorson, 2018).

The LBB uses length frequency data from commercial landings to estimate asymptotic length (L_{inf}), length at first capture (L_c), and somatic growth rate, K. The LBB then estimates natural mortality rate (M) relative to K (M/K), fishing mortality rate (F) relative to K (F/K), F relative to M (F/M), and total mortality rate (Z) relative to K (Z/K). These estimates are further used to derive stock status reference points: the current exploited biomass to unexploited biomass ratio (B/B_0), an indicator of fish stock depletion; the optimal length at first capture (L_{c_opt}) that would maximize catch and biomass at the prevailing fishing effort; the mean optimal length in catch (L_{opt}) that would maximize unexploited biomass; and B/B_{msy}. The LBB assumes that most fish species grow throughout their lives and approach L_{inf} in absence of mortality, that gear selection is sigmoid where small individuals are not caught and all individuals past a certain size are caught, and that CPUE is proportional to biomass. Gillnets and hooks are the main gears for the assessed fish stocks and their selectivity should be consistent with the assumed selectivity because multiple hook sizes and mesh sizes are used and capture of small fish before maturity is discouraged. The LBB method was criticized by Hordyk et al. (2019) for limited sensitivity analysis for parameter estimates, the use of biased L_{inf} and M/K prior, and the failure to account for reduced recruitment at stock sizes below B_0 when estimating B/B_0 and B/B_{msy}. These inefficiencies were addressed and besides, the LBB has a provision to replace the L_{inf} prior with better independent estimates if available (Froese et al., 2019b).

The AMSY approach estimates FRP from relative abundance and resilience, a measure of the speed by which a population can recover from a depleted state and is a summary description for the intrinsic rate of population increase (Froese et al., 2017; Froese et al., 2019a). The estimated FRP are F_{msy}, F/F_{msy}, and B/B_{msy}. The CMSY approach uses catch and resilience data and, if available for analysis by a full BSM, biomass or CPUE to estimate MSY, F_{msy},

B_{msy}, *F*, biomass, B/B_{msy}, and F/F_{msy} (Froese et al., 2017). If biomass or CPUE are available and reliable, as it was the case for our assessed stocks, the results of BSM are typically preferred for fisheries management over those of CMSY because they are based on more data. In addition to the FRP, the CMSY and BSM generate Kobe stock status plots to visualize the status of the stocks. The CMSY and BSM methods build on surplus production principles and assume that every stock in a fishery has a specific carrying capacity (*k*) and that the stock biomass tends to grow back to k when reduced, for example, by fishing. The growth will depend on the intrinsic growth rate of the population (*r*) and is low at low or high populations levels and maximum at *k*/2. Because new biomass production is maximized at *k*/2, the approach assumes that *k* is approximately equal to B_0 and determines MSY as the biomass accumulation when B_0 is halved. The equations and explanations of how these FRP are estimated are described in Froese et al. (2017), Froese et al. (2018a), and Froese et al. (2019a).

2.2 | Assessed species, data acquisition, and application

Only five of the eight species of fisheries importance in the system were assessed (Table 1). The assessed species include the most important species in the fisheries of the waterbodies. The species are benthopelagic or demersal, utilizing nearshore and open water habitats. The species were selected because they had adequate data for the approaches used.

The length frequency data for the LBB (Musinguzi, 2020) were obtained from the National Fisheries Resources Research Institute (NaFIRRI), Uganda. NaFIRRI conducts catch assessment surveys at fish landing sites spread across the waterbodies (Figure S1), generating data representative of the exploited size range of the species, a requirement of the LBB (Froese et al., 2018a). Based on suitable data (Table S1), the assessment included seven stocks belonging to four fish species (Table 1). Length at which 50% of individuals reach maturity (L_{m50}) is an input into the LBB to generate the percentage of mature fish in catches. The L_{m50} for the species, except for Semutundu (*Bagrus docmak*), were obtained from FishBase (Froese & Pauly, 2019). Compared to the observed maximum length (L_{max} of 100 cm), the L_{m50} values for Semutundu available in FishBase appeared to be underestimated because L_{m50} for fish species is generally one third to half of L_{max}, depending on the species (Cushing, 1981; Pauly, 1984). As a result, the L_{m50} for Semutundu was set to 30 cm. The estimated L_{inf} for the same species during the first round of implementation of the LBB with Lake Edward data differed by more than 10, from 66.2 cm in 2006 to 79.9 cm in 2017. As recommended (Froese et al., 2018b), the L_{max} and median L_{max} (80 cm) across the years with data (Table S1) were used as a guide to set L_{inf} to 80 cm for the species.

The data requirements for the AMSY are abundance and resilience (Froese et al., 2019a). Fishery dependent CPUE was used as a proxy for abundance (Musinguzi, 2020). Catch per boat per gear per day derived from fish landings data available at NaFIRRI was used as the CPUE. The fish landings are normally recorded at landing sites (five on Lake Edward, three on Lake George and two on the Kazinga channel; Figure S1; Bassa et al., 2014). To create continuous time series, single data gaps in CPUE were filled by averaging values of the preceding and subsequent years. Linear interpolation was used for two to three consecutive data gaps. Fish stocks with more than three consecutive data gaps were excluded from the analysis to minimize uncertainties.

Ten stocks, belonging to four fish species, were analyzed by the AMSY (Table S2). Resilience for the species was obtained from FishBase. The AMSY method also requires as priors, the lower and upper limits of the relative stock size (B/B_0) for a given year in the time series of the CPUE, preferably the year with the best fit in the LBB if LBB results are available. In our case, LBB results were available for Nile tilapia and Semutundu in Lake Edward. The year with the best fit was 2012 and the estimated B/B_0 95% confidence limits were 0.076–0.17 and 0.021–0.041 for the species respectively. Because these narrow ranges would strongly pre-determine the AMSY analysis, the respective B/B_0 priors were instead set to the strongly depleted range of 0.01–0.2 (Froese et al., 2019a). For the other stocks, relative stock biomass was provided for the first year in the time series and set at the strongly depleted range, informed by our knowledge of fisheries in the system (Bassa et al., 2014; Lubala et al., 2018).

The CMSY and BSM were conducted for the same stocks as AMSY. The catch data used by the CMSY and BSM (Musinguzi, 2020) was estimated by combining the CPUE, the number of boats on the waterbodies and the average number of annual fishing days (LVFO, 2005). The CMSY and BSM methods also require priors for resilience and B/B_0 at the start, intermediate and end of the available catch time series which can be from the LBB estimates, expert knowledge or default values (Froese et al., 2019c). For Semutundu in Lake Edward, the B/B_0 priors at the start and intermediate (2012) stages were obtained from LBB. The estimates of LBB for Nile tilapia in Lake Edward were only used as a guide for the same reason as in AMSY (Froese et al., 2017). The B/B_0 at the end of the time series for both species were default values because the end year (2019) was not covered by the LBB. Default values were adopted for other stocks. All default values suggested very low stock levels (0.01–0.2) based on the existing knowledge of intensive fishing (Bassa et al., 2014; Lubala et al., 2018). The intermediate year was set at 2012 for all the stocks other than Elephant-snout fish (*Mormyrus kannume*) in Lake Edward whose intermediate year was set at 2013 because 2012 is the start year in its time series.

For Semutundu in Lake Edward, a stable CPUE was observed, despite the declining biomass probably due to an unquantified increase in fishing effort (effort creep). The effort creep can be caused, among others, by improved efficiency of fishing (Palomares & Pauly, 2019). Such aspects have been experienced in our stocks as a response of fishers to declining CPUE (Lubala et al., 2018). The CMSY, BSM, and AMSY were, therefore, implemented with an assumed effort creep

TABLE 2 Length-based Bayesian Biomass (LBB) estimates for key stock assessment metrics in Lake Edward (LE), Lake George (LG) and Kazinga channel (KC). Parameters are as defined in the text. All priors are estimated by LBB, unless stated in text; results in bold are means of last 3 years with data (Table S1); L_{inf} is the median across years; and values in parenthesis are approximate 95% confidence limits

Parameter	Nile tilapia_LE	Nile tilapia_LG	North African catfish_LG	Marbled lungfish_LG	Semutundu_KC	Semutundu_LG	Semutundu_LE
L_{inf} prior (cm)	48.8 ± 0.49	44 ± 0.44	123 ± 1.2	134 ± 1.3	80 ± 0.8	80 ± 0.8	80.0 ± 0.8
L_{max}	51	60	124	150	72	102	100
median L_{max}	44	44	106	126	66.5	93	80
Z/K prior	5.7 ± 2.1	5.6 ± 2.4	4.3 ± 2	3.3 ± 5	3.4 ± 0.38	3.9 ± 0.18	5.1 ± 0.34
M/K prior	1.5 ± 0.15	1.5 ± 0.15	1.5 + 0.15	1.5 ± 0.15	1.5 ± 0.15	1.5 ± 15	1.5 ± 0.15
F/K prior	4.16	4.12	2.78	1.84	1.94	2.38	3.62
L_c prior	24.5 ± 2.4	19.4 ± 1.9	37.2 ± 3.7	58.1 ± 5.8	29.6	26.5 ± 2.7	23.5 ± 2.3 cm
Lc50	25.3 (25.2–25.4)	21.1 (21–21.3)	45.7 (45.3–46.1)	64.4 (63.5–65.4)	40.3 (39.7–40.9)	35.3 (34.9–35.8)	31.7 (31.4–32.4) cm
L_{inf}	49(48.3–50)	42.4 (41.6–43.3)	112 (111–114)	135 (133–137)	77.3 (75.9–78.5)	80.5 (79.1–82.1)	81.8(79.8–82.8)
$\mathbf{L_c/L_{inf}}$	0.52 (0.52–0.53)	0.49 (0.49–0.49)	0.41 (0.4–0.41)	0.49 (0.48–0.5)	0.54 (0.53–0.55)	0.45 (0.44–0.45)	0.41 (0.41–0.42)
$\mathbf{L_{mean}/L_{opt}}$	0.87	0.8	0.62	0.84	0.7	0.8	0.69
$\mathbf{L_c/L_{c\_opt}}$	0.8	0.73	0.57	0.78	0.7	0.73	0.65
Mature	85%	3.1%	97%	25%	81%	87%	26%
$\mathbf{F/M}$	6.5 (5.2–8.9)	5.4 (4–7.4)	35 (−317–351)	3.3 (2.6–4.2)3	17 (8.7–71)	14 (7.6–45)	9.6 (7.1–14)
$\mathbf{F/K}$	8.7 (7.9–9.5)	6.7 (6.2–7.4)	11 (10–12)	5.8 (5.1–6.7)	6.3 (5.6–7)	6.7 (6.1–7.6)	12 (11–14)
$\mathbf{Z/K}$	10 (9.4–11)	8.1 (7.5–8.7)	12 (11–13)	7.3 (6.7–8.2)	6.6 (6–7.3)	8 (7.5–8.8)	13 (13–15)
$\mathbf{Y/R'}$	0.024 (0.016–0.037)	0.016 (0.01–0.022)	0.0065 (0.0021–0.011)	0.038 (0.02–0.061)	0.0076 (0.00059–0.032)	0.015 (0.01–0.021)	0.0035 (0.0024–0.0052)
$\mathbf{B/B_0}$	0.11 (0.076–0.17)	0.076 (0.051–0.11)	0.04 (0.022–0.061)	0.17 (0.093–0.26)	0.014 (0.0011–0.06)	0.11 (0.077–0.16)	0.029 (0.021–0.041)
$\mathbf{B/B_{msy}}$	0.31 (0.21–0.46)	0.2 (0.13–0.28)	0.1 (0.056–0.16)	0.45 (0.25–0.71)	0.036 (0.0028–0.15)	0.31 (0.21–0.43)	0.082 (0.059–0.12)
Stock status	Recruitment impaired	Collapsed	Collapsed	Recruitment impaired	Collapsed	Recruitment impaired	Collapsed

of 4% so that the decline in CPUE matches the decline in biomass predicted by the LBB from 2007 onward.

3 | RESULTS

3.1 | LBB results

The length frequency distributions for each of the species were asymmetric, a pattern produced by a combination of multiple gear types and sizes (Figures S2–S8; top middle & right). Table 2 shows the prior variables and current estimates (averages for the last 3 years with data) of stock status.

The estimates of stock status demonstrated that the stocks were exposed to high fishing effort and capture of fish before maturity. Four of the seven analyzed stocks (Nile tilapia in Lake Edward, North African catfish in Lake George, and Semutundu in Kazinga channel and Lake George) had mean length in catch (L_{mean}) above L_{m50} and close to L_{opt} (Figures S2–S8; bottom left). As a result, most of the fish in the catch were mature (Table 2). This observation contrasted with the rest of the stocks whose catches were mostly immature. However, all the stocks had L_{mean}/L_{opt} and L_c/L_{c_opt} less than one, a sign of growth overfishing (capture of young fish). Estimates of F/M, F/K, and Z/K were far above the reference levels showing that the stocks in all water bodies were experiencing high F (excessive fishing pressure). Trends in F/M suggested that the stocks have been exposed to excessive fishing pressure for a long time despite a recent improvement in some stocks (Figures S2–S8 bottom middle). Consequently, the estimates B/B_0 and B/B_{msy} were far below the desired levels, showing that the current biomasses were only a fraction of the unexploited biomasses and those of exploitation at MSY levels (Table 2). Based on estimates of B/B_{msy}, four of the stocks were classified as collapsed and the restt as recruitment impaired. Annual trends in B/B_0 reflected long term stable biomass but at low levels, biomass depletion and the slight recent improvement in some stocks (Figures S2–S8; bottom right).

3.2 | AMSY results

The AMSY suggested that the CPUE for the stocks has been declining or relatively stable. The CPUE declined for most of the stocks, including African catfish in Lake Edward and the Kazinga channel, Elephant-snout fish in Lake Edward and Nile tilapia in all water bodies. The CPUE was stable for African catfish in Lake George and all the Semutundu stocks. Table 3 shows the estimates of stock status for the stocks that were consistent with those of the LBB, further showing evidence of high fishing effort and overfishing, i.e. high F/F_{msy} and low B/B_{msy} values. The F/F_{msy} was highest for Nile tilapia in the Kazinga channel and lowest for Semutundu in the same water body (Table 3). Generally, the estimates of F/F_{msy} were highest for the Nile tilapia stocks. The estimates of B/B_{msy} estimates across stocks showed that the exploited biomass was 18.2%–50.2% of the B_{msy}. Annual trends for these estimates indicated a consistent increase in F and a corresponding decline in B/B_{msy}, indicating the depletion of exploited biomass to levels at which stocks are either recruitment impaired, collapsed or overfished (Table 3; Figures S9–S18e–f).

3.3 | CMSY and BSM results

A BSM using catch and CPUE data generated management recommendations. The observations suggested that the catch for the stocks has been less than MSY over time (Figures S18–S28 top left). Fishing below MSY should ensure high biomass, stable catches and overall healthy status of stocks. However, the observed estimates of stock status were not in line with this expectation, possibly because the catches were still too high for the much-reduced biomass as a result of previous catches overshooting MSY. That the low catches still constitute overfishing can be seen in the high and increasing F/F_{msy} (Table 4; Figures S18–S28 lower left; Figures S29–S38e), the degradation of B/B_{msy} (Figures S29–S38d), and fishing below equilibrium (Figures S29–S38f). The collective poor status of the fisheries is further demonstrated by states of low biomass and high

TABLE 3 Abundance-based maximum sustainable yield stock status estimates for the different stocks in Lakes Edward (LE), George (LG) and the Kazinga channel (KC)

Stock	F_{msy} (r/2)	F/F_{msy}	B/B_{msy}	Stock status
Elephant-snout fish-LE	0.167 (0.0891–0.303)	1.58 (0.169–4.23)	0.332 (0.18–0.592)	Recruitment impaired
Nile tilapia-LE	0.165 (0.0974–0.281)	3.03 (0.937–6.12)	0.186 (0.102–0.344)	Collapsed
Nile tilapia_LG	0.177 (0.097–0.326)	2.44 (0.593–5.21)	0.228 (0.127–0.403)	Collapsed
Nile tilapia_KC	0.129 (0.0671–0.267)	3.51 (0.728–6.08)	0.182 (0.103–0.302)	Collapsed
North African catfish-LE	0.106 (0.08–0.171)	1.4 (0.301–3.71)	0.238 (0.152–0.417)	Collapsed
North African catfish-LG	0.182 (0.101–0.321)	1.33 (0.114–3.55)	0.469 (0.256–0.847)	Recruitment impaired
North African catfish-KC	0.171 (0.0944–0.297)	2.04 (0.354–4.85)	0.225 (0.124–0.406)	Collapsed
Semutundu-LE	0.176 (0.103–0.309)	1.93 (0.342–4.42)	0.414 (0.229–0.739)	Recruitment impaired
Semutundu-LG	0.17 (0.0956–0.294)	1.52 (0.12–4.07)	0.35 (0.192–0.631)	Recruitment impaired
Semutundu-KC	0.195 (0.106–0.357)	1.27 (0.112–3.25)	0.502 (0.279–0.898)	Overfished

TABLE 4 Estimates of stock status based on CMSY and BSM with approximate 95% confidence limits in parentheses. Estimates for F_{msy}, MSY and BMSY are long-term averages while others are for the last year in the dataset (2019). Bold B/B_{msy} values show recruitment impaired stock status and other values show collapsed stock status. The suffix in the stock name refers to a waterbody: Lake Edward (LE), Lake George (LG), and Kazinga channel (KC)

Stock	F_{msy} (1/year), adjusted for low stock size	MSY (1,000 tonnes/year)	B_{msy} (1,000 tonnes)	B (1,000 tonnes)	B/B_{msy}	F (1/year)	E (F/F_{msy}), adjusted for low stock size
Elephant-snout fish_LE	0.172 (0.103–0.286)	0.813 (0.563–1.17)	3.13 (2.06–4.75)	1.03 (0.708–1.38)	**0.331 (0.226–0.442)**	0.456 (0.341–0.666)	2.67 (1.41–5.68)
Nile tilapia_LE	0.0366 (0.0217–0.0616)	1.96 (1.32–2.91)	10.3 (6.92–15.2)	0.981 (0.662–1.4)	0.0957 (0.0646–0.137)	0.442 (0.31–0.655	12.2 (6.22–24.6
Nile tilapia_LG	0.127(0.0752–0.215)	2.17(1.49–3.17)	7.86(5.07–12.2)	1.81(0.993– 3.11)	0.23(0.126–0.396)	0.272(0.158–0.495)	2.12(0.728–7.16)
Nile tilapia_KC	0.0624 (0.0347–0.112)	0.177 (0.119–0.261)	0.735 (0.478–1.13)	0.0953 (0.0471–0.189)	0.13 (0.0642–0.258)	0.394 (0.198–0.796)	6.36(1.55–25.9)
North African catfish_LE	0.129 (0.0825–0.203)	0.542 (0.388–0.757)	2.59 (1.67–4)	0.798 (0.513–1.11)	0.309 (0.198–0.43)	0.367 (0.263–0.571)	2.87 (1.48–6.45)
North African catfish_LG	0.263 (0.168–0.411)	1.38 (0.957–2)	4.48 (3–6.68)	1.9 (1.46–2.28)	**0.425 (0.326–0.509)**	0.324 (0.27–0.421)	1.25 (0.793–2.11)
North African catfish_KC	0.119 (0.0699–0.203)	0.132 (0.0918–0.19)	0.518 (0.342–0.785)	0.121 (0.0821 –0.175)	0.234 (0.159–0.338)	0.381 (0.263–0.561)	3.21 (1.53–6.93)
Semutundu_LE	0.113 (0.0715–0.18)	1.11 (0.795–1.54)	5.97 (3.74–9.54)	1.83 (1.01–2.67)	**0.306 (0.17–0.447)**	0.413 (0.283–0.746)	3.68 (1.71–10.9)
Semutundu_LG	0.213 (0.134–0.341)	1.42 (1–2.02)	4.82 (3.18–7.31)	1.74 (= 1.19–2.21)	**0.361 (0.248–0.458)**	0.318 (0.25–0.463)	1.51 (0.878–3.08)
Semutundu_KC	0.263 (0.162–0.426)	0.271 (0.182–0.404)	0.885 (0.575–1.36)	0.379 (0.297–0.458)	**0.429 (0.336–0.517)**	0.412 (0.341–0.526)	1.59 (0.993–2.68)

Abbreviations: BSM, Bayesian Schaefer Model; CMSY, catch-based maximum sustainable yield; MSY, maximum sustainable yield.

exploitation rates (Figures S18–S35; bottom right), and by the stock specific Kobe plots, which showed that stocks are in danger, requiring urgent management (Figures S39–S48). Current estimates for the stocks show low B/B_{msy} and high exploitation rates (Table 3). The long-term estimates of MSY, F_{msy} and B_{msy} are given in Table 4. The long-term estimates of these indicators showed that each stock was exploited below its long-term potential as the MSY was higher than the recent catches (2019) for each stock (Figure 1). The gap between MSY and catches was more pronounced for the stocks of Nile tilapia and Semutundu. For instance, 380.5 tonnes were reported in 2019 instead of the long term MSY of 2,170 tonnes for Nile tilapia in Lake George, 453.2 tonnes instead of 1,960 tonnes for the same species in Lake Edward and 616.96 tonnes instead of 1,420 tonnes of Semutundu in Lake George (Table 4; Figure 1).

4 | DISCUSSION

Four stock assessment methods for data-limited fisheries were used to provide first comprehensive FRP for stocks in the Lake Edward system, contributing to the needs to increase national level stock assessments in developing countries (FAO, 2020). Applied to fish stocks elsewhere (Palomares et al., 2018; Wang et al., 2020), such methods are envisaged to be pivotal in increasing the volume of assessed stocks (FAO, 2020).

The data used in this study have some caveats. The length, CPUE, and catch data had data gaps. The gaps in length data, for instance deprived us insights into stocks with no recent data (Table S1). The filling of data gaps in CPUE and catches by averaging and linear interpolation could be a source of uncertainty. This caveat was minimized by eliminating stocks with substantial data gaps. The estimates of life history parameters, such as L_{m50}, from FishBase may not necessary be up-to-date, and updating these estimates could improve future assessments. We assumed minimal exchanges among stocks and fishing effort in Lake Edward between Uganda and DRC and among the water bodies because they are connected. Our assumption holds because none of the species considered is highly migratory (Table 1), and stocks in Uganda are not subjected to the fishing effort from the DRC. The interpretation and use of the FRP should consider these data issues.

4.1 | Status of the stocks

Basing on B/B_{msy} (Palomares et al., 2018), all the stocks were in a poor state, assessed as either collapsed, recruitment impaired, or overfished (Tables 2–4). The four methods used mostly agreed on the status of the stocks. However, the stock status slightly differed for three stocks (North African catfish in Lake George, Semutundu in the Kazinga channel and Semutundu in Lake Edward), which were classified as collapsed by the LBB and as recruitment impaired, overfished, and recruitment impaired respectively, by the AMSY and BSM. In the Lake Edward system, the poor status of the stocks is consistent with increasing fishing effort and illegal fishing (Bassa et al., 2014; Lubala et al., 2018). The aspects of high fishing effort and illegal fishing were evident in our results.

The LBB confirmed the high fishing effort for all the stocks with values of $F/M > 1$, $F/K > 3$, and high values of Z/K, which are indicators of intensive fishing. The $F/F_{msy} \geq 1$ from AMSY and BSM further indicate intensive fishing (Froese et al., 2017; Froese et al., 2019a).

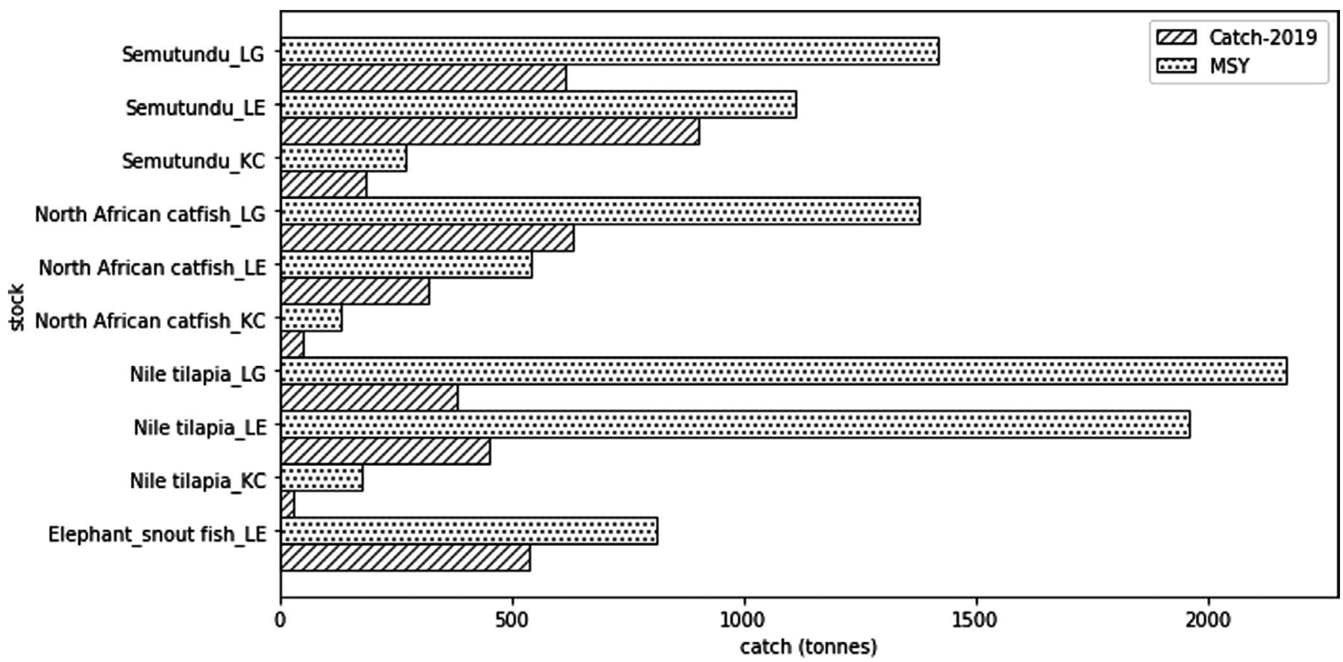

FIGURE 1 Estimates of maximum sustainable yield (MSY) in relation to observed catches in 2019 for stocks in lakes Edward (LE), George (LE) and the Kazinga channel (KC)

Intensive fishing effort depletes fish stocks through habitat degradation, growth and recruitment overfishing (Benoit & Swain, 2008). Growth overfishing was reflected in the assessed stocks by the capture of fish at length lower than $L_{c\text{-}opt}$, low ratios of L_{mean}/L_{opt} and L_c/L_{c_opt}, and recruitment overfishing by low estimates of B/B_0 and B/B_{msy} (Wang et al., 2020). However, four of the assessed stocks had high maturity proportions in the catch (Table 2). With these values, overfishing should be less likely, and biomass would be expected to be close to B_{msy}; instead biomass was found to be far below B_{msy}. This observation suggests that illegal fishing of undersized fish may be ongoing, but not reported at designated fish landing sites, a common practice among fishers. The low B/B_{msy} ratios can also be attributed to the high fishing effort at low biomass levels.

Ripon barbel (*Labeobarbus altianalis*), Blue spotted tilapia (*Oreochromis leucostictus*), and *Labeo forskalii*, three species of commercial importance, were not assessed due to data limitations. The stock status of Ripon barbel and *L. forskalii* is likely to be worse than each of the assessed stocks, emanating from very low resilience and turnover rate, i.e. population doubling time of 14 years for Rippon barbel (Froese & Pauly, 2019), and low abundance for *L. forskalii* (NaFIRRI, 2019). These aspects make the species susceptible to high fishing pressure. On the other hand, the stock status of Blue spotted tilapia is probably comparable to that of Nile tilapia.

4.2 | Fish production potential

Poor stock status emanating from mismanagement reduces catches (Benoit & Swain, 2008). In this assessment, the magnitude of reduction was demonstrated by the comparison of the long-term estimates for MSY with catches for 2019 (Figure 1). The total catches of 4,107 tonnes in 2019 were nearly 2.5 times lower than the estimated MSY of 9,975 tonnes for all the stocks. It is intriguing why sustainable fishing that would result into more fish is difficult to adopt (Boonstra & Österblom, 2014). The magnitude of loss determined in this assessment should be an incentive for adopting more effective management measures to utilize the full fisheries potential of the waterbodies.

4.3 | Implications (targets and limits) for sustainable management

The fish stocks in the Lake Edward system require interventions to rebuild to sustainable levels. Rebuilding of stocks will benefit riparian communities whose livelihoods depend on fisheries, given the restrictions on crop and livestock farming within protected areas (Uganda Wildlife Authority, 2012). The overall target for the interventions should be rebuilding biomass for the stocks to the respective B_{msy} estimated by the BSM (Table 4). Intermediate targets should reduce the high fishing effort and eliminate the capture of fish before maturity. The most realistic solution is postponing the onset of fishing by extending the length at first capture to L_{c_opt} for each stock (Froese et al., 2016). If B_{msy} is achieved, the lower limits of the 95% confidence interval of MSY (Table 4) should be set as the catch limit to cater for uncertainties and species interactions.

Management of the Nile tilapia fisheries has focused on ensuring that length at capture is $\geq L_{m50}$ (25 cm total length) to protect immature fish (Fish Act, 1951). The estimates of stock status by the LBB demonstrate that this approach has been successful to some extent: most of the catch was mature, and L_{mean} above L_{m50} and close to L_{opt} in Lake Edward (Table 2). The stocks of Elephant-snout fish, Marbled lungfish (*Protopterus aethiopicus*), North African catfish, and Semutundu do not have size restrictions, but benefit from legislation that prohibits destructive gears such as trawling, basket traps, cast nets, and beach seining. Enforcing the size limits and legal gears could eliminate capture of immature fish, reduce fishing mortality, and increase biomass (Froese et al., 2016).

The high fishing effort, combined with illegal capture of immature fish, probably diminished the management benefits where size restrictions are enforced. Reluctance to control fishing effort is understandable: it is one of the most difficult aspects of fisheries management (Hilborn, & Walters, 1992). What makes it more difficult in the Lake Edward system is that fishers are poor, with limited livelihood diversification (Uganda Wildlife Authority, 2012). This situation partly explains why fishing effort has been increasing despite the deterioration of the fisheries. Additional factors that keep fishers in such fisheries include investing income from other activities into fishing. In such cases, the focus of management should be on reducing fishing effort by offering alternative employment and reducing the impact of fishing, e.g. by further increasing mesh sizes (Hilborn, & Walters, 1992). Also, the illegal fishing and marketing of undersized fish should be investigated and stopped if present. To support sustainable fishing, fishing communities could be supported to acquire proper gears by for example exchange of inappropriate gears against new, appropriate gears. Because these changes require substantial reductions in fishing effort, difficulties are expected in real implementation. An option could be to execute these changes gradually, species by species or year by year.

The application of data-limited stock assessment methods developed in marine systems to inland fish stocks is recommended to contribute to the sustainable management of inland fisheries (Cooke et al., 2016; Lorenzen et al., 2016). This assessment added to the literature applying such methods to inland fisheries. The assessment, like Fitzgerald et al. (2018) did for a fish stock in an Irish lake using CMSY, demonstrated that useful FRP can be successfully obtained for the inland fisheries if minimum data requirements are met. However, data availability remains a challenge to the extensive application of these methods, especially in developing countries.

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CONFLICT OF INTEREST

Authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data used is publicly available through figshare.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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